The Design of the F-22 "Raptor"

A Case Study of Teaming Agreements In the Aerospace Industry

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Section 1 – Introduction

The last half-century has seen more technological advances than perhaps any other 50-year period in world history. From space travel to microprocessors, the public has been given capabilities and possibilities that would have been unimaginable, let alone achievable, only two generations earlier. Though many different people have been involved in making these things possible, the military and the defense industry have always been two of the leaders in discovering and utilizing new technology.

One of the main forces driving this great leap forward in weapons technology was the Cold War with the former Soviet Union. The two sides constantly battled to produce a better weapons system, one that would make the enemy think twice before striking. This was especially true in the Air Force, as fighters became faster, more agile, and, most importantly, more lethal. In the late 1970's, however, the United States began to fully utilize a technology that would forever alter the battle for air superiority; they had discovered the ability to hide—stealth.

However, as capable as American research and development had become, our capitalist society still fostered competition and, therefore, could divide the best engineers against each other. Instead of combining their efforts on a project, their loyalties lay with their company.

As the size and scope of several of these defense projects grew, many aerospace firms began to realize that they did not have the capital to sink into the development of some of these systems. Moreover, the government began to realize that a single company could not produce as good a product as several companies could if they consolidated their efforts. Therefore, a trend has started over the last two decades of "teaming" for high-tech defense projects. Two or more companies come together to combine their efforts on a project, design and manufacture a quality product, and then split and go their separate ways.

One of the first major defense projects to utilize the teaming concept was the design and construction of the F-22 "Raptor", the United States' first stealth air-to-air fighter. This program covered nearly sixteen years from the time of the initial concept until the first production model fighter rolled out of the factory. There were four major phase for the F-22 program, with three types of contracts awarded. The program began with a Request for Information, asking aerospace companies to discuss technologies to be utilized in the design and construction of the fighter, as well as to develop a generalized concept for the aircraft. From the documents produced by the companies, the Department of Defense awarded contracts of approximately $1 million to seven companies to enter the "concept exploration" phase. During this phase, the seven companies began to research the technologies and improve upon their concepts. They were not tasked to provide detailed blueprints; rather, they were asked to expand upon their initial concept and develop a plan for the processes to be used in the design and manufacture of the fighter. At the end of this phase, two companies were awarded $700 million contracts to enter the demonstration/validation phase, during which they designed, constructed, and tested prototype aircrafts as well as created plans for the production model fighter. The demonstration/validation phase ended with a single contract, awarded to the team of Lockheed/Boeing/General Dynamics, for the Engineering and Manufacturing Development phase. This final contract in the program provided for the design, testing, and mass production of the Air Force's newest fighter.

This paper will examine the F-22 program, focusing on the highly creative design process for the construction of a test prototype during the demonstration/validation phase of the project. It will analyze the benefits of the teaming arrangement, as well as some of the legal, economic, and managerial obstacles that the companies were forced to overcome.

Section 2 – An Overview of the F-22 Program

Section 2.1 – The Advanced Tactical Fighter Concept

During the early 1970's the Air Force realized a need for an Advanced Tactical Fighter (ATF) to counter the increased capabilities of the Soviet Air Force. The ATF concept would utilize stealth technology and become the Air Force's premiere air-to-ground fighter-bomber. However, budget constraints and the need for a mass-produced, relatively cheap fighter forced the military to shelve the ATF concept. Instead, the focus shifted to the program that eventually became the F-16 "Falcon".

However, the ATF concept did not die. Though the F-15 "Eagle" was now the mainstay of Air Force air-to-air combat, it was already being matched by Soviet technology. In 1977, the Soviet Air Force unveiled the MiG-29 "Fulcrum", followed four years later by the Su-27 "Flanker". These two systems, though not as formidable as the F-15, guaranteed that the battle for air superiority would be a bloody fight, something that American planners were not willing to accept.

Section 2.2 – The ATF Request for Information and Concept Exploration

In 1981, the USAF's Aeronautic Systems Division (ASD) issued a Request for Information from the aerospace industry for the ATF concept. Nine different airframe companies responded, as did three engine companies. These firms had a wide variety of perspectives and experience with military aircraft design.

Over the course of the next four years, the companies brainstormed, developing a wide variety of concepts for the Air Force's newest fighter. Seven eventually submitted proposals for the concept exploration phase. All seven were awarded contracts of approximately $1 million each to expand upon their concepts. These companies were tasked to develop plans for the processes to be used during the demonstration and validation phase of the ATF program. They were not asked to produce detailed plans for a vehicle with precise engineering analysis. Rather, the Air Force was more interested in the methods and procedures that companies would use to complete the design, as well as the technologies that would be investigated to meet the military's stringent performance requirements.

Working individually, the companies developed many varied ideas for the ATF, ranging from typical fighter configurations to flying wing designs. The companies were to present their concepts to the Air Force in May 1985. However, two events late in the concept phase drastically changed the design process for the ATF.

Originally, the USAF was to award four contracts of $100 million each for the demonstration and validation (dem/val) portion of the program. This portion would

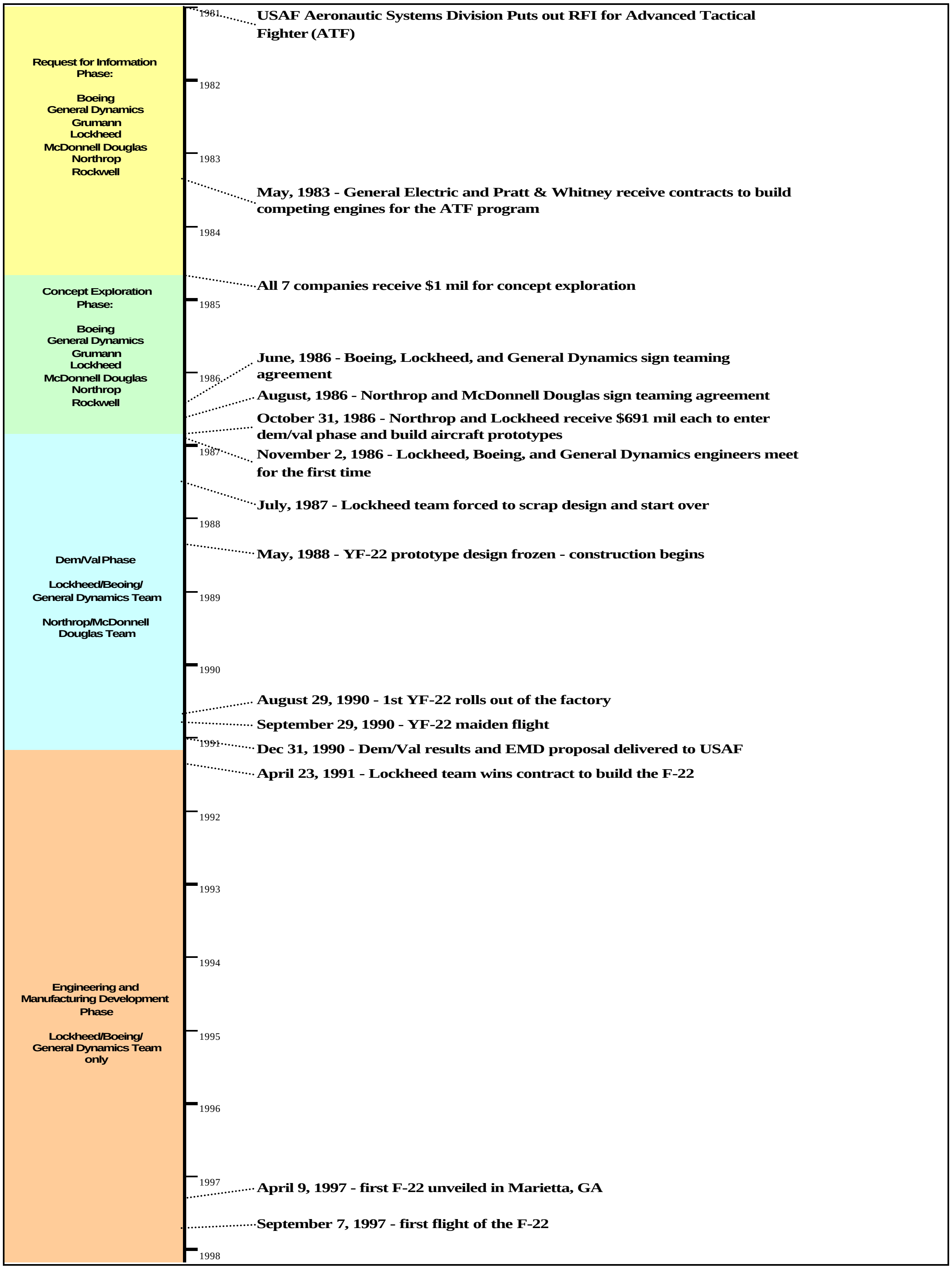

Figure 1 - Advanced Tactical Fighter Development Timeline

involve the creation of detailed plans for the construction of production model fighters. However, changes were afoot in the acquisition methods of the Department of Defense. Due to the success of the F-16 program, the USAF modified its request to include the production of two prototype aircraft during the dem/val portion of the program. This increased the value of the contracts to be awarded to $700 million apiece. To offset this increased cost, the Air Force would only award two contracts for dem/val, instead of four.

The second factor that would significantly alter the engineering process for the ATF was presented in a cover letter that the USAF sent to each of the companies. In it the Air Force suggested that the companies consider teaming. As Col. Albert Piccirillo, head of the USAF ATF Program office at the time, put it, the Air Force "wanted the best resources from industry to be brought to bear on the program" (Hehs 1998). Most of the companies immediately began negotiating and jockeying for position as teams began to emerge. In June 1986, Boeing, Lockheed, and General Dynamics signed a teaming agreement. Two months later, Northrop and McDonnell Douglas signed a similar agreement. Grumman and Rockwell, meanwhile, remained independent.

Section 2.3 – Demonstration/Validation Contract Awards

In October 1986, the Department of Defense announced that Lockheed and Northrop had won contracts of $691 million for the design and construction of the ATF prototypes to be named the YF-22 and YF-23 (Figure 2), respectively. The team of Lockheed, Boeing, and General Dynamics

Figure 2 – YF-23 Black Widow II

immediately went to work on the design process. With Lockheed designated as the team leader, a plan was put in place to best combine the efforts and abilities of the three companies.

Four years later, on August 29, 1990, the YF-22 rolled out of a hangar at Lockheed's Palmdale, California plant. It flew for the first time one month later, undergoing a rigorous flight test program to validate the performance capabilities as designed by the engineers. On December 31, 1990, the team's formal report was delivered to the USAF. On April 23, 1991, the Lockheed/Boeing/General Dynamics design was chosen as the winner for the production of the F-22 "Raptor", beating out the Northrop/McDonnell Douglas YF-23. The program now moved into the Engineering and Manufacturing Development phase to finalize a production model for the ATF.

Section 2.4 – The F-22

For the next six years the team worked diligently to develop the final design for the F-22. On April 9, 1997, Aircraft 4001, the first F-22, was unveiled in Marietta, Georgia, the product of sixteen years of intense brainstorming, designing, and testing. Though it continued to undergo minor changes throughout the next few years, the F-22 provides the "first-look, first-shot, first-kill" capability that the USAF required.

The F-22 "Raptor" is a two-engine, two-tailed air superiority fighter designed to provide absolute control of the skies to the US military. Its maneuverability, stealth, and supercruise capability push it far beyond the technological prowess of potential adversaries.

The F-22's maneuverability is unprecedented in the world of air-to-air-combat. This is due primarily to its unique aerodynamic design and its high thrust-to-weight ratio. During flight-testing, the F-22 was shown to maintain pitch and roll control up to 60 degrees angle of attack (Beesley 1991). In other words, the aircraft can essentially be falling out of the sky and yet still have the control authority to point its nose (and therefore its weapons) anywhere it wants.

The Raptor is powered by two Pratt and Whitney F119 turbojet engines. The design incorporates a 2-dimensional thrust vectoring system that greatly increases the aircraft's turning ability. Because of the power of the engines and the aerodynamics of the aircraft, the F-22 is capable of Mach 1.8 (Sweetman 1998). Moreover, the Raptor can maintain supersonic airspeeds without the use of afterburner (supercruise), greatly decreasing both fuel consumption and infrared signature.

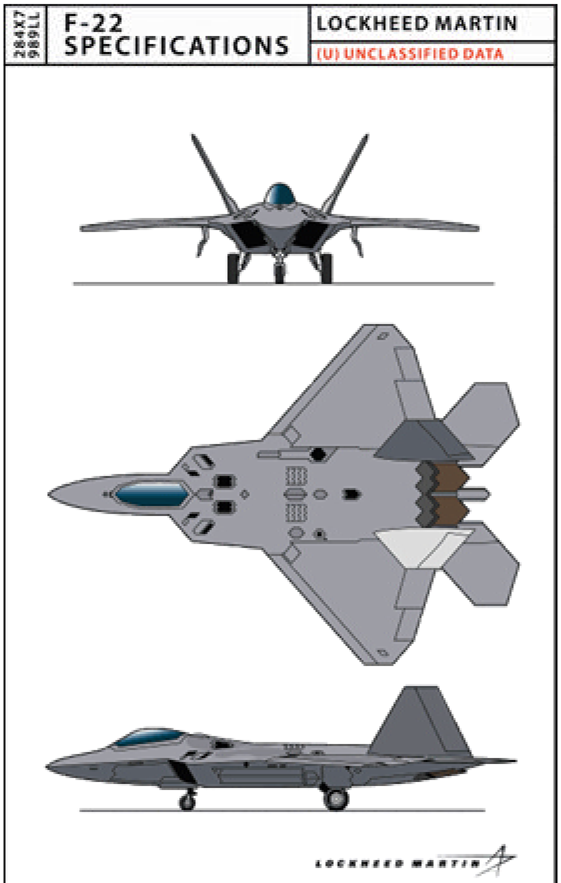

Figure 3 - F-22 Raptor

The aircraft structure is 39% titanium, 24% composite, 16% aluminum, and 1% thermoplastic by weight (Hehs 1998). The structural design and materials used give the F-22 a very small radar cross-section, making it virtually undetectable by enemy radars. On the other hand, it is equipped with the AN/APG-77 radar; although this radar's capabilities are highly classified, it guarantees that the F-22 will dominate the skies over the battlefield.

The fighter is designed to carry up to six air-to-air missiles in an internal weapons bay. It is capable of firing all current missiles in the USAF inventory: the heat-seeking AIM-9 Sidewinder, the radar guided AIM-7 Sparrow, and the AIM-120 Advanced Medium Range Air-to-Air Missile (AMRAAM). It has an M61A2 Vulcan cannon capable of shooting 480 rounds of 20mm ammunition, should it find itself in a dogfight. Finally, the F-22 was designed to carry two air-to-surface Joint Direct Attack Munitions (JDAM) should the Raptor ever be modified for the air-to-ground role.

However, all of the technological advancements of the F-22 would never have come to pass were it not for the hard work and dedication of the engineers and managers from Lockheed, Boeing, and General Dynamics. The origins of the design and the technologies involved, though, can be traced back to the initial request for information of the early 1980's.

<u>Section 3 – The Design of the ATF Pre-Teaming</u>

Section 3.1 – Requests for Information

When the USAF's ASD produced its request for information in 1981, most of the country's aerospace firms had vast experience in designing and developing military aircraft. However, their areas of expertise were varied and they initially took very different approaches to the fabrication of the ATF.

Lockheed had performed several studies on advanced stealth design for the Navy. Though a Navy stealth fighter never materialized, Lockheed had been awarded a contract for the design and production of the Air Force's F-117 stealth fighter-bomber. In fact, as early as 1959, Lockheed had experimented with radar-absorbing material and radar-evasive aerodynamic shaping for the defunct A-12 Navy attack aircraft. This aircraft was considered by many to be the first aircraft to be designed from the beginning with a stealth capability in mind (Hehs 1998). Moreover, Lockheed had developed a computer program called "Echo" that mathematically modeled the radar reflection from various flat surfaces. All these factors made Lockheed the company with the most experience in stealth technology.

General Dynamics, meanwhile, performed several studies on the need for stealth in the modern air battle. In particular, their "Red Baron Study" examined the US military's air losses during the Vietnam War. The study concluded that 80% of the aircraft fired upon and 50% of the aircraft shot down never saw their attackers (Hehs 1998). Therefore, it was General Dynamics' conclusion that stealth was a necessity for future US fighters.

Boeing also had performed early studies for the ATF concept. In 1980, the ASD had commissioned several reports from industry on the concept. Boeing combined with Grumman to produce a report entitled "Tactical Fighter Technology Alternatives." Though the report focused on air-to-ground fighter alternatives, they established themselves early as a company with the experience necessary to design the Air Force's newest fighter.

The companies also recognized several other attributes necessary in a modern fighter. The first of these attributes was “supercruise”. This is defined as the ability of an aircraft to cruise supersonically without the need for afterburners. Supercruise would not only allow an aircraft to get into a fight quicker, but would also increase its range and loiter time by saving fuel. Moreover, a non-afterburning engine has a significantly smaller infrared signature, a feature that is essential when battling an enemy with a highly capable heat seeking air-to-air and surface-to-air missile defense system.

A high degree of maneuverability would also be required in an advanced fighter. Though the ATF was meant to shoot down enemy aircraft before they knew it was there, the designers had to admit the possibility that the ATF would be forced into a visual dogfight with adversary aircraft. As Bill Moran, ATF program manager at General Dynamics, put it, “Down through history, successful air-to-air pilots have generally avoiding maneuvering engagements whenever possible. Sometimes they forgot, however” (Hehs 1998).

One of the major issues facing the companies during the whole of the concept phase was the tradeoff that would have to occur between stealth, maneuverability, and supercruise. For example, a stealthy shape is not very aerodynamic; moreover, weapons must be carried internally, making the cross-section larger. These factors increase aircraft drag, thus hurting supercruise and maneuverability. A highly maneuverable aircraft, meanwhile, requires larger wings and tail surfaces, aspects that increase the aircraft’s radar signature and drag.

Another attribute that was initially considered for the ATF was a short takeoff and land (STOL) capability. However, the structure and equipment required for STOL are very heavy, hurting speed and maneuverability. Moreover, a STOL capability is only necessary if the aircraft must takeoff quickly. Air Force doctrine assumed that the ATF would already be airborne when its services were required, so STOL was eliminated early in the concept phase.

In 1981, the USAF’s Tactical Air Command (TAC) officially published a “statement of need” naming the ATF as the replacement for the F-15. This statement solidified the ATF concept as a must-have in both the Department of Defense and the aerospace industry. Two years later, the USAF opened an ATF Program Office at

Wright-Patterson Air Force Base in Dayton, Ohio under the command of Col. Albert Piccirillo.

The USAF had also performed its own studies on required attributes for the ATF. In particular, they too realized that stealth was not a desire but a requirement for a modern fighter. Ironically, the initial Request for Information had not outlined stealth as a requirement. Therefore, at the last minute the Program Office modified its request mandating that the companies provide information on their concept's stealth capabilities. Since stealth was still a "black" project of a highly classified nature, this change caused several security headaches among the companies. More importantly, however, it forced Lockheed to completely abandon its initial concept and move towards an F-117 derivative.

The last-minute alteration to the Request for Information and the changes it forced upon Lockheed caused the company to finish last in this initial phase. However, all seven companies that submitted a concept were awarded contracts of approximately $1 million to pursue their concepts and create a formal proposal. These proposals, due to the government in May 1985, would move the ATF into the demonstration and validation (dem/val) portion of the design, with four $100 million contracts to be awarded to the top designs.

Section 3.2 – Concept Exploration

Lockheed was forced to completely reevaluate its concept due to its poor showing in the initial phases of the program. Though Lockheed was currently under contract to produce the F-117 stealth fighter, they had recently lost the competition to design the B-2 stealth bomber. Lockheed's stealth computer model "Echo" was excellent for modeling radar reflection from flat surfaces, but was not capable of computing similar results from smooth curves. Therefore, Lockheed's stealth bomber proposal had been a faceted aircraft composed of flat surfaces similar to the F-117 (Figure 4), instead of an aerodynamically curved surface. Northrop, however, designed a smooth shape for the B-2 bomber, which had a lot to do with it being awarded that contract. Because of this, and

Figure 4 - F-117 Nighthawk Stealth Fighter

(Note the faceted shape – there are very few curved edges on the aircraft's exterior.)

its poor showing in the request for information phase, Lockheed began experimenting with smooth shapes by building models and testing them on a radar range.

Lockheed's new concept (Figure 5) was a more aerodynamic fighter with four tails (two vertical, two horizontal). Since the USAF required the ATF to have 240-degree radar search cone (120 degrees either side of the nose), Lockheed mounted three separate radars in the nose. The design also required the inclusion of an Infrared Search and Track System (IRSTS); Lockheed solved this by mounting two sensors, one in each wing root.

General Dynamics began the concept exploration phase by considering a flying wing shape. However, the concept soon changed to a semi-tailless design, with only a single vertical tail (Figure 6). The decision on the number of tails for the fighter was a major stumbling block for General Dynamics. According to their calculations, a two-tailed aircraft would be highly unstable, yet a single-tailed configuration was much less stealthy. In the end, the single-tailed design won out. General Dynamics' design was able to utilize fewer sensors than either Lockheed's or Boeing's models, with a single IRSTS sensor in the nose and two radars total, one mounted on either side of the fuselage aft of the cockpit.

Figure 5 - Lockheed's ATF Concept

Boeing's proposed ATF was larger and faster than those developed by Lockheed or General Dynamics. Because of its length, it required only two tails for stability, though tail configuration was also a major point of contention at Boeing. The engines shared a single chin inlet, similar to a multi-engine F-16. Like Lockheed's design, five major

Figure 6 - General Dynamics' ATF Concept

sensors were required with three radars and two IRSTS's in the nose. Boeing's design would also incorporate unique thermoplastic manufacturing techniques and materials for the structure of the wing.

Similar to the initial Requests for Information, the Air Force again made last minute changes to the requirements. A few months before the dem/val contract was to be awarded, the USAF increased the importance of stealth for the ATF. The late modification had very little effect on Boeing and Lockheed, as stealth had been one of their primary focuses from the very beginning. However, General Dynamics was forced once again to reevaluate the one- vs. two-tail dilemma. Not wanting to make drastic changes at this point late in the competition, the company submitted their proposal with only one tail, realizing that their design was perhaps not optimized.

It was at this time that the Air Force not only modified the dem/val program to include the building of prototypes, but also issued the letter encouraging teaming. When the dust settled, Boeing, Lockheed, and General Dynamics had signed an agreement to create such a team should one of them win the contract. They agreed to each submit their proposals separately, with no cooperation between the members. If any of the three companies received the contract, it would be the team leader with the other two as its partners.

There were several factors helping the team members that perhaps gave them a slight edge over their competitors. Because they had finished dead last in the first portion of the ATF design, Lockheed was forced to assume a completely different approach and to do it in less time, something that was sure to impress the Air Force. Moreover, their vast experience in stealth design as well as their reputation for rapid prototyping, two qualities of ever-increasing importance, were sure to aid their proposal. Boeing's initial concept had done very well and they hoped it would continue to be well received. Though Boeing had never been awarded a modern fighter contract, they possessed vast experience in manufacturing and production processes. General Dynamic's strongest attribute was their recent experience with rapid prototyping; the YF-16, a contract that General Dynamics had eventually been awarded, was considered an "unsurpassed" prototyping program and the model for future prototyping of military aircraft (Hehs 1998).

On October 31, 1986, the announcement was made that Northrop and Lockheed had been awarded the contracts for the dem/val phase of the program. Two days later, approximately 100 senior managers and engineers from Lockheed, Boeing, and General Dynamics met for the first time at Lockheed's famous "Skunkworks" in Burbank, CA, beginning the process of building the members into a cohesive team.

Section 4.0 – General Teaming Concepts

Section 4.1 – The Definition of a Team

There were many reasons why the Air Force suggested to the participating companies that they consider teaming arrangements. However, before the reasons behind this can be examined, the legal meaning of "team" must first be examined.

A "joint venture" can be defined as a partnership "created by two or more separate entities who associate, usually to engage in one specific project or transaction" (Sweet 2000). A joint venture is what most people think of when they hear the term "team" used in industry. However, the Federal Acquisition Regulations (FAR's) define a team as either a joint venture or when "a potential prime contractor agrees with two or more other companies to have them act as subcontractors under a specified Government contract or acquisition program" (*Federal Acquisition Regulations* 2002). In other words, both types of teams are recognized by the government from a contracting and legal perspective.

Section 4.2 – The Benefits of Teaming

Teaming arrangements may be found in many different industries and contracts, both private and public. However, teaming arrangements are mainly used "when the federal government has embarked on programs to fulfill procurement needs, mainly in high-tech defense" (Sweet 2000). The reasons behind this statement are many; however, from the government's standpoint, one motive is the driving force: the government wants the best minds and capabilities from industry working on the development of high-tech weapons and defense systems. As discussed above, Lockheed was strong in the realm of stealth technology, General Dynamics had proven prototyping experience, and Boeing possessed a strong manufacturing and production capability. Combined, these companies could produce a better product than any of the companies could produce on their own. In other words, the Air Force suggested teaming arrangements because it wanted the best performance that industry could provide.

Teaming agreements are beneficial from industry's standpoint as well. One of the main reasons why companies team is to share the risk and cost of research and development. This was particularly true in the development of the F-22. The dem/val contract was worth approximately $700 million; however, many of the companies feared that the cost for the R&D and manufacturing of the two prototypes would be more than this. Therefore, the companies would have to invest their own money in the program in order to continue on the ATF project. Teaming meant that they would share the costs of the project, reducing their own investment.

Besides diversifying the risks and reducing investment, companies may team in order to increase manpower, pool their knowledge, and perhaps reduce the duration of the project. Though the legal aspects are often tricky, the ability to share information may produce a better product for the government.

Section 4.3 – The Types of Teams

As mentioned above, the FAR's specifically recognize two types of teaming arrangements, joint ventures and prime contractor-subcontractor agreements. However, these are simply the two extreme types of teams. A teaming agreement can create any type of relationship that is a middle ground between a pure joint venture and a prime-subcontractor relationship.

A pure prime contractor-subcontractor agreement creates a relationship that is very much like a standard subcontract. In such an agreement, the prime promises, usually before the contract itself is awarded, to sign a subcontract with a separate company. This type of agreement produces a chain-of-command and structure that is familiar to all the players involved and, therefore, is relatively easy to manage. Moreover, administrative and managerial staff does not need to be increased in such an arrangement. Liability issues also do not have to be specifically addressed in the agreement itself since the law treats such arrangements similar to a classic contractor/subcontractor relationship.

A prime contractor-subcontractor teaming agreement does have some disadvantages, however. In such a situation, one of the companies must take the lead as the prime contractor instead of the two fully sharing responsibilities. Furthermore, the agreement must discuss in great detail the guarantees and stipulations of the subcontract award as well as conditions to protect the subcontractor.

Joint ventures allow more interaction between the companies than with a pure prime-subcontractor agreement. Such an arrangement has many benefits but can also cause problems. A joint venture may have a better appearance to potential customers since the companies are combining their efforts. Moreover, the large flow of information between the companies may enlighten the parties as to techniques and procedures that they may be able to use after the partnership is terminated. However, a new organizational structure must be created. Also, there may be difficulties dealing with command and control and legal issues.

Both types of teaming agreements provide several benefits for both the parties involved and the client. However, managerial, legal, and organizational difficulties must be overcome in order to make such an arrangement a success.

Section 4.4 – Legal Aspects of Teaming

As discussed earlier, teaming in government contracts is legal and in fact endorsed by the government. The only stipulations that the government places on teams are that the teaming arrangement must be fully disclosed and that the agreement cannot violate antitrust laws. However, the teaming agreement should be very thorough in an attempt to limit discord among the members and possible litigation. Though a thorough document may be unsuccessful in averting conflict, a well conceived agreement may be able to lessen the possibility of legal disputes.

The teaming agreement document itself should clearly delineate each member's contributions to the project from a financial and personnel point-of-view. It should also discuss project control, both leadership and project management responsibilities as well as methods used to control. The division of work must be outlined as well as cost contributions and profit sharing. It is also helpful to discuss how disputes will be resolved (arbitration vs. litigation), both internally and externally.

The team members must discuss the issue of liability for the project. As mentioned earlier, before the arrangement begins the companies should lay out the methods for dealing with liability. They should determine how they will deal with each other, should legal disputes between the two arise. Moreover, they must decide whether they will go to court as a team or separately, should third-party issues arise. Finally, the companies must consider whether or not they will indemnify each other.

A good teaming agreement will also discuss the exchange of trade secrets and proprietary information. Though not held to the same stringent requirements as a patent, the courts have upheld the secrecy and right to protect trade secrets. On the other hand, in order for the team to design a quality product, they must freely exchange information and techniques. The teaming agreement must allow for enough exchange of proprietary information to successfully complete the project but at the same time allow for competition once the project is complete; antitrust laws must be examined carefully.

The teaming agreement is recognized as a valid contract by the government and the courts. The benefits of teaming are many, as long as the agreement is thorough and worded correctly. The success of the Lockheed, General Dynamics, and Boeing teaming agreement will now be examined.

Section 5 – The Teaming Agreement and Initial Actions

Section 5.1 – The Agreement Signing

In June 1986 Lockheed, Boeing, and General Dynamics signed the agreement creating the team that would design the first air-to-air fighter to utilize stealth technology. The three companies had agreed to submit their proposals with no interactions amongst them. This was due to the short duration before submittal and the security issues involved with the program. The winning company, meanwhile, would take the lead, both from a management standpoint and as the beginning design for the ATF.

Section 5.2 – Initial Combined Project Actions

Two days after the award announcement, on November 2, 1986, managers and engineers congregated at Lockheed's Skunkworks facility in Burbank, California to begin the process of uniting the three entities into a team. The next few days would see some events that few of the participants had experienced before.

On the first day, each company presented their concept to the other members. These meetings were particularly interesting in that the companies had never before shared such details with people considered to be the "competition". As Randy Kent, program director at General Dynamics, put it, "That Monday was the most fascinating day I ever spent in the aircraft business" (Hehs 1998). One of the surprises for the members present was the diversity of the different designs. It was also obvious to everyone present that Lockheed was far beyond anyone else in their stealth capability.

The unique developments continued the following day when the Air Force presented their evaluations of the three proposals. In past projects rumors had always floated about why certain proposals had been chosen over others; never before had they received direct feedback from an authoritative source. Moreover, the results surprised everyone.

The driving force in the Air Force's evaluations had not been technological promises or cost savings. Instead, they put a large emphasis on production risk reduction. In other words, they did not want to commit to a proposal that perhaps promised something it could not deliver. Rather, the winning concepts advocated several ways to solve a problem instead of a point solution; in other words, the military did not want a proposal that detailed a single solution to a problem but generalized several different alternative solutions. Moreover, the Air Force wanted companies that were willing to challenge the requirements.

With these issues in mind, the team began to organize itself and split responsibilities. Sherm Mullin, the ATF program manager at Lockheed, would be the overall project manager; however, he worked in close proximity to and shared much authority with the General Dynamics and Boeing ATF program managers, Randy Kent and Dick Hardy, respectively. Much of the design work would be accomplished together as a team; however, each company would take the lead role in different areas of production. As part of the teaming agreement each company had developed its own separate plan for dividing the work. Lockheed's plan obviously carried the most weight, but the top managers sat down to partition the work equitably. (See Figure 7 for a depiction of the work breakdown.)

Lockheed took overall responsibility as the project manager for the YF-22. They were responsible for producing the cockpit, nose section, and forward fuselage. They also took the lead in designing the majority of the control surfaces: the ailerons, fins, stabilators, and flaps. The aircrafts landing gear was also their responsibility. Lockheed would be ultimately responsible for final assembly and flight-testing.

Boeing took the lead in developing the avionics and mission software for the aircraft. Because of their strong structural capabilities, they were responsible for producing the wings and aft fuselage. They would also design the life support system for the Raptor. Finally, they would take the lead in developing training systems, such as simulators and classroom instruction, necessary to teach the pilots and maintainers who would work with the final product.

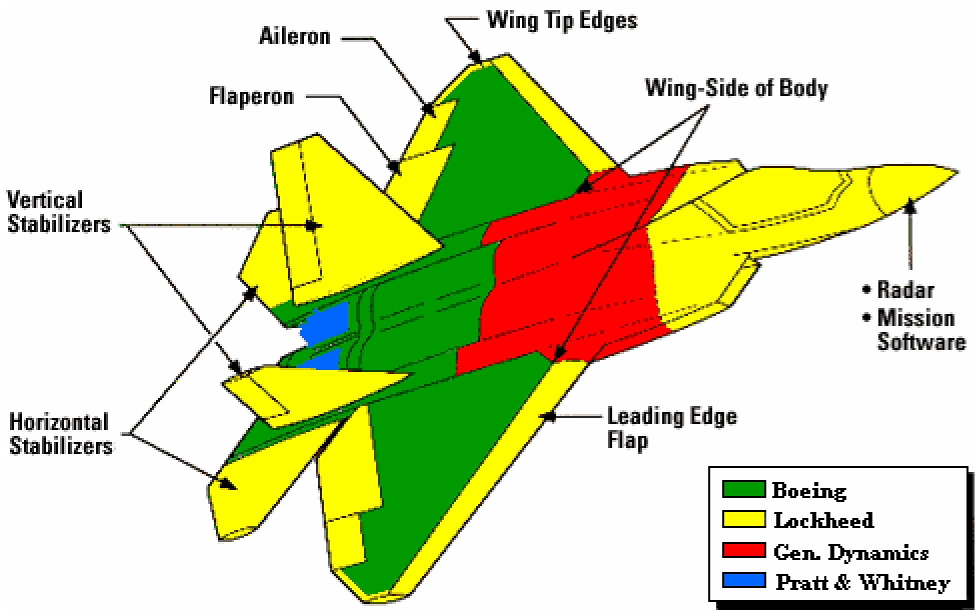

Figure 7 - YF-22 Division of Work

General Dynamics was responsible for producing the center fuselage. They also took the lead for the aircraft's weapons system. They would develop the communication, navigation, and IFF (Identification Friend or Foe) systems as well as the Electronic Warfare suite.

With these divisions in mind the team set to work developing the YF-22. The next few years produced one of the most unique, and secretive, products that the defense industry had ever developed.

Section 5.3 – The YF-22 Design Process

As part of the teaming agreement, it was decided that the winning proposal would be the starting point for the design process. Moreover, the members had determined that it was not smart to immediately design the prototypes. Rather, it was better to design the prototype and production models together so that few if any differences would be required between the two.

Since all of the companies had presented their work, there was a plethora of data and concepts to digest. First, the engineers sat down with the Lockheed concept.

Ironically, after a little investigating, it was determined that the Lockheed design would not fly. It was actually uncontrollable in the pitch axis. And so the tradeoffs began.

One of the first problems facing the engineers was the weight of the aircraft. After crunching the numbers and exploring many options, the designers determined that it would be impossible to build a 50,000-pound aircraft (USAF requirement) and still meet all of the other stipulations. The team presented this dilemma to the Air Force's program office. The USAF was willing to drop some of the requirements, but only if both teams produced similar results. Therefore, when the Northrop team reached the same conclusions, the weight allowance was increased.

By July of 1987 the team had developed an initial plan with which they were ready to proceed. The design, however, was 9,000 pounds overweight and cost $5 million more per aircraft than the USAF required. They were not concerned, assuming that further weight restrictions would be waved and certain avionics requirements could be dropped. However, the USAF decided to stand firm, and the team was forced to reevaluate their concept.

After considering all the options before them, the team made a difficult decision and completely trashed their design. A new director of design engineering, Dick Cantrell, was assigned to the project and on July 13 the team began "one of the most creative periods of conceptual design for any fighter aircraft" (Hehs 1998). Over the next three months, the engineers started from scratch to create a new ATF model.

One of the first issues to determine was wing shape. After analyzing various configurations, the team decided on a diamond-shaped wing, a configuration that was both structurally strong and aerodynamically efficient. However, the wing design forced the engineers to alter the tail design which, in turn, drastically affected the forward fuselage shape. The best design the team could produce, however, still had too much drag; supercruise was not possible. Luckily, Northrop was having similar issues; therefore, the USAF dropped the requirement for thrust reversers. This allowed the team to redesign the engine exhaust nozzles, greatly reducing drag and allowing supercruise.

Figure 8 - The YF-22 "Raptor"

In May 1988 the team froze the prototype design and construction began with fuselage parts at General Dynamics' plant in Fort Worth, Texas. When these parts were completed, they were shipped to Lockheed's Palmdale, California plant, where the wings from Boeing's Seattle factory were waiting. Somewhat surprisingly, the parts were assembled with very few problems.

Meanwhile, the plans for the production model aircraft continued to undergo changes. The structure of the fighter was reexamined, and minor modifications made. The biggest change, however, dealt with the avionics. As Boeing had continued to research, design, and build the avionics suite for the YF-22, the cost of the program continued to grow. Meanwhile, the Northrop team was having similar issues. The average price of an avionics package that fulfilled the Air Force's requirements was approximately $16 million. The USAF was forced into a difficult decision; eventually they determined that the maximum cost for the avionics would be $9 million. In doing so, the IRSTS system had to be eliminated and the cone of radar coverage had to be reduced.

On August 29, 1990, the YF-22 was rolled out of the hangar. Exactly one month later it first took to the skies, thus beginning a rigorous test flight program. Approximately 15 years earlier, General Dynamics had competed with Northrop for the contract that would eventually become the F-16. During the prototype testing phase, General Dynamic's YF-16 flew many more hours than its competitor. Many people felt that this was one of the factors that helped General Dynamics win the contract. This was a major consideration that the team used in developing its flight test program. The YF-22 was flown to all of the edges of the design envelope, including demonstrating its supercruise capability. Also, unlike the YF-23's test flight program, the YF-22 fired actual missiles from its weapons bay at drone targets, thus validating its lethality.

On New Years Eve, 1990, the Lockheed/Boeing/General Dynamics team delivered its proposal to the Air Force. The USAF program office examined the designs present by both teams, as well as both engine types under consideration. They also closely scrutinized the flight test results of the prototypes. On April 23, 1991, the USAF announced its decision: the YF-22 design with Pratt & Whitney engines would be the fighter that would shepherd the Air Force into the 21st century.

Section 6 – Teaming Issues for the YF-22 Project

Though teaming is not a foreign concept in the defense industry, it can create many obstacles in a project of the magnitude of the F-22. The Lockheed, Boeing, and General Dynamics team had many difficulties to overcome in order to build a cohesive team.

Section 6.1 – Legal Issues

As mentioned above, there are two kinds of teaming relationships recognized by the government in the FAR's: joint ventures and prime contractor-subcontractor relationships. The team created for the F-22 program was neither of these types. Rather, it was a mix of the two. By creating a teaming relationship between the companies, the three members did not create a separate entity, as characterized by a joint venture. Moreover, the relationship was stronger than that of a prime contractor-subcontractor. In such a relationship it is assumed that, should a company receive a contract, it will in turn give a subcontract to another company. In such a case, the subcontractor is usually not competing for the same prime contract; in other words, such a teaming agreement would not apply if the prime and sub roles were reversed. This was not the case for the F-22 team, however. The agreement was worded in such a way that a team would be formed if **any** of the members received the prime contract.

The teaming agreement for the YF-22 created a relationship that took advantage of many of the benefits of both types of teams. First and foremost, the formation of a team improved the image of the companies in the eyes of the customer, the United States

Air Force. It showed that the companies were willing to do whatever it took to pool their resources and develop the best product for the military. Lockheed and Northrop were the two big winners for the dem/val program, and Northrop had signed a teaming agreement with McDonnell Douglas. It cannot be determined for sure, but it is reasonable to assume that the fact that Lockheed and Northrop had created teams helped their chances of receiving a contract.

As mentioned earlier, a good teaming agreement should be very detailed, outlining as many contingencies and proposed solutions as possible. The teaming agreement signed by Lockheed, Boeing, and General Dynamics was a 55-page document that outlined many of the initial procedures and relationships of team members, dealt with the legal issues involved, and gave the team a common point from which to start the design process. It did, however, give the team a good deal of freedom to adapt the relationship as the project developed.

The teaming agreement dealt with several different areas. First, the contract discussed the roles and responsibilities of the team leader. It continued on to address procedures for assigning work obligations among the members. The methods and responsibilities for preparation of future proposals were outlined as well as the exchange of proprietary information and patent development. In order to mitigate future disagreements, the companies outlined the methods they would use to resolve any legal disputes between them. They also determined the methods to be utilized for cost sharing as well as cost reporting. Finally, the agreement specifically outlined timelines and procedures for teaming termination.

The teaming agreement clearly delineated project control and authority. The winning company, in this case Lockheed, assumed project control and project management responsibilities. The division-of-work and individual contributions to the project were not specifically outlined in the teaming agreement. However, the document laid the ground rules for such contributions. It was decided that each member would develop its own individual plan for how to divide the work. Once the team was formed and the dem/val contract was awarded, the members would sit down and negotiate for design, testing, and production responsibilities, with the winning company's plan as the baseline for such bargaining.

A major issue that the teaming agreement was forced to deal with was the exchange of trade secrets and proprietary information. As discussed earlier, the companies had to be careful not to violate any antitrust laws. Compared to many industries, the aerospace family is rather small. Moreover, the number of companies continues to shrink as many firms are forced to shut down or are bought by their competitors. (Lockheed itself eventually bought General Dynamics; it also merged with Martin Marietta and today is known as "Lockheed Martin".) Therefore, the three team members had to be very careful not to create the impression that they were forming a "supercompany". They were able to mitigate many of the government's concerns by specifically addressing the methods for teaming termination.

Another aspect that the teams had to consider with the exchange of proprietary information was the security issues involved. All through the 1980's, stealth was a "black" project. The ATF program itself was very secretive. Almost nothing about the project was released to the public between the times of the dem/val contract award in 1986 until the YF-22 was chosen as the winner in 1991. In fact, during that five-year period, Col Jim Fain, program director for the USAF, did not give a single on-the-record comment to the press (Hehs 1998). The teaming agreement itself discussed in detail the coordination of publicity between the companies. Though procedures for exchanging information and dealing with the complexities of the government classification system were outlined in the agreement, many difficulties still arose during the design process, as will be discussed in the next few pages.

Section 6.2 – Organizational Issues

Shortly after the dem/val contract was awarded and upper management first came together, the engineers themselves and mid-level management had to be organized into a cohesive unit. This meant combining people from different companies, and, therefore, different loyalties, into sections that could put aside their differences and develop a superior product. This was not an easy process, though the managers at the top set a great example that eventually trickled down to the lower levels of the organization.

Once the companies came together, the overall leadership for the project was assumed by Lockheed, with Sherm Mullin taking the position of overall project manager. However, he did not have as much authority as the traditional project manager. In fact, in many ways he had to share control with Randy Kent and Dick Hardy, the program managers at General Dynamics and Boeing, respectively. Together, the three were the "ultimate arbitrators" for the design process (Hehs 1998).

In many ways, the team was organized in a traditional aerospace manner. Sections were formed for the major design areas: aerodynamics, structures, weapons, etc. These teams contained members from each of the different companies. From a design standpoint, a specific company was in charge of a specific area; for example, Boeing was ultimately responsible for the wing design. However, personnel issues had to be dealt with in a different way. As can be guessed, many engineers had a difficult time accepting the fact that they were working with the "competition". In fact, the initial days were very strained. As Paul Martin, Lockheed deputy chief engineer for design, put it, "We spent a lot of time convincing each other what great he-men engineers we all were" (Hehs 1998). What was also surprising to some degree was that the engineers with the most technical expertise also were the individuals who took the longest to adjust.

To combat the personnel issues that the teaming situation was sure to foster, an informal chain-of-command was established. If an individual was having problems that could not be resolved in his or her design section, he or she first went to their company's chief engineer in the section. If it could not be resolved at that level, the problem was elevated to the Mullin/Hardy/Kent level. At first this two-fold organizational structure might seem detrimental, since an engineer had two individuals to whom he "reported". However, it was clearly delineated that technical issues were to be resolved within the section using the methods determined by the section chief. Eventually, the engineers began to accept the fact that they were working in an unfamiliar environment, but one that could foster tremendous advances in technology and creativity. Instead of fighting the urge to work with the competitor, they began to embrace the opportunity and thrive. As Kent put it, "I began to sense that we were becoming a more cohesive team when the aerodynamicists from all three companies began voting against the structural engineers from all three companies" (Hehs 1998).

Another major problem that the team was forced to deal with from an organizational standpoint was communication. It must be remember that the three companies were physically scatter across the United States with Boeing based in Seattle, General Dynamics in Fort Worth, Texas, and Lockheed in California. It also must be considered that this was taking place in the late 1980's, before the Internet was as developed as it is today. On the other hand, the ATF was one of the first fighters to be developed from the very beginning using computers and computer-aided design (Hehs 1998). Therefore, a system needed to be created to rapidly exchange plans between the facilities. In 1987, a datalink was installed between the major sites of the three companies. The link was both encrypted and secure to allow for the transfer of highly sensitive and secretive data and information.

The companies also had to overcome the fact that they were using different software programs for the design. General Dynamics had the strongest computer-aided design capability of the three companies. Therefore, when combined work began on the YF-22, Lockheed's concept plan was flown out to Fort Worth to be digitized and entered in the computer database. However, two things made this process difficult. First of all, Lockheed's initial design was simply a concept and not intricately engineered; in other words, the dimensions for the aircraft parts did not make sense and the computer could not handle them. Secondly, from the very beginning the design was changing rapidly. Therefore, to improve the process, General Dynamics was forced to pack up their Perq computers and ship them directly to the Lockheed facilities. Ironically, once they arrived, they were unusable for a long time: the systems had to be approved by Lockheed security before they could be hooked up to existing Lockheed systems. Finally, a network was established that allowed the YF-22 plans to be digitized. The General Dynamics program, ACAD, was utilized for 3-dimensional design. Once the parts were designed they were transferred to Lockheed's system, known as CATIA, which was used in the manufacturing process. Though the team members had to overcome some initial computing and communication obstacles, they were able to develop a system that took advantage of each other's strengths to improve the efficiency of the design process.

Section 6.3 – Economic Issues

When the companies joined together to create a team, there were several economic issues that had to be worked out. Luckily, the teaming agreement itself discussed several of these issues, thus eliminating many initial problems.

One of the items that the teaming agreement dealt with was cost sharing and cost reporting. Obviously, the companies would be forced to use their own money for the project, be it for individual salaries or factory overhead. Therefore, procedures had to be determined for the companies to share not only everyday costs, but also large investments in research and development.

Secondly, the companies had to develop a common method of accounting. There are often several different methods for dealing with certain costs, each of which is perfectly legal and generally accepted. However, one must be consistent with the accounting procedures used in order to compute accurate results. Therefore, the team members were obligated to set forth from the beginning common procedures to be used in order to reconcile expenses within the team.

Though the teaming agreement was thorough in dealing with many accounting issues, a few problems still developed in the initial stages of the teaming arrangement. After the first meeting following the dem/val contract award, a group was formed simply to deal with the economics of the proposals. As part of their individual submissions for the concept phase of the ATF program, each of the companies had included a detailed analysis of the proposed costs for the design and construction of a prototype aircraft. However, as mentioned above, each company used different accounting procedures. Moreover, the concept phase did not involve direct costs but forced the companies to estimate the expected costs of the processes. Therefore, differing estimation procedures had to be reconciled. Moreover, labor is a large factor in the construction of such a technologically advanced aircraft; thus, differing labor rates could cause drastic variances in final projected costs. These initial estimation and budgeting difference had to be resolved in order for the team to start out on a common footing.

Section 6.4 – Project Management Issues

"It takes a delicate blend of solid interpersonal; administrative; and, to a lesser degree, technical skills to succeed as a project manager" (Badaway 1995). This statement is definitely true when it came to designing the F-22 prototype. As a project manager, Sherm Mullin had dealt with the complex problems and politics of organizing and managing an aerospace project. However, the teaming agreement caused several difficulties that were unique.

The three leaders at the top, Mullin, Kent, and Hardy, were forced to put aside their differences and lead by example. Remarkably, they did fairly well at setting the tone for the project. Mullin and Hardy were opposites; Mullin tended to be aggressive and excitable while Hardy was conservative and stubborn. Kent, meanwhile, kept these two differing personalities in check (Hehs 1998). Though the personalities of the three were very different they got along fairly well, or at least gave the appearance of such to the other members of the project. As Bill Moran put it, "Upper management's lead established the right tone for success" (Hehs 1998).

Mullin was faced with many of the standard difficulties associated with a large-scale project. For example, he had to deal with individuals from a variety of different engineering fields and specialties, some areas with which he himself was not necessarily familiar; moreover, he often did not have the authority required to successfully manage the project. However, he began to be well respected both as an engineer and a manager, thus gaining some referential power with which to control.

Often a project is composed of individuals from different functional areas. However, in this project the individual employees also had different corporate loyalties. This also caused increased headaches for Mullin. Most of the Lockheed employees knew Mullin and recognized him as a manager who dealt with functional and interpersonal disputes fairly. However, Mullin not only had to be fair, but he had to convince the Boeing and General Dynamics employees that he was fair and had the project's best interests at heart.

The teaming arrangement also caused difficulties when it came to problem solving and decision-making. As mentioned earlier, from the very beginning many of the engineers were very defensive about their concepts. This would be a common occurrence in any project. However, the differing corporate loyalties exacerbated this problem. Moreover, there was no well-defined final authority who could make a decision should negotiations fail. In other words, the group was forced to make decisions by committee.

Many individuals also had difficulty initially thinking about the good of the project. Instead, they often voted the "party line," choosing sides based on corporate loyalties instead of technologically sound data. However, the tone set forth by upper management eventually filtered down to the individual sections, as the engineers began to unite around their functional disciplines instead of their employers.

Section 7 – Conclusions

The teaming agreement formed by Lockheed, Boeing, and General Dynamics for the design and construction of the F-22 brought together some of the aerospace industry's best minds in a groundbreaking display of cooperation. The motivations behind the teaming arrangement were not altruistic, however. The decision to team was a sound business judgment designed to minimize capital investment risk and improve the team's chances of winning the contract.

Many obstacles had to be overcome in order to design the fighter, especially in the initial stages of the project. Several of these problems were common to any type of project. Other, however, were caused by the unique situation established by the teaming agreement.

Figure 9 - F-22 Raptor Air Superiority Fighter

The Lockheed/Boeing/ General Dynamics partnering has also established precedents for future defense industry projects. The V-22 Tilt Rotor aircraft is one example. Designed for the Navy for short-field troop movements as well as a search and rescue capability, the “Osprey” was designed by a partnership between Boeing and Bell Helicopter Textron, Inc. The Army’s newest anti-tank missile system, the Advanced Anti-Tank Weapons System-Medium (AAWS-M), was also designed as a partnership among industry competitors. The “Javelin” was engineered and manufactured by Hughes Aircraft Co. in conjunction with Ford Aerospace and Texas Instrument.

As Dr. Sheila Widnall, former Secretary of the Air Force, stated, “We have used every tool in the acquisition…tool kit on the Raptor and then we invented new tools. This is a model program and everyone on the F-22 team is committed to maintaining that status” (*F-22 Rollout* 1997). By breaking new ground in the defense industry, the F-22 Team has shown that not only does teaming work well in weapons system development, it also helps create a higher-quality product. The examples set by Lockheed, Boeing, and General Dynamics ensure that the aerospace industry will continue to design the best systems for our nation’s defense. The F-22, meanwhile, will ensure that the United States Air Force continues to control the skies over the battlefield for the next quarter of a century.

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