TECHNOLOGY READINESS

FOR A NEW

LONG-RANGE BOMBER

On the cover, close up detail of the F-35's inlet shows a technology advancement that meets aerodynamic and low observable requirements through a less complex design. The F-22, F-35 and unmanned vehicle programs have advanced technology readiness for a new bomber in many areas in the quarter-century since the design of the B-2.

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Executive Summary

America has counted on bombers for tough missions for decades, but the bomber fleet will struggle to do its job as a capability void opens after 2015.

Talk of a new bomber has come in fits and starts since the Pentagon reached the decision to curtail the B-2 program over fifteen years ago. However, new threat assessments and the relative decline of older systems have made a new program urgent. According to General John D. W. Corley, Commander, Air Combat Command, direct attack of mobile or moving targets will grow difficult after 2015 and the new threat environment will be at full flush by 2020. The fleet of 20 B-2 bombers is just too small for persistent attacks in heavily defended airspace, and the B-1s and B-52s are not survivable there.

In February 2006, the Department of Defense called for a new long-range bomber to be fielded by 2018. Since then, there have been signs of activity, but questions linger. Is the Air Force ready to settle on requirements for a new bomber? Can industry partners really produce a bomber that fast?

The Air Force has set clear top-level criteria for the new bomber. It will have a combat radius of between 2000 and 3000 miles, high subsonic speed, improved survivability, and a whole new approach to the battlespace information architecture.

Despite the dark threat forecast, there is a silver lining in the form of increased technology maturity which has grown out of the stealth fighter and unmanned vehicle programs. As the paper discusses, early stealth programs like the F-117 and B-2 assumed considerable risk to pioneer new technologies. The B-2 was an example of a major weapons program explicitly designed to mature critical technologies. The F-22 closed many gaps, but still took on the challenges of supercruise, better maintainability and more integrated avionics. By the time of the Joint Strike Fighter downselect in 2001, the art of stealth had matured to the point where customers deliberately set requirements so as to control risk and cost.

Most technologies for the 2018 bomber are already closer to the Technology Readiness Level (TRL) 7 than for any previous stealth aircraft program. Old obstacles such as the integration of antennae, improved maintenance, and the best in lean manufacturing have largely been mastered. Focused program management in government and industry can drive forward technology maturation in critical areas. Four decades of investment in research and development of stealth combat aircraft since the 1970s are about to pay off in rapid fielding of a vital new system.

This report grew out of working group sessions held to discuss bomber concepts and technology readiness. Members of the group included General John Jumper, USAF, Ret., General William Hartzog, USA, Ret., General Gregory S. Martin, USAF, Ret., Admiral John B. Nathman, USN, Ret., Lieutenant General Gordon Fornell, USAF, Ret., Lieutenant General Lansford Trapp, USAF, Ret., Major General Don Sheppard, ANG, Ret., and Major General Rick Lewis, USAF, Ret. The author gratefully acknowledges their insights and observations, while remaining responsible for all conclusions wise or wayward.

– Rebecca Grant

Introduction: The Bomber Problem

America has relied on its bombers to attack the toughest targets when nothing else in the arsenal of democracy could do the job. From Ploesti in 1943 to Hanoi in 1972 to Belgrade in the spring of 1999 to Baghdad in 2003, bombers answered the call.

Now for the first time the Air Force has candidly admitted that when the red phone rings after 2015, bombers may not be up to the job.

Talk of a new bomber has come in fits and starts since the Pentagon reached the decision to curtail the B-2 program over fifteen years ago. But no one was serious about putting the money behind it until very recently.

Then, in 2006, top officials in the Air Force and the Office of the Secretary of Defense agreed that the nation could not risk putting off development of a new bomber any longer. They inserted terse but significant language into the Quadrennial Defense Review Report to Congress released in February 2006. The goal: "Develop a new land-based, penetrating long-range strike capability to be fielded by 2018 while modernizing the current bomber force," the QDR stated. Restructuring of other programs may have moved as much as $5 billon into bomber research and development.

Since then, signs have indicated that the Air Force has been quietly at work on the development of a new bomber.

Why is the situation so urgent? What caused the Air Force to scrap its plan for a new bomber in 2035 and push for a date that is now just ten years away? For that matter, can the Air Force finalize its requirements and hold firm on funding? Most of all, is the American aerospace industry ready to design, fly and deliver a bomber that fast?

This report examines the technology trends in development of stealth aircraft and whether the technology is ready to produce, on or near 2018, a new bomber with significantly enhanced capability.

Why Now?

For over a decade, the Air Force and the nation have been running a calculated risk. In 1995, a Pentagon study on the heavy bomber force led by Undersecretary of Defense for Acquisition Dr. Paul Kaminski asked whether there were risks to the industrial base if the US did not start a new bomber program soon. The answer was no. "When we examined the specific industrial capabilities needed for the B-2 and previous bombers, we found there is not a unique bomber industrial base," he said in 1995. "The capabilities required to design, develop and produce bombers are available in the broader military and commercial aircraft industries. For example, all 54 of the key B-2 suppliers also supply other aircraft and/or other non-aircraft programs."[1]

Kaminski was right. The F-22 and later, the F-35, pushed forward the art of stealth and survivability. Knowledge gained on these and other programs, including research on unmanned combat air vehicles, assembled a strong base of technological innovation, manufacturing expertise and managerial savvy.

However, there was a second component: operational risk. The Kaminski study evaluated scenarios occurring in 1998, 2006, and 2014 and found that for the time being, the force mix of B-52s, B-1s and

B-2s would be adequate to cope with threats out to 2014. Specifically, the study found "that with 20 B-2s, our bomber fleet size and mix will meet our mission needs."

What changed? Over the next ten years, threat assessments darkened while technology prospects brightened. By April 2004, Air Combat Command had indications of increasing risk. The Air Force issued a request for information to the aerospace industry in the spring of 2004 and laid plans for a formal analysis of alternatives focused on roll-out in 2015 and full initial operational capability in 2020.[2]

"It's not a panic," an Air Force official told reporters at the time. "It's the looming reality that we are running out of time."[3]

In 2008, General John D. W. Corley, Commander, Air Combat Command, explained that the most recent intelligence indicated that beginning in about 2015, the bomber fleet would struggle with its toughest mission, direct attack of mobile or moving targets. He laid out a capability void expected to open "in about 2015 and it's really going to be at full flush by about 2020," said Corley. While threats will increase in quality and numbers, the US bomber fleet will be too small and will really feel the lack of a full set of advanced capabilities.

The capability void as described by Corley is a function of several factors.

- The force of 20 B-2s is survivable only at night and it's just too small to attack big target sets over a period of days and weeks (known as persistence.) The primary aircraft inventory yields only about 6 bombers available for a mission on any given day for a sustained campaign at intercontinental distances.
- Neither the B-1 nor the B-52 can cross through modern SAM rings. Both have played exceptional roles in major combat operations in Iraq and in providing close air support in Iraq and Afghanistan, but they cannot be tasked for adversary airspace with modern surface-to-air missiles and fighters.
- The B-2 was originally designed to cope with an older generation of surface-to-air missiles such as the SA-5, a long-range, high-altitude SAM first fielded by the USSR in 1966.
- China has a mix of modern fighters and S-400 surface-to-air missiles which serve its doctrine of airspace dominance and defensive operations in a limited, local geographic area designed to keep perceived aggressors out.
- China also has ballistic missiles positioned along its coast. The US Navy's July 2008 decision to cancel DDG 1000 was in part a response to the vulnerability of the close-in naval gunfire platform to missiles of this type.
- Pacific bases are vulnerable to missile attacks, which will place a premium on having a fifth-generation long range bomber to take the pressure off forward basing.
- A bomber functioning in the battlespace beyond 2015 will have to make a leap forward as an information platform capable of superior offensive and defensive performance and linked tightly with other aircraft to do its mission.

The US won a grace period for air dominance by pioneering stealth with the F-117 and B-2. However, the grace period is gone. The bottom line is that without a new bomber, the USAF will not be able to carry out persistent operations or make the full range of options available to the President. As Corley said the Air Force must "fill that void with a new bomber to deal with the problems."[4]

Air Force Requirements and Choices

What does the Air Force need to do to deter and counter the threats beyond 2015? How ready is the technology?

"In order to make 2018, you have to use the far end of the technology you have your hands on," said General Ron Keys, Air Combat Command, when discussion of the new bomber heated up in 2006.[5]

The good news is that while the operational risk forecast has darkened, there's a "silver lining" in increased technology readiness. Several technologies have progressed in recent years to the point where the USAF can develop and deploy a much more advanced stealth bomber. Design and manufacturing for low observables is much more mature now that major hurdles in stealth coatings and software have been mastered. Beyond this, it's possible to combine stealth and electronic countermeasures to a greater extent than ever before. This bomber will have offensive and defensive sensors, data and communications links akin to those of the F-22 and the F-35. Key subsystems which weren't yet in operation when the B-2 was developed are now at significant levels of maturity.

Based on this technology progression, the Air Force has outlined characteristics of the new bomber in broad form:

- Combat radius of about 2000-3000 miles
- Payload of up to 28,000 lbs.
- Subsonic engines capable of speeds just below Mach 1
- Improved stealth signature
- Manned systems, at least in the first tranche
- Nuclear and conventional-weapons capable

The Air Force has done well to set for industry a broad set of requirements. Final specifications for the bomber may vary. For example, early proposals for the B-2 bomber discussed 12,000 lbs. of payload but the bomber ended up able to carry 40,000 lbs. Trade-offs to set final performance parameters will depend on how the industry teams approach the top-level requirements, and how the customer, the Air Force, ultimately sets its threat assessment and finalized operational concept.

The overall question is whether a bomber with these attributes can be fielded by 2018. That depends on technology readiness – but first it's worth a moment to consider the top-level requirements. The list of characteristics laid out by the Air Force opens up questions about four areas in particular. Why has the Air Force opted for subsonic engines? Can stealth aircraft be maintained more efficiently? Are design skills fresh? And finally, how will the new bomber take full advantage of information in the battlespace to augment survivability and accomplish its missions? This section discusses these crucial questions and the technology decisions behind them.

Why Bombers Use Subsonic Engines

Speed is an old friend for fighters in air combat. However, the Air Force has consistently said it will develop the new bomber with subsonic engines, limiting its speed to just below Mach 1. The decision to go subsonic reflects operational wisdom, and a commitment to taking advantage of mature engine technology.

The Air Force thoroughly explored supersonic bomber technology over 40 years ago. The B-70 achieved sustained operating speeds of Mach 3 during flight tests in the early 1960s. Like its contemporary, the SR-71, the B-70 was a state-of-the-art aircraft but perfectly capable of achieving and sustaining supersonic dash speeds. However, the Air Force decided that speeds of Mach 3 were not enough to outrun a missile given the bomber's mission profile. The SA-5 cited earlier had a peak missile speed of Mach 8. Other factors, such as high altitude performance, low altitude evasion and finally, stealth, took over in place of survivability built on sheer speed. There were other dilemmas, too. Fuel consumption seriously cut into range.

Startling as it may be, the trade-off has not changed much even today. Supersonic speed below about Mach 4 still is not a panacea for survivability. While supersonic speed does have a pay-off in certain engagement scenarios, a long-range bomber has a limited ability to take advantage of them.

Take the example of a supersonic fighter – especially the F-22, with its supercruise ability to go above Mach 1 without afterburner. For the F-22, speeds of Mach 1.3-Mach 1.7 assist with dash speed to win, avoid or break off engagement with fighters in hostile airspace. Supersonic speeds also limit exposure time to lobes of surface-to-air missile tracking radars when the F-22 is on a SAM-killing mission.

However, there are known trade-offs. Speeds of above Mach 1.6 start to build heat and incur infrared signature penalties. Current stealth materials are very durable but unproven for sustained flight beyond about Mach 2.

The real penalty for a bomber comes two ways. First, with current engine inlets, supersonic cruise uses too much fuel and takes away range and payload for a bomber. Supersonic "buys you nothing but fuel consumption," noted one expert.

Second, a bomber is not designed to engage with enemy fighters. It cannot use all of the combination of speed and maneuverability in the same ways that benefit a fighter. Instead, it must sense them a long way out, avoid them, depend on protection from friendly fighters and ideally, be able to fire an air-to-air missile at any leakers. With improvements in stealth, and a high operating altitude, a subsonic bomber is highly survivable at an affordable cost provided it is equipped with proper air-to-air and air-to-ground advanced weapons.

The prospect of hypersonics has also done much to cloud the issue. Hypersonics remain an enticing possibility, but not one for a bomber-sized airframe for the near or even the medium term. Current estimates still place hypersonic bomber technology at least 25 years in the future. While the principles of hypersonics have long been understood, applying them to an efficient, combat airframe is another matter. As Keys explained in late 2006: "Hypersonics are cool things, but what do I get out of it....If I am there, with my persistent force, I can engage anything in seven minutes. If I had hypersonics, it would get me down to three minutes. But the people I want to kill can get away in the first two minutes. Am I willing to pay x billions of dollars for hypersonic weapons that don't solve my problem? Those are the harsh decisions we have to make when people come to us with great technology."[6]

Not much has changed with the laws of physics or the laws of air combat. Bomber survivability relies on eluding detection against major threats, not outrunning them. Similar decisions taken long ago dictated design approaches for both the B-1 and B-2, and will do so again for the 2018 bomber.

Progress on Stealth Materials

In contrast to the supersonic conundrum, one area where stunning progress has been made in the last three decades is in the manufacturing and maintenance of stealth aircraft. Work on the F-22, the F-35 and on what is now the Navy UCAS program has kept the state of the art advancing at a rapid pace.

One of the biggest benefits is the move away from the fragile radar-absorbing material and coatings initially used on both the F-117 and the B-2. For these platforms, achieving signature reduction was more important than anything else. Designers and production specialists experimented with literally hundreds of off-the-shelf and purpose-made materials to find the right combination of effective, conductive coatings to meet the requirements of low observable missions.[7] In the case of the B-2, that included coatings rugged enough for nuclear-blast hardening. The assumption was that maintainers would do whatever it took to restore surfaces and make their signatures pristine for the next mission.

In the first years of their operational lives, both the F-117 and B-2 required exotic, labor-intensive processes to restore stealth coatings on a regular basis. The work was deemed worth it due to the performance they delivered, but it also drove very high hourly flying costs and had a negative impact on aircraft availability.

The F-22 was the first aircraft to change the pattern. Reduced maintenance was a top goal in the aircraft's design. Several factors helped Lockheed Martin and the F-22 team achieve the goal of an aircraft where low observable maintenance was much less demanding. First, in the years since the B-2, new conductive coatings had been developed which were much more resilient and easier to apply. (New coatings were applied to the B-2 through upgrades.) Second, more care went into the design of maintenance panels. Instead of opening a panel, closing it, and applying a stealth sealant, the F-22 used innovations such as the J-seal and the form-in-place FIP seal to control electromagnetic conductivity while allowing frequent, routine access. Field experience with the F-22 at operational bases has confirmed that when maintainers in a new unit learn the jet, the mean time between maintenance for the F-22s far surpasses fleet averages for older, aluminum aircraft like the F-15.

Materials science advanced again for the design of the F-35. The competition for the Navy UCAS program also gave the state of the art another boost.

The bottom line is that the crew chiefs for the 2018 bomber will not be overburdened with stealth maintenance requirements. Bombers usually have a fairly high flying hour cost. The 2018 bomber won't be the cheapest in the fleet, but it should at maturity cost less to fly than the B-52 and B-1, and far less than the B-2.

Stealth Design

Finally, is the talent pool for stealth aircraft design still fresh? Basic principles came from a feverish period of activity mainly between 1975 and 1985 as Democratic and Republican administrations spurred technology development. The F-22 competition advanced the art, but both it and the F-35 design were set several years ago.

Since then, work on unmanned systems has kept the skill set sharp. The competition for the Navy UCAS helped spur development of a range of technologies directly applicable to the next bomber – be it manned or unmanned. Boeing and Northrop Grumman each produced full-scale demonstrators that had already considered the problems of stealth, ECM and information integration. Without a doubt, the UCAS competition advanced the state of the art and left all participants with rejuvenated advanced design teams ready to apply their skills to a larger, long-range bomber for the Air Force.

Work on unmanned demonstrators and other vehicles like Predator and Global Hawk was so successful that it raised the question about an unmanned bomber. From a technology standpoint, the prospect is closer than ever. But for now, the Air Force has said it will seek to acquire a manned bomber. There are several reasons why but one is that the technology maturity in a few bomber-specific areas most likely will not be ready in time for 2018. For example, great progress is being made in autonomous aerial refueling, and the technique may well become standard procedure for all aircrews early in the lifespan of the 2018 bomber. However, other issues, such as contending with a critical 4-5 second communication delay in a hostile battlespace may not be resolved as rapidly.

Later, the Air Force has the opportunity to produce an optionally-manned version of the bomber. "Optionally-manned means just that," explained an Air Combat Command official. "It has a cockpit and a crew can fly it, or in autonomous mode, you can fly it like a Predator."[8]

In sum, the technology progress in unmanned vehicles has outpaced expectations. Industry – spurred by combat users – has presented a technically valid choice, whatever the Air Force's final decision on manned vs. unmanned may be.

Data Links and Fifth Generation Survivability

Finally, the world of stealth is ready for another leap forward, and just in time. The 2018 bomber will depend for its survival on sophisticated information exploitation and linkage with other platforms in the battlespace. Creating this information architecture will be one of the most challenging tasks in building the 2018 bomber.

The old concept as seen in the F-117 and in the B-2 at the beginning of its design was for the stealth aircraft to "go it alone." Emissions needed to transmit information risked giving away the aircraft's position and canceling out the stealth. Mission systems would have been a big design parameter if they had all worked as hoped. There were numerous efforts, some more successful than others, to design in more information. However, in general, the approach was still platform first and information second – a constraint that reflected technology readiness. Even such recent aircraft as the F-22 and F-35 were largely designed "platform first" and have been adapted through design changes and upgrades.

The 2018 bomber will be the first stealth aircraft to take full advantage of the revolution in digital sensor data from the outset. In recent years, the digitization of data has cut the lag time in reconnaissance and surveillance. This has also allowed multiple aircraft to share common data while in flight and pass it back to command centers on the ground as well. As analyst Chris Bowie concluded "a growing variety of sensors are generating information in the form of digital data, which, when combined with data links, opens the door to near-real time integration."[9] The first effects of this change came during the Kosovo crisis air war in 1999, and tactical applications evolved fast during the conflicts in Afghanistan and Iraq. Currently, forces can pass image files, sensor tracks and other digital information via dedicated aircraft links which form a battlespace network. In fact, the F-22 and F-35 concept of operations are built around increasingly sophisticated links of this type, and current bombers have added networking capabilities.

However, the 2018 bomber will be the first long-range aircraft with digital data network functions as key design criteria. By incorporating advanced sensors and data transmission the new bomber will be far better at sensing threats and searching for targets – which greatly increases its tactical and operational roles.

On the defensive side, presenting a low signature to enemy radar has always been part of stealth. In the past, stealth aircraft like the B-2 and F-117 enhanced signature reduction by also flying a pre-planned course through the battlespace. Currently, the F-22 and F-35 fighters already have the ability to sense the shape and intensity of enemy radar waves while on a mission and react accordingly. A bomber operating in a heavily defended battlespace after 2015 will need a similar ability to detect threats and plot a flight path to its best advantage. It will also have to link with other strike aircraft in the battle area, and their support aircraft standing off nearby (such as tankers and some ISR aircraft) to spot and deal with pop-up SAMs and fighters.

It has taken several generations of stealth technology and airborne network links to make the fusion possible.

The F-117 had very limited connectivity in the battlespace, because it had always been designed as a go-it-alone platform. The B-2 strove for more use of radar, including synthetic aperture radar for imaging targets. The F-22 was the first stealth aircraft to be designed for the Link 16 in receive mode and for an in-flight data link with other F-22s. The F-35's data link takes it another step ahead and can serve as the basis of enhanced communication among other F-35s and other stealth platforms. Beyond this, there are other airborne network configurations which could benefit all stealth aircraft.

Pulling it all together, work on the F-22, F-35 (and modifications to the B-2) have produced a set of proven abilities. These were not mature technologies the last time a bomber was conceived. For example, the development of AESA radar has created many possibilities. AESA radar combines many small transmit and receive modules into a powerful solid state radar. The modules generate multiple beams and produce a radar with much greater search volume and range. AESA radar can switch between air-to-air and air-to-ground modes so rapidly that the pilot to all intents and purposes is using both simultaneously. The characteristics of the AESA "beam" also make it harder to track, intercept or jam. AESA-based communications can enable aircraft to send or receive large chunks of data, such as a detailed SAR map of an area. Information can circulate between airborne and ground-based users.

AESA-based communications open up new options for bombers and fighters to operate together in the battlespace. A four-ship of F-22s ranging in enemy airspace some distance away from the bomber can collect information on active threats and transmit it to the bomber very rapidly.

Technologies like these allow the new bomber to be an information architecture as much as a platform. Consider the possibilities:

- Inflight data links enable four F-22s, for example, to share information such as fuel and weapons status with the other jets, and to swap threat information and other tactical data. Together this four-ship can "see" more threats and its leader can allocate responsibilities depending on who is in the best position. As a result, a group of F-22s can more efficiently cover a larger battlespace. The lead aircraft can hand off a target such as an enemy fighter to another ship in the formation. The in-flight data link makes the four operate as one.
- Now imagine that one aircraft ties into another source, such as a satellite, with low probability of intercept, which can connect it to yet more sources of information. The mini-battlespace network is now empowered with all the reachback information, analysis and orders that can move across the data link.
- Further picture the 2018 bomber as the next link in this information-centered architecture. It is both a consumer and a producer, able to work in autonomous mode or in a "wolfpack"of stealth bombers and fighters. New targeting data can come from other F-22s, F-35s, stealth bombers or off-board sources. With this technology, the stealth platforms act as information conduits, too. This greatly enhances their ability to get the most out of their stealth, any onboard ECM capabilities, and their precision targeting systems.

The 2018 bomber will have to incorporate these advances and move them further along. However, it would be wrong to picture the new bomber as just "plugging in" to fully-formed pre-existing systems. Part of the task for this bomber program will be to corral and help fund the common, open-architecture system for all stealth aircraft to use in future. Much of this work is already underway either in programs like F-35 or as a logical continuation of other research programs. While several technologies are mature, others require an injection of focused research to boost their maturity levels.

Battlespace dominance beyond 2015 will require a suite of capabilities. Among them are:

- **Passive emitter location systems.** Here, the platforms must be able to sense and categorize "emitters" such as surface-to-air missile tracking and fire control radars without giving away too much about their own location.
- **Automated mission planning.** Already in use to a degree, the automated mission planning systems for a 2018 bomber must accelerate processing time while adding in information from a variety of sources, such as other fighters in the battlespace, UAVs and other ISR platforms, and stand-off platforms such as E-3, E-8 or tankers carrying new capabilities.
- **High-resolution endgame sensor.** The bomber needs to have the best possible endgame targeting sensor, equivalent to a one-foot SAR resolution or better.
- **Back-up communications.** When necessary, the bomber should be able to function as an airborne communications relay platform for itself and other platforms in the event of satellite communications disruption, for example.
- **High-speed transmit and receive data links.** Numerous possibilities exist, and any solutions have to be interoperable with selected systems.

With these and other systems, the 2018 bomber can take full advantage of digital signals advances to create a new advantage against SAMs, fighters and cyber tactics. Improved survivability will be one result, and the ability to bring all intelligence, surveillance, and reconnaissance advantages to bear on difficult targets will be another.

These requirements set the bar high.

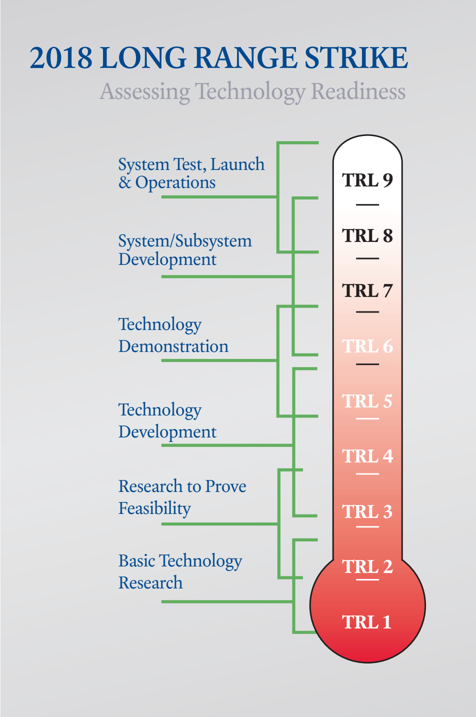
Perhaps the top question affecting development of a 2018 bomber is whether enough of these technologies are ready – and whether program managers, both in industry and government, can craft requirements and an acquisition strategy to deliver on the potential in the US aerospace industrial base.

Technology Readiness Levels

The case for the 2018 bomber rests on the premise that the Air Force launches the formal program with a high level of technology readiness.

"To be able to give you that airplane in 2018," elaborated Corley in spring 2008, "I need to have a technology readiness level. I need to have a manufacturing readiness level. I need to have an integration readiness level that I have confidence in, so that I can harvest what I learned out of F-117s, F-22s, F-35s, B-2s [and] import those technologies and those capabilities into this next generation bomber that will take us down another level in terms of survivability and the ability to persist."[10]

One way to get an overview of the progress is to compare the technology readiness levels for older programs to the prospective 2018 bomber. In recent years, Technology Readiness Levels or TRLs for short have become the favorite yardstick for program maturity.



The TRLs were first outlined by NASA. A seminal 1995 paper by NASA scientist John C. Mankins codified this "systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology." The figure depicts a summary of the NASA TRL levels.

The Air Force also began using TRLs in the 1990s. In 2001, DoD formally adopted Technology Readiness Levels as a method of assessing program risk.

Current DoD definitions of the TRLs differ slightly from the NASA set, and will be used in this paper.

The lowest TRLs capture stages of basic research. For example, TRL 1 is a paper study of basic technology properties. TRL 2 moves into invention and application of principles, still on paper. TRL 3 encompasses proof of concept in active research and development. Components may be validated but they are not integrated or representative.

For assessing the 2018 bomber, distinctions between the later-stage TRL levels are especially important.

- At TRL 4, components are on the lab bench.
- At TRL 5, the components may still be on the lab bench, but they are functioning reliably.
- TRL 6 is a representative prototype or scaleable model, going well beyond the ad hoc integration of TRL 5.
- TRL 7 moves up to prototype demonstration, which may take place on another system. For DoD, this may include testing avionics for a new aircraft in a flying test bed.
- TRL 8 is the actual system proven in test. At this point the system may have completed all the engineering and manufacturing elements of system development (termed SDD or EMD.)
- TRL 9 is an operational system, as at IOC.

By the end of the decade, the TRL concept attracted the attention of the GAO. Their July 1999 report titled *Best Practices: Better Management of Technology Can Improve Weapon Systems Outcomes*, researched the relationship between technology maturity and smooth product development in both commercial and defense projects. It said, in part:

- "DOD programs that accepted technologies at a readiness level of 5 or less experienced significant cost and schedule increases due, in part, to problems with the technologies."
- "The more successful of the 23 technologies [studied in the report] were managed by science and technology organizations until they reached at least TRL 6, and often TRL 8 or higher."
- For DoD, "as a practical matter, it is often necessary to move immature technology to a weapon system program to get needed funds and management support."
- DoD should "require that technologies needed to meet a weapon's requirements reach a high readiness level (analogous to TRL 7)"[11]

The report also pointed out that sometimes technologies took a long time to incubate – often a decade or more – and that those given time to develop were generally very successful. On the whole, the report writers hoped that "program managers" would feel empowered to reject technologies not yet beyond TRL 5. They did acknowledge that in practice, DoD systems often included path-breaking technologies that required all parties to assume risk.

To be sure, the TRLs are not perfect. They are a metric that boils down complexity, and they do little to capture any program manager's long-range concerns such as risk closure and funding stability. Elusive qualities such as skill in program management, manufacturing expertise, and customer support contribute mightily to technology maturation, although they are not part of the TRL calculus. However, since the TRL metric is in wide circulation, it makes a useful tool for scoping where 2018 bomber technologies stand today.

Reducing Risk for Stealth Aircraft

How does the technology status today compare to the early days of the B-2, F-22 and F-35, for example?

To answer this question, 12 key categories were selected to give an overall picture of technology readiness for the B-2, F-22, and F-35 at year of system downselect. A projection was made for the 2018 bomber. It's important to keep in mind that TRLs were not used during the period 1981-2001, which this look-back covers. The categories have been devised to measure technology readiness trends for the 2018 bomber, and therefore applied retroactively to the three other systems.

Since this exercise is intended to give an overview, both traditional categories like airframe and propulsion, and new ones such as endgame sensors, are included. There are also two categories that speak to systems engineering expertise, an important part of bringing the technology to fruition.

Traditionally, both the advanced design teams and those conducting an analysis of alternatives focus on the air vehicle, its range, payload and propulsion. Design maturity depends on the level of confidence in the overall airframe design, especially for a stealth aircraft, which will be built to exacting specifications. Engine selection is equally critical. These categories capture some major system design elements.

- **Air vehicle.** Defined as the flight test article.
- **Engines.** Typically a mature area, this category is defined as the production-representative engine variant.
- **Stealth coatings.** The third category is the maturity of the application, maintenance and assessment process for stealth coatings.
- **Software.** This category is defined as key software from fly-by-wire systems to CNI interface and stores management.

The next categories address subsystems essential to the 2018 bomber's performance in the battlespace. All 5th generation systems will have to link for mutual support to function effectively in heavily defended airspace. In the past, programs focused on the air vehicle and its attributes (including stealth.) Now, the mission systems are of equal importance. These systems are not entirely self-contained but each individual platform must have the correct ability to perform and/or link to these tasks.

- **Radar.** Incorporating advanced radar systems for multiple tasks has been a feature of stealth aircraft since the B-2, and an area of rapid advancement in recent years with the fielding of AESA radars.
- **Battlespace network.** The battlespace network refers generically to that collection of secure communications links for passing various types of data among multiple platforms in the battlespace, and back to other airborne platforms or to command centers. The network must have low probability of intercept and sufficient data rates for passing real-time information among stealth platforms.
- **En route targeting.** This category covers the ability to gather and update critical targeting data for air-to-ground or air-to-air en route to targets and in the battlespace and to share that information as required.

- **Defensive mission planning.** This includes signature management and electronic countermeasures from all sources.
- **Conventional weapons.** Consideration of the inventory has affected both bomber and fighter programs. (Nuclear weapons designs were already mature and relatively compact.)
- **End-game sensor.** What's also needed for 21st century missions is a high-resolution endgame sensor. If the bomber attacks through weather and threats, it must be able to find and positively identify the target when it gets there.

The final categories are not traditional TRL categories but they are included to capture the overall readiness of aerospace industry teams to put together an efficient production line and program.

- **Lean manufacturing.** Lean techniques are now an essential part of aerospace production.
- **Program integration.** Lastly, program integration is a set of technology and management skills integral to success for a new weapons system. While this is not generally graded according to TRL, it has been a leading source of doubt about technology readiness for the 2018 bomber. The program integration category is included here to assess and compare the maturity of the aerospace industry expertise and ingenuity that can be tapped for technology problem-solving.

Early Risk in the B-2 Program

The first stealth program to attempt broad mission integration was the Advanced Technology Bomber, now known as the B-2.

In the early days of stealth, the Air Force and the Pentagon had little choice but to embrace significant risk in the development of low observable combat aircraft. So great were the risks in the 1970s that Pentagon officials kept leading companies competing with each other on highly classified, advanced program development. The approach paid off, as Lockheed won the F-117 program, while Northrop, with major subcontract partners Boeing and Vought, journeyed in a different direction to win the B-2 program.

However, the B-2 was an example of a major weapons program explicitly designed to mature critical technologies. Basic concepts evolved from an Advanced Strategic Penetrating Aircraft (ASPA) competition initiated in 1980. By today's TRL standards, few elements of the B-2 were mature when Northrop was selected over Lockheed in 1981. In short, the Air Force accepted and managed substantial risk in the pioneering effort to build a stealth bomber.

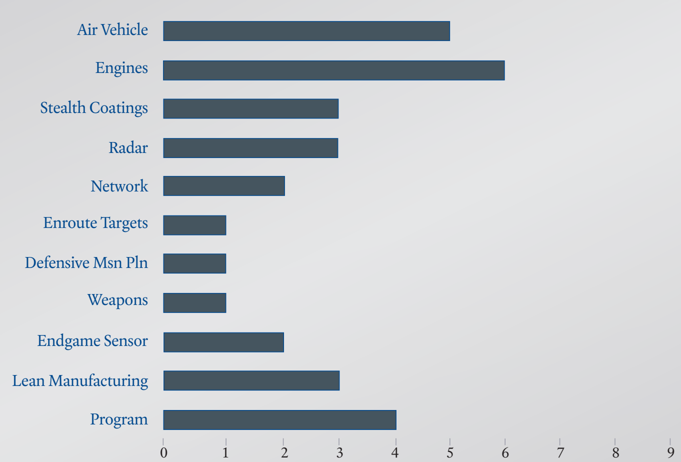
Air Force requirements for the bomber ushered in demanding new challenges. Northrop's advanced design team decided on a flying wing design as the stealthiest shape and drew on their experience with another radical demonstrator, Tacit Blue, to shape the rounded center section for the bomber. Initial Air Force requirements called for the new bomber to fly its missions at high altitude to optimize range and to erode the tracking abilities of enemy radar. The advanced design engineers chose four existing General Electric F118-GE-100 engines for propulsion. Early pole model tests confirmed that the Northrop design offered an exceptional, all-aspect signature reduction. [12]

Yet just as the final contract was being awarded in 1981, the Air Force asked for the new bomber to perform missions at extreme low altitude as well as high altitude. Northrop ultimately completed a substantial redesign of the entire airframe to strengthen the center section and add a gust load alleviation system. As the program proceeded, there were never-before-seen challenges such as housing the engine intakes to mask infrared signature. The B-2 was the first stealth aircraft to integrate substantial mission electronics such as advanced radar and defensive systems. Strategic Air Command also specified a high level of hardening against nuclear blast and radiation effects – a first for a stealth aircraft. The curved surfaces of the B-2 required Northrop to develop its own computer-aided design tools, to fabricate composites, and to invent a host of stealth coatings different from the magnetic radar absorbing material on the F-117.

The chart depicts estimated TRL levels.

B-2 TECHNOLOGY MATURITY AT SYSTEM DOWNSELECT

Estimated B-2 TRLs at Downselect (1981)



Engines were perhaps the most mature element because they came from an existing, demonstrated program. The airframe design was fairly mature from pole model testing, but no demonstrator had flown. Many mission avionics were theoretical. The stealth coatings were headed for extensive trial and error.

Unquestionably, the state of Soviet air defenses made the risk worth taking. Both the Air Force leadership and Secretaries of Defense Harold Brown in the Carter Administration and Caspar Weinberger in the Reagan administration recognized that investing to mature the B-2's technologies was an essential step to achieve the kind of national security breakthrough a stealth bomber promised. Brown and his legendary deputy Dr. William Perry (who later became Secretary of Defense himself) supported numerous tricky development programs. Weinberger's support was so firm he personally took the quarterly briefings from the Air Force's B-2 program manager with a small group in his office.

Nonetheless, the risk was there. Of course, the TRLs were not in use at the time, but this retrospective assessment shows plainly that technology readiness levels in most areas were not high. None were truly at TRL 7. From contract award in 1981 until first flight in 1989, the B-2 cleared many hurdles. The initial years of the contract were phased and funded so as to control and reduce risk. Overall there was a slip of about two years beyond the planned date for first flight. The B-2 attained initial operational capability in December 1993, eleven years after contract award.

By then, another stealth aircraft was flying. The F-22 set out to achieve another huge leap forward by integrating fighter performance and supersonic speed with low observables. The F-22 program took a different path to maturing technology. Like the F-117 and B-2 before it, the F-22 was a big departure from its stealth predecessors. Again, the Air Force and the Pentagon decided to accept risk in order to pioneer supercruise, thrust vectoring, new stealth materials and mission systems.

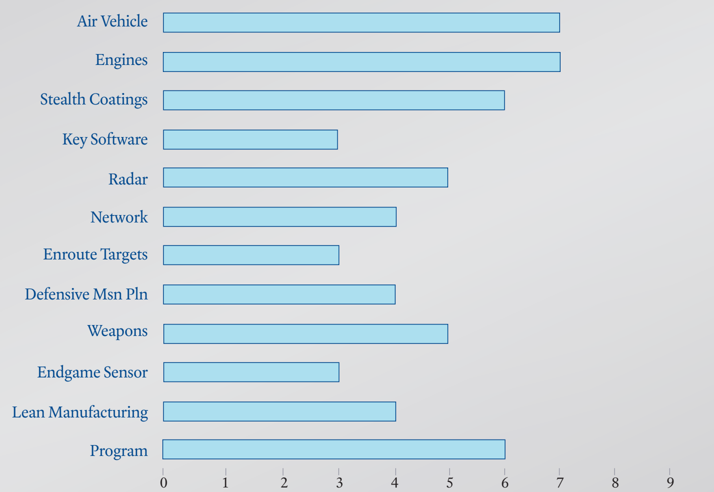
Downselect occurred in 1991 after the Lockheed YF-22 won a fly-off against the Northrop YF-23. The result was a brilliant, fresh approach, but with a substantial element of risk.

The chart shows that technology readiness for F-22 was more mature than for the B-2. Unlike the B-2, the YF-22 air vehicle had actually flown. Although later testing would lead to minor changes to the wing tips and horizontal stabilizers, there was nothing on the order of the B-2 redesign. Advances in key mission systems had pushed technology readiness forward. Lean manufacturing techniques were already being incorporated at factories and overall program management was a step ahead, too.

Even still, the F-22 continued to carry risk in the form of key technologies such as software integration which had to mature during system development. The F-22 was also coming along almost in parallel with new weapons such as JDAM and later, the Small Diameter Bomb, so some of the key conventional weapons could not be rated very high on the TRL scale.

F-22 TECHNOLOGY MATURITY AT SYSTEM DOWNSELECT

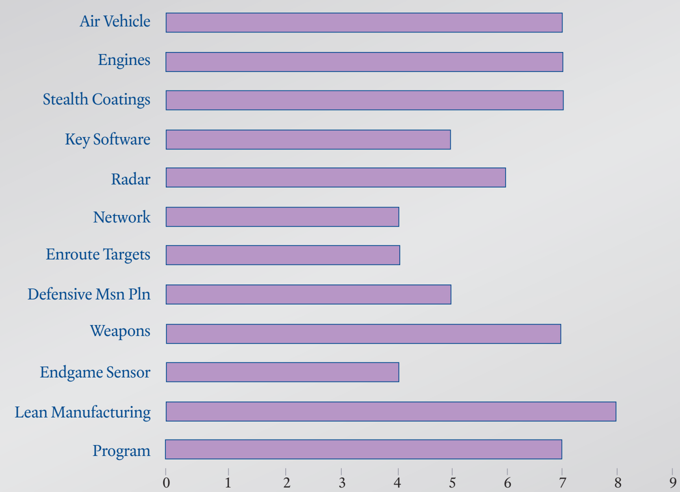
Estimated F-22 TRLs at Downselect (1991)



Ten years later, Boeing squared off with a Lockheed Martin team for the Joint Strike Fighter competition. The JSF program had been configured specifically to minimize risks and keep costs down. The Air Force planned to replace all its older fighters with stealth aircraft and needed an affordable, stealthy strike fighter to complement the F-22. Joint partners and allies also sought good performance but at controlled cost and risk. The JSF program actually grew out of a technology maturity effort known as JAST, which began with joint service and allied participation in 1994. By the time of the JSF downselect in October 2001, the two prototypes had been extensively flown by Boeing and Lockheed Martin. Both completed all their flight test requirements. Adding short take-off and vertical landing requirements onto the stealth platform upped the technological risk for both competitors. However, the prototypes marked another big gain in technology readiness and the emergence of Boeing as a full-fledged stealth aircraft advanced design house.

F-35 TECHNOLOGY MATURITY AT SYSTEM DOWNSELECT

Estimated F-35 TRLs at Downselect (2001)



When Lockheed Martin won the competition, the technology maturity was at the highest level yet seen for a stealth aircraft. The F-35 had innovative lift fan technology, and it also benefitted greatly from technologies matured during the F-22 program. For example, a variation of the F-22's F119 engine was selected to become the F135 engine for the joint fighter program. The Lockheed Martin team incorporated design and materials advances that largely made low observable maintenance a non-factor. For example, maintenance panel seals such as the form-in-place or FIP seal were developed for the F-22 and transferred to the F-35. The FIP seal allowed technicians to open maintenance panel doors, perform tasks and close the doors with no need to "recoat" to maintain a low observable signature.

The chart shows the higher technology readiness levels of the F-35 at downselect. Here, the military customers and DoD were intentionally minimizing risk in a program where cost was a very important variable – important enough to limit capability requirements. However, the stand-out trend was the advance in technologies across the board as a result of leveraging the previous two decades of research and development.

In the decade from 1991 to 2001, lean manufacturing became a standard at all prime aerospace manufacturers. The F-35 line was conceived with those principles in mind. The F-35 gathered software lessons learned from the F-22 program and others and applied techniques to capture and measure software performance data early on to mature software more rapidly and minimize delay.

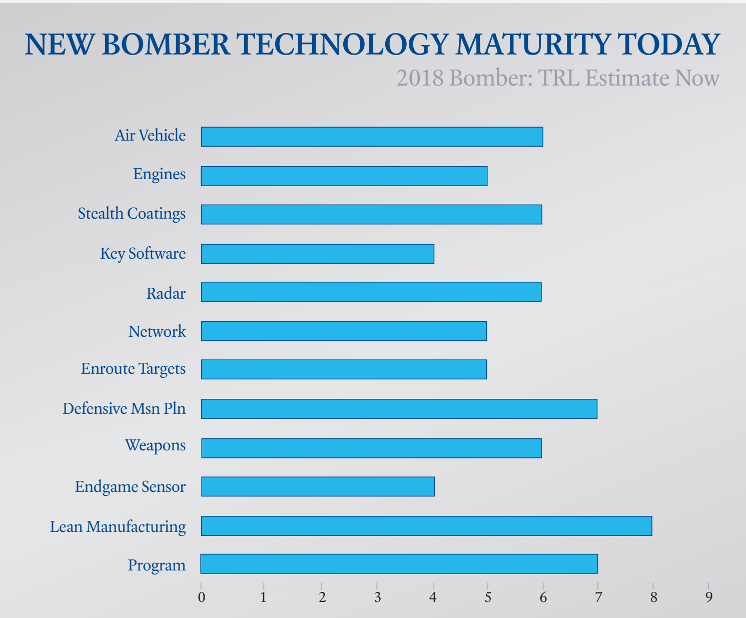
Radar advances were also significant. The F-35 took advantage of AESA radar and other new mission systems such as infrared sensors. The joint helmet mounted cuing system was well-developed by 2001, whereas it had been barely a theoretical concept in 1991.

GPS weapons were proven and new weapons such as Small Diameter Bomb had been conceived, tested, and approved for program development. The F-35 took immediate advantage of defensive system techniques onboard the F-22 which allowed pilots to monitor their aircraft's signature in relation to battlefield threats. Endgame targeting sensors such as high-resolution synthetic aperture radar had also progressed.

The net result was a program which reaped the rewards from years of risk reduction work on other systems. Accordingly, the TRLs for the F-35 were higher than ever before. It reflected achievement of know-how across multiple prime partners and suppliers. Of course, the F-35, like any advanced program, encountered challenges in final design and test. Still, there was no doubt technology maturity for stealth aircraft had reached a new level.

Technology Status for the 2018 Bomber

In the 20 years from B-2 downselect to F-35 contract award, the aerospace industry jumped ahead by leaps and bounds. Recent years have seen additional advances in certain technology areas. Where does technology for the 2018 bomber stand?



Technology for the 2018 bomber is much more mature than for any other stealth aircraft program. This is to be expected in the fourth decade of investment in stealth combat aircraft. Two key elements emerge. First, the state of the art today permits much lower program risk. Second, the 2018 bomber TRLs are already comparable to those achieved by F-35. The main differences reflect the assumption that current engines will be modified and that a full system demonstrator has yet to fly. Under the TRL criteria, even a planned modification reduces the maturity index of an engine, for example, as the finished article is broken down into components while incorporating new features. The final result is in effect a new product which must regain the higher TRL level.

The charts on the notional 2018 bomber differ from the B-2, F-22 and F-35 charts in that they estimate current TRLs, not TRLs at program downselect. No firm date is set for downselect, but it may occur between 2012 and 2014.

TECHNOLOGY READINESS

1-2 3-4 5 6 7-8

Technology Area	TRL	Estimate	Comment
Air Vehicle	6		Based on UCAS and other design evolution
Engines	5		Subsonic; modification of F-135
Stealth Coatings	6		Progress from B-2, F-22, F-35
Key Software (CNI, stores mgt.)	6		Components proven on F-22, F-35
Lean Manufacturing	8		Full transition complete
Radar	6		AESA development and integration with other systems
Battlespace Network	5		LPI and other comm demonstrated; link to multiple platforms
Enroute Targets	5		Passive emitter location and other automated characterization
Defensive Msn Pln	7		Signature management; integrated ECM support
Weapons	5		Maintain funding and align development with 2018 inventory
High Resolution Endgame Sensor	4		Requires further development
Program Integration	7		Aerospace industry retains deep experience

However, the overall message stands out. Most technologies for the 2018 bomber are closer to the DoD goal of TRL 7 than on any previous stealth aircraft program.

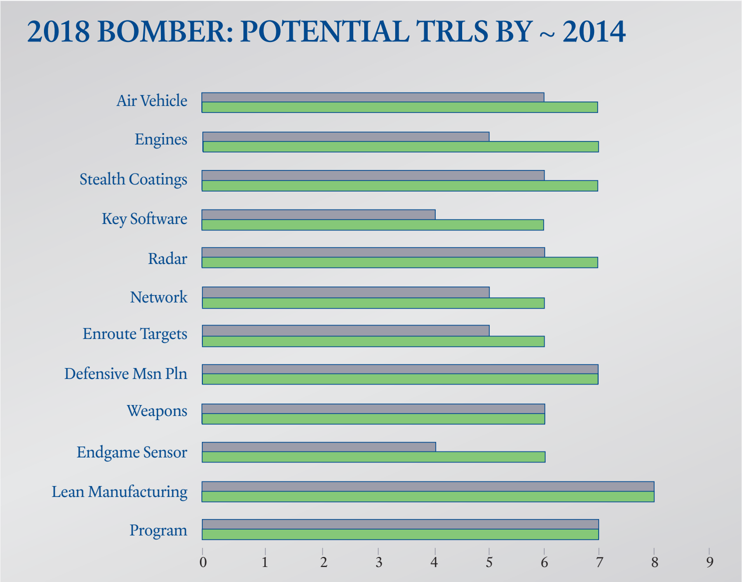
For example, air vehicle technology has been pushed forward not only by the fighter programs but by work on UCAS. The Northrop Grumman and Boeing contenders for the Navy UCAS demonstration program both exhibited a high degree of refinement. Look at the vehicles and all the elements are there. It's easy to picture the evolution from the X-47 and X-45 to a 2018 bomber prototype, scaled up to include more range, payload and mission systems.

The most challenging aspects will be mission systems: that combination of sensors, processors and communications links which make modern stealth aircraft true information platforms. The information flow is now essential to survivability and mission execution. Several promising systems are either onboard F-22 and F-35 or in laboratory development. For this reason, it is possible for the Air Force to set requirements and introduce a new generation of integrated mission systems into the 2018 bomber.

It will take focused program management to drive the technologies toward further maturity. When the 2018 bomber becomes a formal program, the chief engineer and program managers both in industry and government will need to formulate a solid risk reduction plan designed to deliver technology maturity at the right time, and to keep it aligned with the technical baseline of the bomber. Risk closure is perhaps the most important overall management task for a program nearing and achieving downselect. The good news is that the risk closure differences are smaller than ever. It will take astute management and brilliant engineering to deliver the program, but the 2018 bomber does not need "a miracle a day" as engineers on the B-2 program often said of their bomber in the 1980s.

In fact, the next few years should see even more dramatic technology maturation. Assume a downselect after flight test in the year 2014. By then, it should be possible to bring several major systems and subsystems to TRL 7.

The chart shows a projection of technology maturity for a 2018 bomber program. This assumes a demonstrator first flight and coordinated progress on mission systems technologies. With this projection, it is possible that 7 of 12 technology areas will be at or above TRL 7 and that the others will achieve TRL 6.



The 2018 bomber could well be more mature than the Joint Strike Fighter suite of technologies when it moves into formal system development on the way to low rate production. The bomber will also be free of some of the constraints dictated by the mission of the JSF to be an affordable, common solution yet deliver conventional, carrier and STOVL variants.

One way to ensure more maturity will be to incorporate some systems directly from the F-35 program. For example, the 2018 bomber could adopt the JSF sensor suite to ensure interoperability and to minimize the software development risk. The JSF sensor suite is the most advanced system currently in development. The bomber should use a common system – not develop a "bomber-unique" system. It will deliver return on investment (ROI) already made in the JSF program and provide a common baseline for pushing forward upgrades for all stealth aircraft and smooth the way for common data links. Using the JSF sensor suite will also capture the labs and system support without having to duplicate these and add cost.

The bottom line is that a new stealth bomber program can start from a higher level of technology maturity than ever before. Old obstacles such as the integration of antennae, improved maintenance, and the best in lean manufacturing have largely been mastered. Four decades of investment in research and development since the 1970s will pay off.

Conclusion: Fostering Joint Strike Technology

As the work on a new bomber moves closer to program status, it may be time for a review of how the program is structured and its linkages to wider development of strike technologies. Airframe technology – engines, air vehicle, and the variables of range and payload – are no longer the only critical ingredients in strike platforms. Probably the most challenging areas for the 2018 bomber technologies will come from the advanced mission systems which now make up such a crucial part of the bomber's concept of operations. Air Force leadership could make the next generation bomber the centerpiece of a wider joint initiative chartered to develop key technology areas. This would help accelerate and standardize a range of new systems to be used by the bomber and by other platforms.

The reasons for a new Joint Strike Technology initiative built around the new bomber program go beyond budget stewardship. As discussed, the new requirement to gather and exchange information at low probability of intercept is a central requirement for the 2018 bomber. But it's not enough to design a system unique to the bomber alone. What's more important is to harness several development programs to ensure that all 5th generation aircraft (and beyond) can tie into the same system. This will also affect supporting aircraft including tankers, battle managers like the E-3 and E-8, ISR UAVs and the ECM family, including decoys. These developments have an equal place at the table (or the CAD screens) along with traditional design requirements.

Investment toward a new bomber can be the driver for new technologies for joint strike. Setting up the bomber within a program office designed to rapidly mature joint strike technologies would guide both technology development and technology fielding under an ongoing program.

A similar concept lay behind the Joint Advanced Strike Technology (JAST) initiative of the mid-1990s. JAST was originally chartered in January 1994 as a technology development program to nourish research without necessarily dictating the final product. Its official mission was to "define and develop aircraft, weapon, and sensor technology that would support the future development of tactical aircraft." A handful of research and development programs were cancelled with the intent that JAST would explore many facets of strike technology from airframes to sensors and subsystems. Early contract awards ranged from $20M plus contracts with prime manufacturers for joint strike weapons system concept design research on air vehicles, to smaller contracts for EO/IR sensors, scaleable processors and on-board, off-board information fusion.[13]

Within a few years, JAST was spun off into the more focused Joint Strike Fighter development program, which ultimately produced the family of F-35 aircraft. While this was a positive development, the change in JAST resulted in a lost opportunity to pursue independent research and development in airframes, weapons and sensors without the constraints specific to the F-35. Had the JAST effort stayed on course even after spinning off F-35, it could have provided a more focused menu for technologies at known TRL levels to incorporate into new programs such as the 2018 bomber.

The intent behind the original JAST charter remains relevant today. The 2018 bomber could enfold that tasking, maintaining research in mission avionics, propulsion, sensors and other areas alongside development of a bomber program. While the Air Force will be funding the next generation bomber, a new Joint Strike Technology initiative should incorporate joint service representation from the start. The intent is not to reach for executive agency or but to keep mission systems development on a steady track to ensure common spin-offs to all generations in the battlespace.

A Final Word

For more than ten years, the Air Force has prudently waited out new technology development before investing serious money in a new bomber. Now the time is here.

While praising the work of the B-52 and B-1, Chief of Staff General T. Michael Moseley explained in 2006:

> "we're not going to be able to fly these old airplanes into the 21st Century and keep them survivable and be able to penetrate a 5th Generation threat array. We can stand off now with some of the finest aircraft ever built....And when you control the air space you can park yourself over the top of a set of targets and hold them at risk with the B-1 and B-52. But against a fifth-generation defensive system, this is not going to work for us." [14]

Threat estimates have accelerated, and the steady research on stealth fighters, UAVs and better radars and data transfer have created the "perfect storm" of conditions for making the investment in a new bomber. "I don't think there is a question that we can bring a bomber on by 2018," said General Bruce Carlson, who was head of Air Force Materiel Command. "It will have to be a block-type program and we will have to walk through this with our eyes open and restrain requirements," he added. [15]

With more mature technologies than ever, the new bomber program can go forward with more technology maturity and less risk than any other stealth aircraft in history. That is the payoff of the technology maturity gained over the past two decades. Timelines are tight to meet the threats beyond 2015, but well within the realm of the possible.

In 1947, Army Chief of Staff General Dwight D. Eisenhower testified to Congress that America should have an independent Air Force because of "the paramount influence of air power upon modern warfare." [16]

America entered the 21st Century at peace, but was attacked just nine months later. So far this century has been dominated by the struggle against terrorist networks and safe havens. It is impossible to predict where, or when, the United States will find itself involved in conflict in the next 30 years. "We cannot accurately characterize the security environment of 2025; therefore, we must hedge against this uncertainty by identifying and developing a broad range of capabilities," said Chairman of the Joint Chiefs of Staff General Peter Pace in the Chairman's assessment of the 2006 QDR.[17]

What does seem assured is that America will remain an active guardian of world order. In this, readiness at every level of the spectrum of conflict will be important. This is no time to shortchange the mission of long-range airpower.

(Endnotes)

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