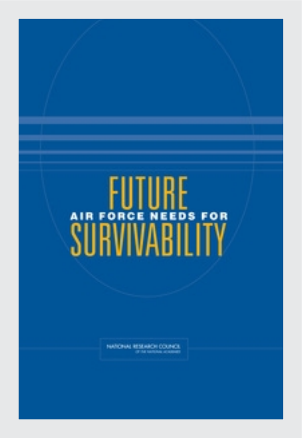

Future Air Force Needs for Survivability

DETAILS

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FUTURE
AIR FORCE NEEDS FOR
SURVIVABILITY

Committee on Future Air Force Needs for Survivability

Air Force Studies Board

Divivion on Engineering and Physical Sciences

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Preface

The chair wishes to thank the members of this committee for generously taking time from their demanding schedules and working hard to complete this report in the short time allotted. As noted in Chapter 1 in the section "Scope and Committee Approach," in the time available the committee could not address all aspects of the statement of task as fully as it would have liked, but it put its emphasis where it felt that the issues were most important.

The entire committee thanks the many organizations and guest speakers that provided excellent briefings and background information, and wants to single out for special appreciation the support provided by the Secretary of the Air Force's Special Programs Office (AQL). The security requirements associated with this effort presented many challenges to the staff and committee members in completing this work, which could not have been accomplished without AQL's assistance and that of the security personnel of the National Academies.

Finally, the committee thanks the National Research Council staff members who supported the study. Primary among them were Michael Clarke, LaNita Jones, William Campbell, Gregory Eyring, and Carter Ford.

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Committee on Future Air Force
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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Lawrence J. Delaney, Titan Corporation (ret.), Reston, Virginia,
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Alton D. Romig, Jr., Sandia National Laboratories, Albuquerque, New Mexico, and
David A. Whelan, Boeing Phantom Works, Seal Beach, California.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Robert Frosch, Harvard University. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Acronyms and Abbreviations

AAA	anti-aircraft artillery
AAM	air-to-air missiles
ADVENT	Adaptive Versatile Engine Technology
AFRL	Air Force Research Laboratory
AI	airborne interceptor
AQL	Special Programs Office of the Secretary of the Air Force
ATC	Automatic Target Correlation
ATR	Automatic Target Recognition
BLOS	beyond line of sight
C4ISR	command, control, communications, and computers, intelligence, surveillance, and reconnaissance
CCM	counter countermeasures
CDD	concept development and demonstration
CM	countermeasures
CONOPS	concept of operations
CRRA	Capabilities Review and Risk Assessment
DARPA	Defense Advanced Research Projects Agency
dBsm	decibels per square meter
DE	directed energy
DOD	Department of Defense

E	effectiveness, a function
EADSIM	Extended Air Defense Simulation
EO	electro-optical (includes ultraviolet, visible, and infrared)
ESM	electronic support measures
EW	electronic warfare
GBU-28	Guided Bomb Unit-28
GIG	Global Information Grid
GPA	Global Persistent Attack
GPS	Global Positioning System
GS	Global Strike
IADS	integrated air defense system
IHPTET	Integrated High Performance Turbine Engine Technologies
IOC	initial operational capability
IR	infrared
IRST	infrared surveillance and tracking
ISR	intelligence, surveillance, and reconnaissance
JASSM	joint air-to-surface standoff missile
LO	low observable
LOS	line of sight
LPI	low probability of intercept
LRSS	long-range strike system
LWIR	long-wave infrared
M	Mach number
M&S	modeling and simulation
MANPADS	Man-Portable Air Defense System
MCO	major combat operation
MWIR	medium-wave infrared
NATO	North Atlantic Treaty Organization
NMS	National Military Strategy
NRC	National Research Council
O&S	operations and support
ONR	Office of Naval Research

Ops Sit	operational situation
P3I	pre-planned product improvement
PDE	pulse detonation engine
PGA	Persistent Global Attack
Pr	probability
QDR	Quadrennial Defense Review
R&D	research and development
RADGUNS	Radar Directed Gun Simulation
RAM	radar-absorbing material
RAS	radar-absorbing structure
RATTLRS	Revolutionary Approach to Time Critical Long Range Strike program
RCS	radar cross section
RF	radio frequency
S	survivability, a function
S&T	science and technology
SA	situation awareness
SAM	surface-to-air missile
SDD	system definition and design
SRAAM	short-range air-to-air missile
SWIR	short-wave infrared
TBCC	turbine-based combined cycle
TRL	technology readiness level
USAF	U.S. Air Force
VAATE	Versatile Affordable Advanced Technology Engines
WMD	weapon of mass destruction

Executive Summary

The Air Force Studies Board of the National Research Council (NRC) was asked by the U.S. Air Force (USAF) to investigate combinations of speed and stealth that would provide U.S. aircraft with high levels of survivability[1] against potential enemy air defense systems in the 2018 time frame. The missions considered were to include but not be limited to long-range strike. The NRC was also asked to identify changes that might be needed in current research and development (R&D) investment plans to enable such survivable aircraft to have initial operational capability by 2018. Accordingly, the NRC convened the Committee on Future Air Force Needs for Survivability (see Appendix A), which held six meetings at which it received numerous briefings on related matters (see Appendix B). Given the security implications of the subject matter, the committee produced both a classified and an unclassified version of its report.

The committee conducted a somewhat limited analysis, as follows. Chapter 1 provides a brief review of the history of stealth technology development. In Chapter 2, the committee discusses the missions that future U.S. aircraft are expected to undertake, the threats they are likely to face, and the capabilities that are likely to be required to complete these missions. In Chapter 3, it assesses the technical feasibility of achieving various levels of stealth at subsonic, supersonic, and hypersonic speeds by 2018, including consideration of specific aircraft subcomponent technologies (airframe,

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[1] The capability to avoid or withstand a man-made hostile environment.

key mission sensors, propulsion, and so on). Also in Chapter 3, near-term R&D needs and priorities and far-term R&D opportunities are identified, both for the fielding of a survivable air vehicle in 2018 and for subsequent generations of aircraft.

In Chapter 4, the committee analyzes the results of recently published reports in the field and combines these insights with information provided during briefings as well as its own expertise to make observations about the utility of speed and stealth trade-offs against evolving threats. In the limited time available, the committee was not able to conduct a comprehensive analysis of the many variables, including speed and stealth, that affect aircraft survivability, although a framework for conducting such an analysis is presented in Appendix C. A glossary providing the definitions of key terms is presented in Appendix D. The committee's overall findings and recommendations, including recommendations for changes in the Air Force R&D investment portfolio to achieve these results, are presented in Chapter 5 and discussed below. Note that the committee generally recommends a rebalancing of the R&D portfolio to address Recommendations 3 through 6.

Finding 1: The Air Force Global Strike (GS) Concept of Operations (CONOPS) in high-threat environments determines survivability requirements for the long-range strike system and other systems because it simultaneously stresses range, signature reduction, persistence, timeliness, and payload characteristics.

The GS CONOPS stresses long range, speed, and payload, while the Global Persistent Attack (GPA) and the persistent Intelligence, Surveillance, and Reconnaissance (ISR) CONOPS stress long range, loiter, and persistence. Separate platforms for GS, GPA, or persistent ISR may be required. However, the committee concludes that emerging technologies might enable multimission capabilities. These technologies promise both system flexibility and affordability. Following are facts to be considered when evaluating these technologies:

- Range, persistence, and "24/7" (day and night stealth) operations against improved and proliferated threats increase the future survivability challenge.
- Increasing multimission capabilities tend to increase aircraft size and cost.

- Future threat uncertainties call for robust solutions that incorporate speed, stealth, and other important survivability techniques.
- The committee finds that multiple combinations of speed and stealth capabilities provide equivalent levels of survivability against surface-to-air missile (SAM), airborne interceptor (AI), and integrated air defense system threats. These combinations range from very significant stealth at subsonic speeds to moderate stealth at speeds approaching the hypersonic region.

Recommendation 1: The U.S. Air Force should develop and exploit technologies to enable efficient airframe and propulsion operation at both subsonic and supersonic speeds, and at medium and high altitudes, with appropriate levels of signature reduction to enhance survivability against plausible future threats.

Finding 2: The USAF has not completely investigated the combinations of speed, stealth, situation awareness (SA), countermeasures,[2] and tactics to enable a solid judgment as to what level of speed is required for acceptable survivability in the future.

Specifically, neither the Air Force nor industry has invested sufficiently in analysis of the impact of combinations of speed and stealth when employed against postulated future AI and SAM threats. Further in-depth analysis of the potential performance of electro-optical/infrared (EO/IR) and visual sensors based on postulated sensors as well as signatures is needed.

Recommendation 2: Before choosing a design point on the speed-stealth performance curve, the Air Force needs to conduct rigorous analyses and trade-off studies as a basis for that decision. The USAF should carry out the following:

- Perform mission-level analyses (using multiple major combat operation threat baselines and multiple CONOPS) including EO/IR and visual threats, as well as the impact of AIs;
- Conduct trade-off studies constrained by the needed or expected technology capabilities;

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[2] The committee considers self-defense technologies to be a subset of countermeasures in this report.

- Develop enhanced mission-level analytical tools capable of investigating the subtle but critical aspects of detection, tracking, fusion, and cueing of SAM and AI threats;
- Develop models more accurately representing the human cognitive processes involved in the kill chain command-and-control and decision processes;
- Assess the impact of speed and stealth on the mission-critical sensor suite; and
- Strengthen system design and engineering capabilities in the Air Force and in industry.

Finding 3: Broad selections of speed and stealth combinations that meet the GS CONOPS capability requirements are technically feasible.

Subsonic, supersonic dash, and supersonic cruise, all with appropriate stealth treatments for consistently high levels of survivability, are feasible with increased funding in a few areas. The committee found reasonable consensus on stealth capability achievable at speeds ranging from subsonic to hypersonic.

Based on numerous briefings from government and industry sources, the committee concludes that radio-frequency (RF) signature-reduction technology development for supersonic designs needs additional emphasis, including technology for designs incorporating a supersonic dash requirement if value or need is determined.

The committee concludes that investment in RF stealth in subsonic regions is currently strong and at the appropriate levels, but that advanced propulsion development is the single technology that can provide the most impact to the success of future aircraft for GS CONOPS. For example, advanced variable-cycle engines could provide the air vehicle with both high speed *and* efficient loiter capabilities, thus adding greatly to its mission flexibility.

Recommendation 3: The USAF should balance its research efforts between speed and stealth to bring advances in various speed regimes:

- Improve the balance across the speed range by preserving current subsonic programs while increasing funding for supersonic aircraft technology;

  - —Analyze the extent to which all-aspect, RF stealth performance is required for supersonic aircraft and the ability of technology to provide that performance;
  - —Provide additional investment in technologies that enable supersonic operations to support fielding in 2018 if required. One such technology is high-temperature radar-absorbing structure materials;
- Fully fund the Versatile Affordable Advanced Technology Engines program to original program levels for both subsonic and supersonic applications, including increased hot-section capability, improved materials, and thermal-management system technologies;
- Establish a variable-cycle engine demonstration program to achieve technology readiness level 6 by 2009 in a supersonic cruise aircraft; and
- Investigate the feasibility of adaptable airframe and skin technology, including morphing technology, to support multimission capabilities.

Finding 4: The design balance of speed and stealth will depend on the quality of available friendly and adversary situation awareness.

SA has a very significant potential to improve vehicle survivability. However, with the available test results and current modeling and simulation tools, the incremental impact of SA on overall survivability is not quantifiable. The committee also notes that the relative contribution of onboard and offboard sensors to SA remains unresolved.

Recommendation 4: The USAF should include SA as a high-priority requirement for all platforms, and include in the design, from the beginning, the essential sensors, apertures, and data links. In addition, it should do the following:

- Improve modeling, simulation, and analysis tools to enable the development of insight into the trade-offs among speed, signature reduction, and SA in future CONOPS scenarios; and
- Assess the best mix of onboard and offboard sources for derived SA based on trade-offs of risk and complexity.

Finding 5: Countermeasures will continue to have the capability to enhance the survivability of aircraft and offer a significant hedge against future threat advances.

Electronic attack, electronic countermeasures, information warfare, EO and IR countermeasures, RF countermeasures, and self-defense weapons (air-to-air missiles and directed energy) can complement signature reduction and offer additional survivability improvements in their own right. The committee believes that there is insufficient effort on high-speed penetration aids.

Recommendation 5: The USAF should continue to implement countermeasure improvements, and:

- If the Air Force concludes after further trade-off studies and evaluation that *sustained* supersonic cruise is essential to GS CONOPS, it should implement a high-speed penetration aid effort compatible with contemporary stealth signature levels.
- The Air Force should evaluate the relative effectiveness of self-defense weapons and define requirements for any new or upgraded capability for next-generation aircraft.
- This committee urges that, to the maximum extent possible, the basic weapon system be designed with the capability to complete its assigned mission without relying on countermeasures. In other words, although countermeasure systems can significantly enhance the survivability of a weapon, they should be hedges against future threat evolution and improvement and not a requirement for the baseline. The same holds for SA and tactics.

Finding 6: Hypersonic missiles with ranges comparable to those of current missiles could increase targeting timeliness and flexibility and thus increase operational utility in the 2018 time frame. It is not clear, however, whether a hypersonic cruise aircraft (other than a missile) designed for long-range flight and recovery offers unique capability and operational utility. Furthermore, it is unlikely that such an air-breathing hypersonic platform, other than a missile, will be available in the near term.

An attempt to field a hypersonic cruise aircraft by 2018 would be very high risk.

Recommendation 6: The USAF should increase the investment in hypersonic missile propulsion, materials technologies, and sensor and seeker apertures to be carried on both current and future platforms for long-range strike and begin development as soon as possible, if warranted. It should also conduct a study to determine the technical feasibility, operational utility, and affordability of a hypersonic cruise aircraft with appropriate sensors and weapons. If warranted by the results of the study and the readiness level of the technology, the USAF should begin development of a hypersonic aircraft.

1

Background and Overview

INTRODUCTION

The history of warfare contains many examples of "measure-countermeasure" cycles in which one side develops a "leap ahead" capability that redefines the battlespace, whereupon the adversary is forced to expend significant resources to catch up and counter this new capability. In the late 1970s and early 1980s, the U.S. military was able to demonstrate and deploy innovative aircraft with reduced radar signature (stealth), giving it a significant advantage against air defenses of that period. In response, however, integrated and networked air defense systems have continued to improve, including longer-range early warning radar detection, computerized integration of radars, airborne interceptors, effective surface-to-air missiles, and defensive weapons with greater range, speed, tracking, and kill capability. These defensive improvements have threatened the *survivability* of conventional U.S. aircraft—that is, their capability to avoid or withstand a hostile man-made environment.[1] This threat has led in turn to the development of onboard electronic countermeasures and weapons to attack enemy air defenses, as well as to recognition of the importance of having up-to-date knowledge of the location and capability of enemy assets in the battlespace (situation awareness). As enemy air defense capabilities continue

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[1] Robert E. Ball, *The Fundamentals of Aircraft Combat Survivability Analysis and Design*, Second Edition, American Institute of Aeronautics and Astronautics Education Series, 2003.

to improve in the future, U.S. aircraft technologies must also evolve so as to maintain the level of survivability necessary to accomplish missions that are deemed essential to the achievement of U.S. military objectives.

Stealth technology is defined here as the technology that allows a weapons system and/or vehicle to be difficult to detect. In the case of a threat radar system, the radar return is reduced below the noise level or clutter. In this way, the weapons system gains advantages in surprise, time lines, and battle management. Such advantages are relevant for attacking entities from leopards to aircraft.

Many speak of aircraft stealth as the key attribute of modern aircraft system mission success. It is very important, however, that one not think of stealth or speed or electronic countermeasures as ends in themselves, but rather in the context of the ultimate objective that these technologies provide—*survivability*, not only of the aircrew but of the system itself—so that both can live to fight another day. The many attributes (stealth, speed, situation awareness, tactics, and countermeasures) work synergistically so that the sum total of their contribution is mission success. To discuss how to ensure survivability in modern systems, it is necessary to go back in time.

HISTORICAL CONTEXT

World War I witnessed the advent of powered air warfare. In that conflict, airmen observed one another by relying totally on their natural vision and used their innate flying skills to achieve victory.

Air warfare in World War II was characterized by the introduction of radar systems that saw beyond visual range and created for the first time in history an opportunity for long-range detection and tracking of hostile aircraft. The successful defense of Great Britain was to a great extent enabled not only by the resolute attitude of the English people in the face of repeated attacks and by the implausible strategic blunders of Adolph Hitler, but by the ability of the Royal Air Force to know where the enemy air forces were and how to employ its relatively meager air assets most efficiently to ensure their defeat. Electronic countermeasures also became a factor in the avoidance of German radar detection.

Vietnam was the real crucible for the employment of weapons systems designed to attack militarily meaningful targets and penetrate enemy defenses protecting those targets. That conflict demonstrated the power of precision bombing to destroy critical targets such as bridges, and through increased effectiveness to reduce the number of sorties required and the attrition of attack aircraft. Enemy missile defense systems, especially the SA-2, had to be dealt with, along with Soviet-built fighters equipped with air-to-air missiles and greatly improved antiaircraft gun systems used for point defense.

During and after the Vietnam conflict, Department of Defense air components absorbed lessons learned in that conflict and were developing new systems and tactics, doctrine, and operational concepts to cope with the rapidly improving Warsaw Pact conventional weapons capability led by the Soviet Union. The United States and the North Atlantic Treaty Organization (NATO) were preparing for major battles in two areas: central Europe and the North Atlantic and Norwegian Sea ocean basins.

In the former, the Pact tactical air forces posed a major threat to NATO ground forces, aircraft, and air bases. In addition, the Pact, led by Soviet development and the fielding of the new air defense systems, was prepared to pose a major threat to NATO air forces should NATO counterattack Warsaw Pact ground forces and air bases. The United States and NATO developed capability to penetrate the Pact defenses by flying at low altitude (100 to 200 ft) while employing electronic countermeasures and lethal defense suppression. In order to achieve acceptable levels of survivability, the ratio of support aircraft to attack and close-air-support aircraft was high in some regions. Low-altitude operations impeded the ability to locate targets; thus, the USAF adopted the pop-up and roll-in maneuver performed as the target was approached. Still, to survive, the final approach to the target was limited to 10 to 20 seconds, which was marginally enough time for effective target acquisition and attack. It became very obvious, from the heavy air asset losses when attacking heavily defended targets in Vietnam and from the difficulties faced in central Europe planning, that a better way had to be found.

It is pertinent to recount also the introduction of both reduced radar signature and high speed into U.S. reconnaissance aircraft. Following the missile intercept and destruction of the U-2 flown by Gary Powers over the Soviet Union, the A-12, YF-12, and SR-71 family was developed with a Mach 3+ capability (according to the press), along with shape features and materials to decrease the radar cross section. The speed, signature, and a high-altitude operation combined to make the aircraft quite survivable against ground air defenses as well as airborne interceptors. The MiG-25 Foxbat was the one aircraft most likely to attempt an intercept, and it did, but the intercept time window was only a few seconds, requiring precision command and control beyond Soviet capability.

There is no reason to assume that evolution of integrated air defense systems, including defensive aircraft intercept, will not continue, or even accelerate, during the time horizon of this study (2018). Improvements in detection range, lethality, and system performance will challenge the United States to keep pace until the cumulative risk reduces the probability of mission success below an accepted threshold.

In the past, the spectrum of possible warfare spanned extremes from actions against underdeveloped countries with dated defense systems to modern peer competitors with the latest equipment. Over time, however, the low end of the threat spectrum has been vastly improved by the acquisition of modern systems such that, if the necessity arises, U.S. forces must plan to face integrated air defense systems that will continue to be improved by evolution and possibly new concepts wherever these forces are employed. For this reason, the world of 2018 (and during the subsequent operational life of the aircraft—perhaps 40 or more years) presents a much more difficult and hostile operational environment than ever before.

However, the United States has also continued working to keep pace. U.S. systems in use in 2018 and beyond must be able to complete their missions despite threat lethality evolution. Continued offensive mission success depends on improved situation awareness and low observables, increased speed, better system protection, and more capable weapons.

Defense planning guidance demands that the Air Force be prepared to conduct its worldwide missions. To successfully accomplish these missions—Global Strike and Persistent Global Attack—serious consideration must be given to the quality of improved enemy air defense threats to ensure that analyses of alternatives result in systems that can accomplish the mission despite that expected threat.

There is no need to recount in detail in this report the incredible success that has been demonstrated in recent conflicts by U.S. Air Force aircraft systems. We have all seen television footage of attacks in which not a single American aircraft has been lost despite fully functional and highly capable enemy air defenses. The question of this study, in its simplest form, is this: Can this nation continue to rely on these technologies to project power? This capability was not developed overnight. For example, there have been three generations of stealth technology from the 1970s until the present day.

History of Stealth

Early first-generation investigations emphasized materials and shape management to gauge their potential for improved aircraft survivability against known air defense systems and resulted in the first operational stealth aircraft—the F-117A. One penalty for stealth was lower aerodynamic performance as a result of the faceted shape.

The second generation, that is, the B-2A, incorporated improved low-observable technologies, including curved shapes that were more favorable to aerodynamic performance and improved operational capability. The B-2A, however, presented maintenance cost challenges that helped to inspire the third generation.

The third generation includes further improvements of all of the attributes, including operational performance, while at the same time reducing the acquisition cost penalty and maintenance cost burden. An example of a third-generation system is the F-22A. (In fact, because of its proven operational test performance, the USAF refers to it as a "fifth generation" fighter.)

The Speed Factor

Speed is also a contributor to survivability. Obviously, reduced exposure time affects defensive-system success. With the exception of the F-22 and the SR-71, all previous aircraft operate at subsonic speeds for most of their operational missions. Many earlier aircraft were capable of supersonic dash (beginning with the F-100), but the fuel consumption at supersonic speeds in afterburner was simply too high to sustain for more than a few minutes. The specific design of the SR-71 allowed it to perform its reconnaissance mission at very high altitude at a Mach number of 3+. The F-22, however, is the first U.S. aircraft that can operate efficiently at supersonic speeds without the use of afterburner; hence the term "supercruise" was created. Its speed performance contributes significantly to survivability.

For very-high-speed systems such as current missiles, speed begins to be the dominant factor determining survivability, as stealth attributes are degraded owing to the severe thermodynamic and aerodynamic environment.

Tomorrow's aircraft systems must exploit the lessons of the past and provide the optimized systems and attributes that allow continued operations in enemy territory, with impunity, even beyond the time horizon of this study. These systems will not depend only on speed and stealth for enhanced survivability. They will also rely on better situation awareness, defensive systems, tactics, and weapons to ensure their mission survival. True systems-engineered designs become essential.

Components of Survivability

Robert E. Ball, Distinguished Professor Emeritus at the Naval Postgraduate School at Monterey, California, is considered a survivability expert by many who are involved in the field of designing aircraft systems that are expected to survive in combat environments. He has authored several books on the subject, and anyone interested in this field of science and design is encouraged to seek them out and read further on the subject. His books delve into the definition of survivability and provide information on the following: the aircraft survivability discipline, the anatomy of aircraft, missions and threats, and on the constituent elements of survivability—*susceptibility* and *vulnerability*.

Susceptibility

Ball defines *survivability* as the "capability of an aircraft to avoid or withstand a man-made hostile environment."[2] In the same reference, Ball defines *susceptibility* as "the inability of an aircraft to avoid the guns, approaching missiles, exploding warheads, air interceptors, radars, and all of the other elements of an enemy's air defense . . ." and *vulnerability* as "the inability of an aircraft to withstand the man-made hostile environment." Notice the fine distinction between the two. Susceptibility is framed in terms of what constitutes the hostile environment, while vulnerability is the ability to withstand those elements.

Not to be susceptible is to avoid detection and interception through aircraft design and by characteristics that mitigate susceptibility, such as smokeless engines, low radar and infrared signatures, capable self-defense ordnance, and speed, and through the application of evasive tactics.

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[2] Robert E. Ball, *The Fundamentals of Aircraft Combat Survivability Analysis and Design*, Second Edition, American Institute of Aeronautics and Astronautics Education Series, 2003.

Vulnerability

Vulnerability, as distinct from susceptibility, is mainly in the hands of the aircraft designer and of structured assessment analyses used to determine how well an aircraft can resist damage in a hostile environment and keep on flying, through to successful mission accomplishment.

The aircraft designer knows that resistance to enemy threats (reduced vulnerability) can be built into the system up to a point. Modern aircraft, by nature, are inherently fragile—tough enough to handle flight conditions of high speed and high G forces—but at the same time too thin-skinned to survive proximate lethal warhead effects. In some ways, design efforts to make them less susceptible to enemy efforts to destroy them make them more vulnerable if hit. Susceptibility relies on speed, stealth, and tactics. The best way to avoid problems is to develop mission profiles that avoid most threats. However, that is not always possible, thus demanding other methods to avoid aircraft damage or loss.

It is important that methods to reduce aircraft vulnerability continue to be considered by the Air Force and its airframe contractors.

Importance of Situation Awareness

As usual in warfare, safety lies in the quality of intelligence gathered and provided to the aircrew regarding threat location and type. And then, once in the combat area, that safety lies in possessing outstanding situation awareness about all that is occurring—the presence of hostile and friendly aircraft, ground-based threat system activity status, missiles on the way, radars locked on, and many other indications that a pilot must know about and act upon. Modern systems have this ability, which is what separates them from their predecessors. Some, as in the case of the F-22, are capable of sustained supersonic speed that, when combined with stealth, tactics, and battlefield awareness, makes it very difficult for enemy air defense systems to prevent them from accomplishing their assigned missions.

STATEMENT OF TASK

In 2005, the U.S. Air Force asked the Air Force Studies Board of the National Research Council to conduct a study addressing the following five tasks:

1. Review the current state-of-the art capability achievable in both stealth and speed for air vehicles (including unmanned systems) and missile systems as postulated by both Air Force and industry sources inclusive of, but not limited to, long-range strike options.
2. Capture the various views from diverse sources on the effect of speed and stealth on the combat capability of these systems and provide a framework for evaluation.
3. Provide an assessment of levels of survivability (provide committee definition) achievable by capitalizing on "speed-stealth" combinations within 15 years against current and future threats.
4. Discuss the missions/capabilities enabled by greater stealth and/or speed for which no other more cost-effective alternative is obvious.
5. Generally assess and discuss cost and schedule issues to obtain the associated speed-stealth technology and compare them to current R&D investment plans.

It was understood that addressing these tasks in detail would require briefings and discussions held in a secure environment and that the Committee on Future Air Force Needs for Survivability would produce a nonpublic version of the final report.

SCOPE AND COMMITTEE APPROACH

Consistent with the priority expressed in Task 1, the committee focused on options for long-range strike: that is, a mission requiring the aircraft to have long range, penetrate alone and unsupported into heavily defended territory, deliver precision weapons onto fixed or moving targets, and return safely to base. The committee considered a range of threat air defense capabilities, as well as how these threats might evolve in the future. It discussed aircraft survivability in the context of defeating the threat's kill chain (see Chapter 2) as it would apply to the Global Strike (GS) mission, and considered the sensitivity of survivability to speed, signature reduction, and situation awareness with regard to GS and persistent Intelligence, Surveillance, and Reconnaissance. The committee did not discuss whether the next-generation long-range strike system should be manned or unmanned, reasoning that the system design of an aircraft with the range, payload, speed, and defensive capabilities necessary for long-range strike would likely not be significantly affected by the presence or absence of a pilot.

To address Task 2, the committee's approach was to gather available information through briefings at its meetings (see Appendix B), as well as to review recent relevant studies authored by government agencies, federally funded R&D centers, and industry. The "survivability" of an air vehicle depends on many factors, including the type of mission; the quality and doctrine of enemy air defense systems; aircraft characteristics such as speed, stealth, range, payload, and maneuverability; situation awareness; countermeasures; electronic warfare; and weapons against threats, tactics, and so on. In the limited time available for this study, the committee was unable to consider all of these factors in detail; rather, the committee outlined a framework for a more formal, quantitative evaluation in Appendix C.

To address Task 3, the committee drew upon the information gathered in Task 2 and used its own expertise to propose consensus combinations of speed and stealth that it believes would result in equivalent survivability levels in the long-range strike mission. Based on the expertise of individual committee members and drawing on their sponsoring organizations, the committee also assessed the technical feasibility of achieving the speed-stealth combinations mentioned above for an aircraft with initial operational capability (IOC) of 2018—a date that was agreed upon in discussions with the sponsor.

Regarding Task 4, the committee did not have time to examine in detail the variety of missions and capabilities enabled by greater stealth and/or speed, nor to lay out and assess the cost-effectiveness of alternatives. However, the committee placed a premium on those technologies that would enable maximum versatility to accomplish a variety of missions with a single platform. These technologies are highlighted in the recommendations, as discussed in Chapter 5.

In addressing Task 5, the committee did not have time to fully discuss cost and schedule issues associated with speed and stealth technologies, although implicit in the technical feasibility analysis conducted for Task 3 was the requirement that the technology be available for a 2018 IOC aircraft. The committee overlaid this feasibility analysis on its proposed consensus speed-stealth targets for survivability (Task 3) to identify gaps and needed changes in R&D investment plans, as called for in this task. The sponsor can use the committee's conclusions and recommendations to evaluate the detailed cost and schedule implications of the changes to current R&D investment plans.

STRUCTURE OF THIS REPORT

Chapter 2 discusses the various missions that U.S. military aircraft may be called on to perform and the operational environment associated with those missions, including the types of threats that may be encountered. A general discussion of technologies needed for achieving various speed and radar signature combinations is included in Chapter 3, and the feasibility of achieving these advances for platform IOCs of 2018 is assessed. Research and development priorities for applications both near term (2018 IOC) and later (2025 IOC and beyond) are discussed. Chapter 4 describes the committee's observations regarding aircraft stealth, speed, and survivability drawn from its analysis of relevant recently published reports, supplemented by briefings received by the committee and its own expertise in the field. It overlays the technical feasibility analysis of Chapter 3 on the proposed speed and stealth targets for aircraft survivability to highlight the gaps in current R&D investment plans. Appendix C, which is associated with Chapter 4, describes the variables (and interactions among the variables) that influence the survivability of mission aircraft and presents a formal framework that the Air Force can use to evaluate platform performance for various mission scenarios. Chapter 5 presents the committee's overarching findings and recommendations regarding changes to current R&D investment programs that are needed to maximize the versatility of system performance.

2

Operational Environment

As the United States Air Force considers the capabilities it will need to successfully complete the tasks it will be assigned in the years ahead, a critical review of potential scenarios and their projected threat environments must be accomplished. In selecting appropriate scenarios, the *National Defense Strategy,* published in March 2005,[1] and the *Quadrennial Defense Review Report* (QDR),[2] published in February 2006, provide a solid foundation for understanding the types of missions, the likely locations, and the kinds of threats that U.S. forces will probably face.

THREATS AND NEEDED CAPABILITIES

To implement the National Defense Strategy, the Department of Defense's (DOD's) senior civilian and military leaders identified four priority areas in the QDR for examination:[3]

1. Defeating terrorist networks,
2. Defending the homeland in depth,[4]

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[1] *National Defense Strategy of the United States of America,* U.S. Department of Defense, Washington, D.C., March 2005.

[2] *Quadrennial Defense Review Report*, U.S. Department of Defense, Washington, D.C., February 6, 2006 (hereafter cited as QDR, 2006).

[3] QDR, 2006, p. 19.

[4] The committee did not consider this area to be a focus of this report.

3. Shaping the choices of countries at strategic crossroads, and
4. Preventing hostile states and nonstate actors from acquiring or using weapons of mass destruction (WMDs).

These threats evolve at different rates: peer and/or competitor states with high-technology capabilities continue to improve their already highly capable integrated air defense systems (IADSs), while the best current systems may become available to hostile underdeveloped countries or nonstate actors through international arms markets within a couple of decades. Three of the four priority areas listed above (1, 3, and 4) require force-projection capabilities into hostile environments; this study will concentrate on scenarios related to these three priority areas.

In defeating terrorist networks, "the enemies we face are not traditional, conventional military forces, but rather distributed, multinational and multiethnic networks of terrorists."[5] Clearly, the nation with its allies, coalition members, and other partners will need to use all of the tools of national power in defeating terrorist networks. To gather intelligence, it will be necessary to establish persistent surveillance over an area of interest and then be able to rapidly strike a terrorist cell or node that might be fleeting in nature. New threats associated with the engagement of unconventional forces in the global war on terror may place greater emphasis on the capability to persist in the battlespace for extended periods of time.

The QDR states: "Shaping the choices of major and emerging powers requires a balanced approach, one that seeks cooperation, but also creates prudent hedges."[6] With that in mind, critical national capabilities[7] required are "persistent surveillance, including systems that can penetrate and loiter in denied or contested areas" as well as "prompt and high volume global strike to deter aggression or coercion, and if deterrence fails, to provide a broader range of conventional response options."

In preventing the acquisition or use of WMDs, "the United States must be prepared to: deter attacks; locate, tag, and track WMD materials; act in cases where a state that possesses WMD loses control of its weapons, especially nuclear devices; detect WMD across all domains. . . ." Further, "if prevention efforts fail, the United States must be prepared to respond." "This will require growth in capability to locate, characterize, secure, disable

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[5] QDR, 2006, p. 20.
[6] QDR, 2006, p. 30.
[7] QDR, 2006, p. 31.

and/or destroy a state or non-state actor's WMD capabilities and programs in a hostile or uncertain environment."[8]

After assessing the DOD's performance in the above priority areas, the QDR states that "joint air capabilities must be re-oriented to favor, where appropriate, systems that have far greater range and persistence; larger and more flexible payloads for surveillance or strike; and the ability to penetrate and sustain operations in denied areas. The future force will place a premium on capabilities that are responsive and survivable. It will be able to destroy moving targets around the clock in all weather conditions, exploit non-traditional intelligence, and conduct next generation electronic warfare."[9]

In consideration of the above QDR guidance, the committee believes that the U.S. Air Force needs the overarching capability to achieve precise effects on a global basis, at will, and with impunity. In order to fulfill that overarching capability, the Air Force needs the capability to achieve global situation awareness, to make decisions rapidly, and to deliver weapons rapidly, with precision guidance. Further, those systems contributing to the overarching capability that are intended to be reusable must also have *survivability* and those systems not intended to be reusable must have *survivability* until they have achieved their intended missions.

ASPECTS OF AIR VEHICLE SURVIVABILITY

For this study, as stated in Chapter 1, *survivability* is defined as the capability to avoid or withstand a hostile man-made environment.[10] The primary characteristics of a system's survivability are its *susceptibility* and its *vulnerability.* This study deals primarily with the susceptibility aspect of survivability. It does not address broader measures of mission effectiveness in detail, such as the delivery of precision weapons onto the target, though such measures are discussed qualitatively in Appendix C.

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[8] QDR, 2006, p. 34.

[9] QDR, 2006, p. 45.

[10] Robert E. Ball, *The Fundamentals of Aircraft Combat Survivability Analysis and Design*, Second Edition, American Institute of Aeronautics and Astronautics Education Series, 2003.

SURVIVABILITY AGAINST INTEGRATED AIR DEFENSE SYSTEMS

In planning to execute a tasked mission in an adversary's airspace, it is useful to consider the adversary's IADS in the context of a *kill chain.* By convention, a kill chain comprises four links, as listed below.

1. Surveillance
    - Search
    - Detect
    - Track
    - Classify
2. Track/fire control
    - Extract targets
    - Develop fire-control solution
    - Launch missile
3. Missile fly-out and guidance
    - Air vehicle kinematics
    - Midcourse guidance
    - Target acquisition
    - Terminal homing
4. End game
    - Fuze detection
    - Detonation

An IADS is a complex network of hierarchically structured, often geographically separated radar, communications, automated information management, fire control, and weapons systems that control and direct an aircraft interceptor or missile system against intruding threats. In order to complete the kill chain successfully, the IADS's connectivity, processes, and exchange of information must be able to respond in a synchronized and rapid fashion; therefore, as one considers how best to defeat an IADS structure, one must be aware of the time dimension with which an adversary deals in executing the individual, but interconnected, defensive tasks and processes.

In many modeling and simulation activities, there is a tendency to portray an adversary's capability against a friendly system from a parametric perspective in a one-on-one scenario. This committee, in its review of the various analyses published in the past several years (see Chapter 4), also considered the realities of a many-on-many scenario. The committee also considered the implications of the "fog of war" associated with presenting the enemy with parallel actions. Based on the committee's experience, it determined that the Air Force can improve its modeling and simulation techniques in the area of the human cognitive processes or time delays associated with the effect on an adversary of parallel actions and the "fog of war." In future analyses of alternatives and trade-off studies and prior to beginning an integrated capability development for a next-generation strike system, these improvements should be included.

In addition to using sophisticated cyber and information operations techniques, the committee finds that the ability to decrease a weapon system's susceptibility in an adversary's airspace is a result of achieving the right balance of speed and signature reduction. The contribution of both to survivability is synergistically enhanced by situation awareness. Additionally, countermeasures (including electronic attack, information warfare, and offensive weapons) and tactics provide flexibility, relatively rapid response to adversary measures, and improvements to the first-order characteristics (speed and stealth). From mission planning through mission execution, gaining and maintaining situation awareness will provide the weapons system operator an advantage in battlespace understanding that contributes to lethality as well as survivability.

By decreasing the weapon system's signature, the adversary's detection range—and hence the reaction time—available to the adversary for executing the kill chain can be dramatically reduced. Low observability affects the surveillance, acquisition and tracking, and fire-control functions, whether located on the ground or on airborne platforms. Similarly, reduced signature reduces the space and time available for surface-to-air missiles (SAMs) or air-to-air missiles (AAMs) to acquire their target, perform guided flight to the target, and then fuze and detonate successfully.

Further, in some cases and in some situations, appropriate signature reductions may prevent the adversary from being able to complete all elements of the kill chain. For example, a weapon system can be designed to reduce the adversary's detection range and hence the time available to transfer control from the detection radar to the tracking radar and then to the fire-control radar before a missile can be launched.

The use of appropriate countermeasures at the right time may conceal, disguise, deceive, confuse, or disrupt the adversary during certain phases of the kill chain. When used in conjunction with signature-reduction techniques, they can greatly enhance the effectiveness of those signature-reduction efforts and provide a means in future years to respond to unanticipated improvements or changes in the threat IADS.

Clearly, when trying to shrink an adversary's reaction time, increasing the weapon system's speed for the same signature can reduce its exposure time in the adversary's weapons engagement zone. From the Radar Range Equation one can derive the approximate ratio that increasing the speed by a factor of 10 is equivalent to decreasing the frontal radar cross section (RCS) by a factor of 40,000 to provide the same exposure time. Note, however, that increased speed also creates increased demands on precise onboard sensors and vehicle control systems.

Increased speed can also contribute to increasing the strike radius of action during any given period of time; this contributes to providing options for attacking more targets and/or engaging fleeting and time-sensitive targets of importance. Finally, increasing speed provides more possibilities for the employment of tactics and maneuver profiles during engagements with an IADS.

As the committee explores the right balance of speed, signature, situation awareness, countermeasures, and tactics, it is important to remember that the history of warfare is populated with a multitude of "action-reaction" or "measure-countermeasure" cycles in which new capabilities are envisioned, invented, developed, and employed to gain an advantage in the battlespace. The longbow, gunpowder, Gatling gun, submarine, tank, airplane, radar, nuclear weapons, air-to-air refueling, and precision weapons are all examples of leap-ahead capabilities that have redefined the battlespace and forced those without the latest capability to both catch up and expend significant resources to counter their adversary's new capability. Occasionally, a special capability is developed that resets the action-reaction chain and gives the innovator a quantum advantage in capability for a significant period of time. The stealth capability fielded in the early 1980s has proven to be an example of a "special capability."

Nonetheless, it is clear that potential U.S. adversaries are acquiring or improving their IADS capabilities and attempting to develop what they think would be counter-low-observable capabilities. Thus, choosing the right balance among speed, signature reduction, situation awareness, countermeasures, and tactics enables the United States to present its adversaries with the largest number of challenges in the shortest period of time.

In developing the right balance of speed, signature reduction, situation awareness, countermeasures, and tactics, a careful analysis of the potential adversary's integrated air defense system is essential, along with the knowledge of how the adversary uses each part of that system to accomplish the kill chain. In this study, however, the command-and-control links and the end-game systems will not be assessed.

The committee looked at trends in elements of IADS in assessing Air Force future needs for survivability, including ground-based surveillance radars, aircraft radars, infrared surveillance and tracking sensitivity trends, AAM seeker sensitivity trends, and SAM performance and improvement trends. From a global perspective, over several decades there have been gradual improvements in all of these capabilities. Significant improvements in ground-based radars, airborne surveillance radar systems, and fighter aircraft radars have been developed over the past several decades in terms of the minimum detectable RCS.

Improvements have also been made in infrared sensor technologies for surveillance and tracking as well as missile guidance for SAMs and AAMs.

The utility of infrared (IR) surveillance sensors combined with radars in an IADS needs further detailed analysis using engagement simulation and modeling. Employment of IR seekers in missiles is much better understood, particularly for AAMs, since IR has been used in short-range AAMs for 50 years.

Since the U.S. Missile Defense Agency and the Air Force are developing the airborne laser, which is a fully integrated detection, tracking, fire-control, and speed-of-light interception system, the development of future survivable air vehicles should assess whether such lasers might appear as a future threat and include appropriate countermeasures.

The committee reviewed an adversary's kill chain for employing various types of SAMs and concluded that there is continuing potential for signature reduction to degrade the range at which adversaries can detect, track, fire, and guide missiles to penetrating weapon systems.

Additionally, the committee projected the capability of potential U.S. adversaries to evolve and improve SAM performance against low-observable systems in the years ahead.

In summary then, and after viewing the continuing improvements to contemporary surface-to-air missile systems along with the continuing development of next-generation air defense and air superiority aircraft, the committee believes (1) that the future threat will consist of robust IADSs populated primarily with radio-frequency-based detection, acquisition, fire-control, and guidance systems; and (2) that those systems will continue to improve in their ability to engage air vehicles with reduced signature. Lastly, the committee believes that it is imperative to continue to guard against potential asymmetric advances on an adversary's ability to detect airborne objects.

U.S. AIR FORCE CONCEPTS OF OPERATIONS

To prepare for the missions that it will be asked to perform, the U.S. Air Force has formulated a capabilities-based analysis process known as the Capabilities Review and Risk Assessment (CRRA). This process captures most of the USAF's operational capabilities in seven concepts of operation (CONOPS) that have become the foundation for conducting the CRRA, as follows:

1. Global Strike;
2. Global Persistent Attack;
3. Nuclear Response;
4. Homeland Security;
5. Global Mobility;
6. Space and Command, Control, Communications, and Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR); and
7. Agile Combat Support.

These CONOPS are used to define the tasks and objectives inherent in each of those seven capability areas and then to detail the way that the USAF intends to accomplish those tasks and achieve its objectives. The CRRA process takes a time-definite, scenario-based approach to accomplishing the tasks defined in the CONOPS with the current and projected weapons systems that will be available during that time frame in order to fully understand the overlaps, gaps, and deficiencies in the Air Force's capabilities with regard to those defined tasks and objectives.

In addressing the statement of task in the context of QDR results, the committee reviewed the right balance of speed, signature reduction, countermeasures, situation awareness, and tactics for the Space and C4ISR, Global Strike, and Global Persistent Attack CONOPS.

Space and C4ISR Concept of Operations

Quoting from the Space and C4ISR CONOPS:

> The family of joint concepts aims to achieve the National Military Strategy (NMS)-directed overarching goal of full spectrum dominance—the defeat of any adversary in any situation across the full range of military operations. Full spectrum dominance, in turn, is based on the enabling effect of full spectrum decision superiority—the ability to sense, understand, decide, and act faster than any adversary in any situation. The S&C4ISR CONOPS articulates how the Air Force creates effects through capabilities that underpin full spectrum decision superiority. These effects and capabilities allow joint commanders to see first, understand first, and act first.[11]

For any scenario in which the United States may have to become engaged, it will need to have the highest degree of battlespace awareness. Whether it be in finding cells of global or regional terrorists, WMD production and/or storage facilities, or high-value targets on the move in either permissive or denied airspace, establishing persistent surveillance over any area of interest is necessary if the United States is to be able to *develop global situation awareness* in order to conduct *rapid decision making, rapid delivery* so that it can *achieve precise effects on a global basis, at will and with impunity.* The Space and C4ISR CONOPS seeks to achieve three high-level effects: full-spectrum battlespace awareness, information superiority, and space superiority. As General T. Michael Moseley, Air Force Chief of Staff, stated in that CONOPS document:

> We are responsible, unique from the Navy or the Army, for being able to locate targets on a global scale, 24 hours a day, seven days a week, day or night, good weather or bad. We're tasked to be able to find things on the surface on a global scale. . . . From the vantage of being in the air or in space, Airmen have a unique perspective.[12]

In reviewing the Space and C4ISR CONOPS, the committee focused primarily on the full-spectrum battlespace awareness effect. As delineated in the CONOPS, achieving full-spectrum battlespace awareness will require a networked and interactive "system of systems" approach. As shown in Figure 2-1, space, air, and terrestrial systems will all be required to be able

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[11] U.S. Air Force Space and C4ISR CONOPS, Final, December 19, 2005, p. 6.

[12] U.S. Air Force Space and C4ISR CONOPS, Final, December 19, 2005, p. 7.

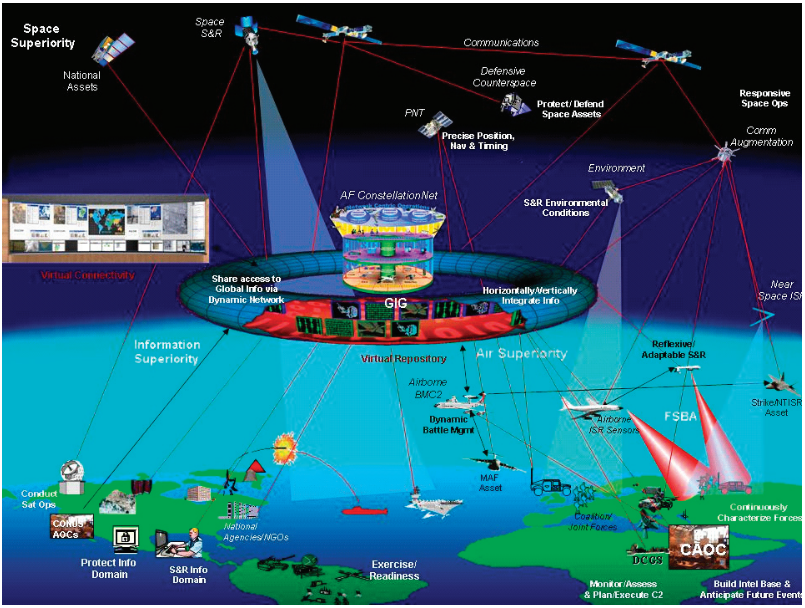

FIGURE 2-1 The Space and C4ISR Concept of Operations' operational view. Information gathered from space, in the air, and on land is combined to give commanders an integrated, full-spectrum view of the battlespace. NOTE: S&R, surveillance and reconnaissance; PNT, position, navigation, and timing; BMC2, battle management command and control; GIG, Global Information Grid; FSBA, full-spectrum battlespace awareness; CAOC, Combined Air and Space Operations Center; DCGS, distributed common ground system. SOURCE: U.S. Air Force Space and C4ISR CONOPS, Final, December 19, 2005, p. 5.

to present battlespace commanders with the information they will need to achieve full-spectrum decision superiority.

Although both standoff and penetrating airborne platforms are needed for full-spectrum battlespace awareness, this committee confined its review to the penetrating systems. The committee believes that such platforms must be able to penetrate, perhaps long distances, into denied airspace and loiter for long periods of time, thereby increasing their susceptibility to enemy ground and air threats. Thus, the key attributes for airborne, penetrating systems executing Space and C4ISR tasks are long range, loiter, stealth, and persistence coupled with the appropriate payload capacity to carry the requisite sensor systems.

Global Strike Concept of Operations

As detailed in the Global Strike CONOPS,[13] there are two desired capabilities for effects on the battlespace:

- *Rapid Strike* to achieve national objectives: Quickly neutralize the adversary's key high-value targets throughout the depth of any battlespace, at any time.
- *Gain Access* for persistent joint forces: Gain and maintain battlespace access. Project forces in antiaccess environments, and create conditions for persistent follow-on forces to operate with acceptable risk.

Although in some cases the rapid strike construct may require a one-time, single-target attack, similar to the U.S. Strategic Command's *prompt global strike* scenario, in which case a conventional ICBM might suffice, this committee considered the QDR language that U.S. forces be able to "conduct prompt and *high volume* global strike to deter aggression or coercion . . ." as necessitating the use of airborne systems.

The committee reviewed survivability analyses for aircraft with various levels of stealth, speed, and altitude while they are conducting the Global Strike CONOPS. For a hypothetical region with typical defense sites and targets, the size of the threat-defended areas is reduced by the combination of stealth, speed, and altitude of the attacking aircraft. As a result, employing an optimum combination of these characteristics, the attacking aircraft that can be developed before 2018 have much greater scope for operating without concern about being engaged by enemy air defenses. Strike aircraft may be required to remain in the battlespace for some time to attack multiple targets.

The Global Strike CONOPS envisions a capability to attack a limited number of targets in a highly defended region or to be able to open up a region or appropriate corridors (i.e., "kick down the door") to enable the follow-on forces. The committee believes the characteristics most beneficial to achieving this CONOPS are long range, speed, stealth, persistence,[14] and payload.

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[13] In a presentation to the committee by Mr. David N. Garten, AF/XOX-CONOPS, November 29, 2005.

[14] In the GS context, *persistence* refers to the capability to hold potential targets at risk. This might be accomplished either by loitering in the threat area, standing off at a safe

Global Persistent Attack Concept of Operations

The primary objective of the Global Persistent Attack CONOPS is to prevent a potential adversary's ability to do the following:

- Conduct major combat operations;
- Seek sanctuary;
- Disappear within the population or in complex terrain;
- Relocate their leadership and operational capabilities to other states;
- Produce, weaponize, store, and deliver chemical, biological, radiological, and nuclear weapons and/or agents;
- Conduct insurgency operations;
- Conduct space operations or deny joint and coalition forces the same;
- Conduct ISR against the joint and coalition forces;
- Conduct denial and deception;
- Develop and employ disruptive innovative technologies;
- Employ antiaccess capabilities;
- Maneuver to threaten friendly and/or neutral forces or ethnic populations;
- Create humanitarian and/or environmental crises;
- Protect leadership and strategic resources; and
- Command, control, and communicate with their own forces and allies.

Clearly, the forces required to conduct such operations will need to provide "24/7" coverage in both permissive and denied airspace and will probably require enough assets to "blanket" the enemy airspace in order to complete the multitude of envisioned tasks.

From its review of the Global Persistent Attack mission and the technologies that can be inserted in the next-generation long-range strike aircraft, the committee believes that multiple attacking forces can have the capability to engage a variety of enemy targets and will have the ability to persist and loiter in the battlespace for extended periods and to attack moving or time-sensitive targets.

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distance and attacking with high-speed missiles, or by standing off at a distance and repeatedly dashing into the battlespace to attack.

The Global Persistent Attack CONOPS envisions a force that can penetrate into enemy airspace after the “door has been kicked down” and persist with mass in a way that blankets an adversary’s airspace and denies the adversary freedom of maneuver and freedom of action as long as required. The committee believes that the characteristics most beneficial to achieving this CONOPS are long range, loiter, and persistence.

In summary, the Air Force has considered some of the most demanding tasks to which it has been assigned, most recently reinforced by the QDR, and has chosen the CONOPS-based approach. After a review of the USAF’s seven CONOPS, this committee believes that the Space and C4ISR, Global Strike, and Global Persistent Attack CONOPS require weapons systems designed with careful balance of the attributes of signature reduction, speed, countermeasures, situation awareness, and tactics. The goal should be to reduce the weapon system’s susceptibility without reducing its ability to accomplish the mission, recognizing the constraints of technological and economic feasibility. That balance must exploit continued evolution of U.S. stealth technologies while considering the projected improvements in counter-low-observable capabilities of potential adversaries. In reviewing the three applicable CONOPS for this study, the committee found that each CONOPS benefited from different combinations of attributes on the weapons systems needed to accomplish their respective tasks. The Global Strike CONOPS benefited most from the long-range, signature-reduction, speed, persistence, and payload attributes, while the Space and C4ISR and Global Persistent Attack CONOPS benefited most from the long-range, loiter, and persistence attributes.

With this chapter providing the operational backdrop, Chapters 3 and 4 discuss generally the requirements and the technical feasibilities of achieving certain speed and signature reductions. The committee also recognized and considered at the same time that countermeasures, situation awareness, and tactics can be used to enhance the survivability of the weapon system. This committee believes that the basic weapon system should be designed with the capability to complete its assigned mission without relying upon countermeasures, to the maximum extent possible. In other words, although countermeasure systems can significantly enhance the survivability of a weapon, they should be hedges against future threat evolution and improvement and not a requirement for the baseline. The same holds for situation awareness and tactics.

3

Technological Setting

This chapter describes the various factors that determine the speed and signature characteristics of an aircraft and its weapons systems, the current status of the technologies involved, and the U.S. Air Force's goals for the future strike system. This assessment draws upon the expertise of committee members, as well as on the databases and analyses of their sponsoring organizations, to assess the feasibility of achieving various levels of speed and stealth in an aircraft with a 2018 initial operational capability (IOC). Finally, the chapter concludes by highlighting near-term research and development (R&D) needed to achieve technology maturity (technology readiness level [TRL] of 6) by 2009 (for the 2018 IOC time frame). It also indicates R&D needed for longer-term opportunities and programs for air vehicles in the 2025 IOC time frame and beyond.

AIRCRAFT SYSTEMS

In this context, aircraft systems are taken to include the airframe, sensors and apertures, propulsion system, weapons and payload, countermeasure systems, and situation awareness systems. In the following subsections, the technology challenges in these areas are addressed, together with near- and far-term technology opportunities. Various trade-offs among these systems must be made using systems engineering approaches in the design of the overall weapon system.

Airframe

Subsonic and low-supersonic airframe design for stealth vehicles is well understood. The issues of platform shaping, sweep angles, and inlet and exhaust shielding are determined by the system requirements. Issues of tails, vectoring, and payload carriage are also determined by the need to meet operational requirements in the pursuit of operational utility.

Motivated by the objective of multimission aircraft, research begun in the early 1960s enabled the successful design of variable-sweep aircraft, including the F-111, F-14, and B-1. This "variable aerodynamics" innovation provided improved performance at supersonic as well as subsonic speeds. Although these aircraft demonstrated dramatic mission capability improvements, the escalation of the Soviet air defense threat drove the need for improved survivability and the shift toward stealth in the late 1970s and early 1980s, as exemplified by the F-117, B-2, and F-22. The F-22 uniquely combines high degrees of stealth, supercruise, situation awareness, and maneuverability for survivability.

Near-Term Technology Needs

Higher flight speeds add complexity to the design process because of the need to increase the high-speed aerodynamic efficiency of the platform while still meeting signature requirements. If long portions of a mission must be conducted at supersonic speeds using existing propulsion technology, the size of the aircraft must increase owing to the need to carry larger fuel loads. Variable-cycle engines offer the opportunity to reduce this platform growth because of their better fuel specifics (specific fuel consumption) in both the subsonic and supersonic speed ranges. While some of the radar cross section (RCS) signature requirements may be relaxed somewhat because of the higher speed, they are nevertheless still challenging for the design team. Systems engineering must be used to balance the conflicting approaches and requirements to yield the most cost-effective, operationally relevant system.

Far-Term Technology Opportunities

Adaptability of the platform shape—possibly using variable wing sweep, the evolving technology of *morphing structures,*[1] or active flow-

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[1] In this report, *morphing structures* refers to wing structures that can change their shape to achieve optimal, uncompromising performance during complex military missions. The

control techniques—offers possible solutions to the need to have the platform optimized aerodynamically in multiple speed ranges. Wing variability, while mature, must be examined closely from a signature perspective (sealing, cracks, and gaps) for its use in a 2018 system. One of the key reasons for the decline of variable aerodynamics during the beginning of the stealth era was the difficulty of integrating the moving surfaces, apertures, and seals of a swing-wing design in a form compatible with RCS requirements. Stealth designs had to make significant cost and/or design compromises (e.g., forgoing variable sweep) in achieving the best survivability owing to planform[2] limitations in various areas of the flight envelope. In the future, however, a combination of stealth and variable aerodynamics may be feasible and could result in an aircraft that has the ability to optimize its signature as well as its aerodynamics during a mission. With the benefit of recent research, variable aerodynamics has the potential to re-emerge as a key enabler for mission flexibility and cost reduction in future strike concepts.

Recent developments in wing morphing technology funded by the Defense Advanced Research Projects Agency (DARPA) have led to material and design concepts that could enable variable-sweep-wing designs.[3] DARPA research efforts cover several applicable technologies, including planform change design technologies and various actuation technologies. Application of the morphing materials and concepts to a swing-wing design may provide the strike aircraft designer with the best of both worlds—a wing that can assume the low-sweep aerodynamics desired for takeoff, landing, cruise, and maximum persistence, as well as sweep-back to create the long continuous lines desired for a stealth design combined with efficient supersonic cruise that further enhances survivability.

Evolving operational requirements demand the careful consideration of proven variable-aerodynamic design techniques to address future threat scenarios effectively. The performance characteristics demonstrated by the previous variable-sweep operational aircraft and other research indicate that there are size reductions and the associated cost reductions to future multimission aircraft that have the potential to provide unprecedented capabilities in responsiveness, persistence, and survivability. The combina-

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ability to change wing shape and vehicle geometry substantially while in flight allows a single vehicle to perform multiple mission tasks.

[2] In aviation, *planform* refers to the shape and layout of an airplane's wing.

[3] See, for example, http://www.darpa.mil/dso/thrust/matdev/mas.htm. Accessed August 22, 2006.

tion of variable aerodynamic and propulsion technologies can further build on that potential.

Sensors and Apertures

All future strike aircraft, weapons, and intelligence, surveillance, and reconnaissance systems will require sensors and apertures to complete their missions. By definition, these sensors must interact with the external environment; therefore, control of the sensors' associated signature with minimal sensor performance degradation is essential to meet both survivability and sensor performance requirements.

Typical sensors that are candidates for incorporation into future aircraft platforms include combat radar systems, radar altimeters, and electro-optical/infrared (EO/IR) systems. Radar systems have been successfully incorporated into both the B-2 and F-22 aircraft. As speeds increase and higher temperatures are encountered, the materials limitations associated with apertures must be evaluated. EO/IR systems have been deployed on existing aircraft, but the high temperatures encountered with increasing speed impact the aperture design, structural size, transmissivity, and the spurious signal input into the sensor. Sensor performance requirements for range, resolution, and processing speed can also be significantly increased by increasing speed.

In addition to onboard sensors, future aircraft systems will require the reception of Global Positioning System signals and continuous communications capabilities. Connectivity to the Global Information Grid (GIG) will require continuous communications connectivity into the aircraft.

Near-Term Technology Needs

In the review of future missions, concepts of operations (CONOPS), and targets, there will be a need to increase the fidelity and capability of active sensors without increasing the susceptibility of such sensors to signal intercept that can lead to the detection and tracking of the aircraft.

Far-Term Technology Opportunities

Signature-reduction techniques in the visible and IR spectral regions represent long-term technologies that may significantly improve survivability in the future. These techniques rely on the ability to sense the background environment from different perspectives.

Propulsion

Future aircraft systems will have an enhanced ability to strike time-critical targets. Propulsion will play a key role in that capability either by enabling high-speed platforms and/or by providing outstanding fuel-consumption characteristics that will allow vehicle persistence over targets. Engine companies and aircraft system contractors will need to study the benefits of both evolutionary and revolutionary engine technologies that can meet a 2018 IOC to understand the capability and return on investment that each technology provides. This activity will be a crucial part of the technology development and concept development and demonstration prior to the system definition and design (SDD) milestone.

The challenges for the propulsion system in a future long-range strike vehicle will be many. Sustained operation at elevated vehicle speeds, when coupled with a requirement for high performance, is a challenge to the engine designer. The engine cycle (fan pressure ratio, bypass ratio, operating pressure ratio) that produces the high specific thrust (thrust per pound of airflow) to enable high-speed flight does not produce the low-fuel-consumption characteristics that will allow long loiter times. From a component design standpoint, high-speed flight will result in the compression system of the engine experiencing much higher temperatures. This will also result in a significantly higher temperature for the cooling air, which poses a challenge for cooling the engine hot section. The hot section will operate for extended periods at near-maximum flow-path temperature, meaning not only that oxidation and/or erosion will be a limiting factor, but also that component creep will become a more prevalent design consideration.

Air vehicle thermal management is a challenge for today's advanced aircraft systems and will be even more so for the next generation of long-range strike aircraft. Heat loads at elevated flight speeds will challenge the temperature limits of the fuel that serves as the primary heat sink. The engine lubrication system will also be taxed by the higher operating temperatures, and reductions in oil system leakage will be critical to long-duration strike missions.

Another challenge of future systems will be to continue previous trends in advancing propulsion capability and, as a result, the capability of the vehicle system. Previous technology-development initiatives have been successful in developing new materials, increasing module performance, and increasing component efficiencies. Further efforts on materials and components can bring about additional improvements in engine capability. A fundamental technology challenge for all future propulsion applications is to find additional ways to improve the total vehicle system. Promising avenues to meet this challenge include focusing on aircraft-system-level improvements such as adaptive cycle engines.

Propulsion is a critical barrier to achieving a high-speed missile capable of cruising at hypersonic speeds. Ramjet propulsion systems have been highly evolved, and flight tests have been carried out in several demonstration programs at such speeds. Supersonic combustion ramjets (i.e., scramjets) have also been investigated for propelling high-speed missiles (see the section below on "Weapons"). Technology challenges include the following: generating stable combustion in the high-speed flow path over a wide speed and altitude range, developing high-temperature structural materials and insulators, and developing efficient cooling techniques that allow thermal balance in the overall weapon system. The fuel consumption and efficiency of such designs must be considered in light of the overall size and weight of the weapon.

Before a ramjet or scramjet is ever started, the vehicle must be moving with a high velocity, so the envisioned high-speed weapon systems are two-stage systems with integral rocket boosters. An alternative approach to a ramjet or scramjet system is an all-rocket propulsion system, which can be either single-stage or multiple-stage. Solid rocket propulsion technology is highly mature and little development risk exists, but the limited specific impulse of solid rocket systems results in shorter ranges for volume-constrained systems compared with air-breathing systems. An additional issue associated with rocket-propelled weapons capable of operation at long range is that the propulsion system burns quickly, resulting in flight along a predictable ballistic trajectory, which makes the weapon susceptible to intercept by advanced SAM systems, unless it has a terminal maneuvering capability.

Near-Term Technology Needs

The very high performance levels of existing propulsion capability were achieved through investments made in the Integrated High Performance Turbine Engine Technologies (IHPTET) program, which funded innovative research from 1985 to 2005. By any measure, the IHPTET program was a great success. It transitioned many technologies and enabled the advanced capability that currently exists in engines such as the F414 and F119 as well as the engines currently under development for the Joint Strike Fighter, the F135 and F136. The follow-on program to IHPTET, called the Versatile Affordable Advanced Technology Engines (VAATE) program, expands the focus of technology development to include items that can drive the performance and affordability of the entire vehicle system. Unfortunately, since the VAATE program's initiation, its funding has been curtailed (by 40 to 50 percent). It will be critical to restore that funding to the levels originally planned in order to enable the timely development and transition of propulsion technologies (increased hot-section capability, improved materials, and thermal-management system) needed for future strike aircraft.

Under the VAATE program, the propulsion community is executing technology-development efforts necessary for aircraft to achieve long life at sustained high temperature. The solution is not a single technology, but rather advances in the state of the art along a broad front. A new generation of high-temperature, creep-resistant disk materials is required for the turbine disk to have sufficient life in this environment. Other materials will have to be employed in new locations—for example, the use of the advanced turbine disk materials in the aft stages of the compressor. Turbine airfoils will require advances in cooling technologies to allow the more efficient distribution of cooling air. In addition, advanced coatings will be required to better insulate hot structure from the gas path. There must also be changes in the combustor to improve efficiencies by reducing the variability in the spatial temperature profile entering the turbine. Less variability allows the turbine to run closer to its temperature limit; alternatively, that capability can be traded for increased service life.

These solutions alone may not produce sufficient life in the turbine section of the engine. There may be an additional need for technologies that can reduce the temperature of the turbine cooling air. One system approach would be to reduce the temperature of the cooling air using a fuel-air heat exchanger. This approach requires the development of new, highly reliable high-temperature heat exchangers configured for the demanding propulsion thermal and acoustic environment. Fuel nozzles and seals will have to be redesigned for the higher temperatures, as will the control system.

Meeting future aircraft range and loiter requirements will require engines with much improved fuel-consumption characteristics. Improved component aerodynamics and sealing to reduce parasitic leakage will be necessary, as will technologies that allow the engines to operate with tighter clearances between the airfoils and the engine casings. Advanced controls will include sensors that provide real-time information on the performance of the engine. With those data, the control will be able to use effectors to optimize the performance of the engine for reduced fuel consumption. Additionally, a new augmenter development program will be needed to study and define potential operability and performance characteristics of the supersonic, long-cruise application for IOC in 2018.

Long-range strike platforms are being investigated that could fly several thousand miles, with a substantial portion of that mission at supersonic speeds, and then could loiter for hours. Today's propulsion system design space will constrain the designer's ability to support this type of mission. To enable this revolutionary performance, adaptability will be required of the next generation of engines and airframes in terms of engine cycles, innovative integrated architectures, and morphing configurations. The propulsion community is positioned, if adequately funded, to bring variable-cycle engines—with their significant air-vehicle system advantages—to support the propulsion needs of a 2018 IOC long-range strike system. For example, DARPA and the Air Force are considering the initiation of an Adaptive Versatile Engine Technology program that aims to select technologies and concepts that are promising for future adaptive cycle engines. As this program is currently envisioned, it will advance adaptive engine technology, but it will not support a 2018 IOC. This program, if reprioritized and started now, could, in the assessment of committee members from the propulsion industry, advance the technology to TRL 6 in time to start SDD in 2009 and IOC by 2018. It is the recognition of these challenges and the contemplated solutions that strongly argue for the development of variable-cycle engine technology. Since aspects of variable-cycle engines have been successfully demonstrated since the 1980s, the technology is available now to permit the packaging of multiple-cycle engines capable of sustained high speed and efficient loiter, if both are required for the long-range strike platform.

Far-Term Technology Opportunities

With declining stocks of oil, the continued availability of existing hydrocarbon fuels must be examined, and propulsion systems capable of operating on alternative fuels must be developed. While this issue is not specific to the question of speed and stealth, future aircraft systems will be significantly impacted by technology advances made in the area of aviation fuels. Desirable characteristics of new fuels include both additional cooling capacity and increased energy density.

Flight at hypersonic speeds will require significant development of new propulsion systems. Hypersonic air-breathing propulsion solutions and aircraft development—other than a missile—are highly unlikely in the time frame necessary to support 2018 IOC systems, but they represent an area of promise for application to future systems. Turbine-based combined-cycle (TBCC) engines have been explored for application to hypersonic aircraft and space-access vehicles, but this class of engine technologies is immature relative to near-term needs. TBCC engines could be enabling to a future hypersonic strike aircraft, but there are a number of integration challenges with the TBCC, including flow-path optimization, transition Mach number between turbine and scramjet, and thermal management. Integrated vehicle-and-propulsion designs need to be made on the basis of system thermal-management considerations. The thermal margins for high-speed propulsion systems are small and unforgiving of poor integration decisions at the start of these highly integrated designs.

In addition to propulsion solutions for the aircraft platform, there are several advanced engine technologies that could be brought to bear on the weapons that would be carried by a long-range strike aircraft. For instance, the pulse detonation engine (PDE) uses a detonation-based combustion cycle and has the potential to offer improved fuel-consumption characteristics and lower fabrication costs. If an engine can be built to fully utilize the efficiency gains of the constant volume cycle, relatively large gains in propulsion system efficiency and performance, which are application-dependent, can be realized. Expendable PDEs for supersonic missiles have the potential to operate at speeds approaching hypersonic, and they integrate well into small, space-constrained high-speed weapons currently under evaluation by the Air Force and the Navy. Vehicle-level analysis of these missiles has shown the potential to offer approximately 50 percent reductions in propulsion system cost compared with similarly performing supersonic turbojet or afterburning turbojet engines.

Weapons

Weapon technologies strongly impact air platform survivability and, ultimately, the mission effectiveness of the launch aircraft. As an example of this interdependency, the increasing of weapons payloads to achieve a

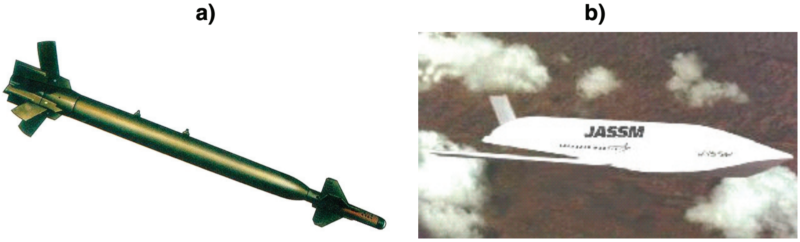

FIGURE 3-1 Examples of existing weapon systems: (a) Guided Bomb Unit-28 (GBU-28); (b) joint air-to-surface standoff missile (JASSM). SOURCES: See http://www.fas.org/man/dod-101/sys/smart/gbu-28.htm, accessed August 22, 2006; and http://www.fas.org/man/dod-101/sys/smart/jassm.htm, accessed August 22, 2006.

specified mission leads to larger air vehicles, larger propulsion systems, and increased signatures. Alternatively, a high-speed missile hosted on a standoff air platform may handle the same mission as a gravity weapon dropped from a stealthy air vehicle that is capable of persisting in a high-threat environment. In the subsections below, technology challenges associated with weapons are discussed, together with near-term and far-term opportunities for advancing the state of the art for weapons.

The critical technologies for weapons include aerodynamics, propulsion, materials and structures, system integration, terminal sensors and apertures, weapons data links, type of warhead, and signature. Many issues associated with weapons technologies overlap those associated with aircraft, although the weapon's single use and limited flight time significantly simplify the system design.

The principal focus of this technology assessment concerns kinetic weapons, which can be subdivided into gravity or glide weapons (e.g., Guided Bomb Unit-28 [GBU-28]) and powered weapons (e.g., joint air-to-surface standoff missile [JASSM]) as seen in Figure 3-1. Gravity weapons are necessarily short-range systems that require the aircraft to closely approach the target, which may stress the aircraft signature requirements. With their short flight times and close spacing, gravity weapons are inherently difficult to intercept, so little attention is paid to signature issues for these weapons.[4]

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[4] Future bombs could have greater standoff distance, which affects survivability considerations.

With respect to powered weapons (i.e., missiles), a large array of potential technologies and system solutions exist. Since missiles may fly for extended ranges within a heavily defended area, the survivability aspects of strike missile concepts are extremely important. Existing air-launched missiles are either turbojet-powered (e.g., air-launched cruise missiles, JASSMs) or rocket-powered (e.g., Maverick). The turbojet-powered systems are subsonic missiles that rely on low signature for survivability or fly within ground clutter at low altitude to evade radar tracking. Rocket-powered systems fly at higher speeds but are necessarily of shorter range.

Near-term advances in weapons system technologies currently being investigated include terminal guidance systems for subsonic weapons, algorithms for the autonomous search and recognition of targets, and data links for communicating continuously with the weapons following release from the air platform.

High-speed weapons potentially add to overall system survivability by enabling the attack of time-sensitive targets or targets outside the range of conventional glide munitions. The issues associated with development of high-speed missiles with significant range were addressed in a 1998 report of the National Research Council (NRC)[5] and in the USAF Scientific Advisory Board (SAB) report published in 2000.[6] The 1998 NRC report found that "completion of the HyTECH program by 2003 followed expeditiously by flight testing of a prototype vehicle, could enable an operational, airbreathing hypersonic missile in the Mach number range of 6 to 8 by 2015." However, the report also found that many other technical challenges beyond propulsion, such as sensors, guidance and control, thermal management, and others, require emphasis and investment as well. The 2000 SAB report states that "long-range, high-speed air-to-surface missiles can have significant military utility, provided that targeting information is available to exploit their inherent advantages."

Given the potential utility of high-speed, long-range weapons, the committee conducted a brief evaluation of the status of weapons technology. The science and technology community within the Department of Defense (DOD) has been investigating high-speed missile technologies to enable a

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[5] National Research Council, *Review and Evaluation of the Air Force Hypersonic Technology Program*, National Academy Press, Washington, D.C., 1998.

[6] United States Air Force Scientific Advisory Board, *Why and Whither Hypersonics Research in the US Air Force*, SAB-TR-00-03, HQ USAF/SB, Washington, D.C., December 2000.

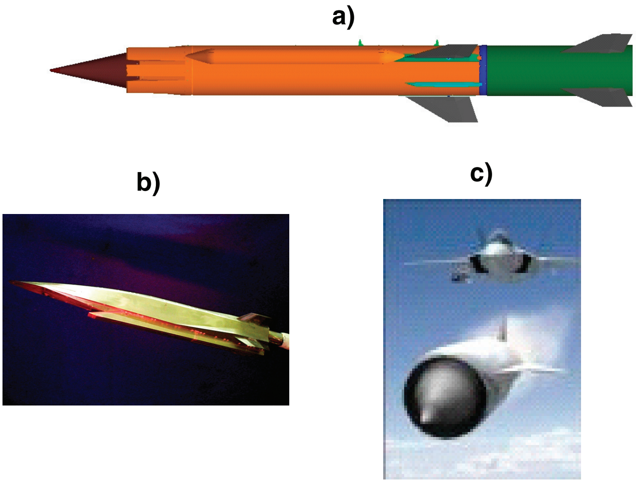

FIGURE 3-2 Missile technology demonstrations and flight experiments: (a) HyFLY Mach 3 to 6 scramjet; (b) X-51 Mach 3 to 8 scramjet; and (c) Revolutionary Approach to Time Critical Long Range Strike (RATTLRS) Mach 3+ turbojet. SOURCES: (a) and (b): Boeing Company; (c): Lockheed Martin Corporation.

broader range of options, as illustrated in Figure 3-2. Currently in the Office of Naval Research's (ONR's) Revolutionary Approach to Time Critical Long Range Strike (RATTLRS) program, flight experiments or demonstrations are planned for supersonic turbine-based missiles at speeds above Mach 3, and for hypersonic scramjet-based missiles in the Joint DARPA/ONR HyFLY program for speeds up to Mach 6, and in the Air Force Research Laboratory X-51 program for speeds of Mach 3 to 8. These programs are rapidly maturing technologies associated with high-speed missile airframes, guidance and control systems, supersonic expendable turbine engines, and hydrocarbon-fueled scramjet engines.

In addition to missile technologies currently under investigation, a significant technology base exists to support strike missiles operating at speeds up to Mach 4 using ramjet propulsion. Demonstrations of these technologies include the Mach 4 Advanced Strategic Air Launch Missile flight vehicle, which was tested in the early 1980s.

Terminal sensors for high-speed missiles can benefit from additional attention. Without a terminal sensor, the missile can be used to attack targets at a known location or must reply on a weapons data link to provide target coordinate updates or on deployment of submunitions to search and attack moving targets. Issues associated with the incorporation of a terminal sensor on a high-speed missile include these: surviving the aerothermal environment, processing data at high speeds, and achieving sufficient maneuverability to correct error in the engagement end game. The deployment of submunitions containing terminal sensors or the provision of target location updates through a weapons data link are potential techniques to overcome the need for a terminal sensor on the weapon, provided the weapon's autonomous guidance system is sufficiently accurate.

In the design of stealth weapons systems, much of the aircraft low-observable (LO) technology is applicable at subsonic and low-supersonic speeds. As the speed is increased in the supersonic regime, the temperature limits of radar-absorbing materials (RAMs), particularly magnetic RAM, will begin to reduce its effectiveness as indicated by the "Curie temperature" where the ferromagnetic properties are degraded significantly. Of course, speed can be traded for stealth, so the increase in RCS with increasing speed does not necessarily increase susceptibility. Another reason for increased signature with increasing speed is the fact that an efficient supersonic or hypersonic vehicle has less latitude in its shape. Shaping for stealth purposes may penalize the aerodynamic performance and vice versa.

Future strike systems will also be capable of operation with directed energy (DE) weapons, including those for self-defense. While the current study did not evaluate DE weapons, the integration of these weapons into aircraft will result in challenges in the areas of onboard power generation and thermal balance.

Near-Term Technology Needs

Several near-term technology opportunities exist regarding weapons systems. Over the next few years, both high-speed turbine and scramjet technologies will be flight-demonstrated. Continued development of high-speed missile technologies will provide a range of options for long-range weapons deployed either from standoff or penetrating platforms. Technology gaps currently exist in improved payload effectiveness, robust techniques for the deployment of submunitions at supersonic speeds, and high-temperature RAM.

Far-Term Technology Opportunities

In the far term, the committee envisions that more compact weapons systems will be required that will be capable of generating a flexible range of effects and that operate with greater impunity at higher speeds and from longer ranges. With the far term defined as 2025+, the committee can only begin to estimate the technical characteristics of these futuristic systems. Sample technologies that should be explored in the base science and technology programs include missile subsystem miniaturization techniques, distributed propulsion systems, novel materials and sensor technologies, and advanced fuels and energy storage systems.

Far-term systems may incorporate DE weapons that will result in significant weapon-aircraft integration issues. The development of lightweight techniques for generating onboard power will be required for the operation of either laser or microwave weapons. Also, the development of advanced techniques to dissipate efficiently the waste heat produced by DE weapons will be required.

Countermeasures

Countermeasures may be active, passive, or self-defensive in nature. Active countermeasures include missiles that home in on enemy radars and the electronic jamming of enemy integrated air defense systems (IADSs). Passive countermeasures include the release of chaff and flares to confuse enemy radars and missile seekers. Self-defense countermeasures include kinetic or DE weapons for defeating enemy threats after they are in the air. Countermeasures have been developed and employed following operationally demonstrated *need* as opposed to *opportunity*. Therefore, discussions regarding countermeasures are based on what is needed, and approximate assessments (near term versus far term) on when they are needed.

The continued development and deployment of aircraft and missile systems with reduced signatures provide a strong motivation to adversaries to search for countermeasures. Some of the possibilities open to them are apparent and some are not. Obviously, moving to multiple and broader frequency bands and to multistatic systems in addition to monostatic are techniques that one would expect an adversary to examine. There are others. It is essential for the Air Force to continue the “red team” process of postulating and evaluating potential enemy countermeasures and the “blue” response. The process should be supported by intelligence collections that seek to verify or refute postulated future capabilities. One such threat projection is based upon intercepts of radio-frequency (RF) emissions at unique frequencies and with characteristics indicating potential new threat concepts applicable throughout the kill chain in one form or another. It is imperative that the Air Force remain vigilant and thorough in exploring how these emissions might become threats to existing or future survivability. Furthermore, it is important to explore countermeasures to potential new threats well ahead of the need for them in the force.

The lack of "active" emissions for IR-based threat systems makes discovery and tracking their development and deployment more difficult. There is more than one reason why IR sensors might be used in the ground elements of an IADS. The Air Force should continue to be concerned about the improvement of aircraft-based sensors that have been employed by the United States and by foreign airborne interceptors for decades. The current understanding of the IR threat does justify the development of countermeasures beyond the extensive effort in DOD and the Department of Homeland Security to develop missile warning and IR countermeasures against Man-Portable Air Defense Systems (MANPADSs).

This discussion of sensor advancements includes signal processing and advanced computational technology, enabling fusion of information from multiple sensors. Indeed future threat postulations and projections should consider multispectral sensor suites that combine RF and EO/IR sensors of various wavelengths.

Near-Term Technology Needs

As the committee reviewed the potential evolving threats and the countermeasures available to the next-generation strike aircraft, several countermeasure technology needs surfaced. One of the priority needs is to identify and demonstrate technologies that enable countermeasures to threat sensors that have expanded bandwidth. Another one is to significantly improve the ability of penetration aircraft to react quickly to threats that are not located precisely when the mission planning is being done. A safe assumption is that the location of some threats may not be known until the aircraft is over hostile territory.

Far-Term Technology Opportunities

The reader should be aware of the fact that imaging IR seekers are effectively used in modern short-range air-to-air missiles (SRAAMs) by the United States and by several foreign countries. As medium- and long-range air-to-air missiles are degraded in performance by lower aircraft RCSs, it is plausible that some U.S. adversaries might begin to look at multimode seekers that use multiple guidance modes. There are several multimode wavelength combinations that are possible. Trade-off studies should be done to postulate system concepts, simulation and modeling should be used to evaluate the potential threat to future Air Force systems, and countermeasures should be explored. If these threats begin to emerge, the Air Force should design and demonstrate countermeasures well ahead of their needs in the force.

Situation Awareness

A maxim of aerial warfare is that the side with the best situation awareness (SA), coupled with the best air vehicle, dominates the fight. This was true in the early 20th century and continues to be true today. In today's context, good SA is required to provide timely and precise knowledge of the enemy's defenses, targets, and intent. More precisely, SA is the temporal and spatial knowledge of what is in a particular environment, where it is located, and what the key characteristics associated with it are. This includes both friendly and threatening features of the environment.

SA requires the gathering and processing of onboard and offboard sensor data to distill relevant information pertinent to the environment and to filter out what is not relevant to the particular role assigned to the participant. Today and in the future, the precision with which these measurements are made in terms of position and time must be increased to support the timelines of modern engagements and the targeting requirements of weapons. Survival in complex threat environments will require that SA sensors and operations not significantly increase the observables of the penetrating aircraft through emissions, communications, or changes to the aircraft design. With the advent of greatly improved sensors, broad bandwidth connectivity, and improved display capabilities, there is a need for "intelligent data management" systems on aircraft that process large amounts of SA data in the background and present the results to the pilot instantaneously so that rapid decisions can be made to enhance survivability.

Some of the requirements associated with improving SA to meet the needs of the next-generation strike aircraft are the following:

- Multisensor data and information fusion;
- Expanded databases on all IADS elements;
- Cross-sensor cueing;
- Mobile networks that are trusted and/or secure, wideband, and self-forming;
- Apertures and processors compatible with the stealth and speed design; and
- Improved sensor aperture integration with advanced sensing modalities.

Near-Term Technology Needs

Commercial off-the-shelf technologies and government off-the-shelf technologies can provide some of the near-term technologies needed for the next-generation survivable aircraft. These include the following:

- Highly accurate low-probability-of-intercept (LPI) or passive sensing capability;
- Higher-resolution radar imagery;
- Electronic support measures (ESM) improvements in sensitivity, accuracy, and geolocation; and
- EO/IR sensors, apertures, and vehicle integration.

Network-enabled platforms must meet all the requirements of the common DOD architecture for information exchange. This network will define with whom and why communications links are formed. Current technology provides line-of-sight (LOS) and beyond-line-of-sight (BLOS) low-bandwidth links with few information assurance provisions. The messages are not content-labeled, so classification and distribution become difficult. The definition of the role of each participant is unclear and is not adaptable to changing situations. The use of networks is currently restricted to preplanned static networks, which has a significant impact on the entire SA process.

Far-Term Technology Opportunities

There are several key offboard issues for both near-term and far-term systems: for example, whether offboard systems will be available when required or tasked, whether an onboard airborne sensor platform will be over the battlefield when needed, whether there will be enough satellite coverage to provide SA over the battlefield, and whether the information will be timely, accurate, and relevant to the battle.

With continued R&D investment, onboard sensors will continue to improve and will be able to provide the essential SA capabilities required for IOC and to upgrade survivability as the threats evolve. These include the following:

- LPI radars with enhanced bandwidth and resolution features,
- Change-detection imaging,
- EO systems with enhanced sensing performance and modalities,
- Automatic Target Recognition/Automatic Target Correlation (ATR/ATC) and other identification modes, and
- ESM systems' improved geolocation, both single-ship and cooperative, LO antennas with enhanced performance features.

In the future, there will be a need for an improved distribution system including BLOS and LOS high-bandwidth links, versatile networks, and secure data handling based on message content. Most important, there will be the need to develop fusion algorithms capable of producing higher levels of information content.

In summary, tomorrow's platforms will be able to exploit enhanced SA in future scenarios—for example, enhanced onboard sensors with LPI and passive techniques. Greater use of offboard sensor systems will provide both the precision and required timeliness. The committee believes that future air vehicles, when coupled with excellent SA, will continue to be survivable and effective against evolving threats.

Systems Engineering Approach Required for Program Success

The success that the United States has enjoyed in fielding low-signature vehicles depended on the systems engineering approach developed and executed by U.S. industry. The understanding of the complexities of stealth integration (e.g., weapons, sensors, antennas, SA, and enabling apertures) into the fundamental airframe/propulsion design paradigm is most challenging and represents a significant accomplishment of U.S. industry-government collaboration. The systems design approaches developed, though often somewhat unique to each company, are critical to the success of any future systems design and represent a national asset that must be protected.

The challenge of increased speed with stealth will not change the basic approach to systems design, but will require even stricter adherence to the discipline of systems engineering. Clear technical and operational requirements must be established to permit the myriad of trade-offs required in any successful systems engineering approach. The committee believes that there is sufficient time available to field a next-generation long-range strike platform with a 2018 IOC if the decision is made soon.

ELEMENTS OF SIGNATURE

Radio Frequency

Current and future threat radar systems operate over a broad frequency range. Early warning systems are typically at the lower end of the bandwidth, with tracking, fire-control, guidance, and fuzing functions operating in progressively higher frequency bands. The lower-frequency systems typically achieve the longest detection ranges and the higher frequencies typically achieve the best resolutions and accuracies. In all bandwidths, the performance levels of the threat systems vary significantly, with the later versions and newer generations showing significant performance improvement over the earlier systems. Foreign IADSs have significant integrated capabilities and will be more integrated in the future. The number of fielded advanced IADSs is proliferating around the world.

The committee focused on the speed and stealth of the aircraft, though similar considerations of Mach number and signature also apply to the weapons. As discussed in the next chapter, higher speed allows a design with less stringent signature requirements for equivalent susceptibility. This is clear from first-order analyses; however, higher-speed designs require more detailed and careful trade-off studies considering all frequencies projected for future IADSs as well as the influence of air vehicle configuration changes on the angular dependence of the signature. Omnidirectional or “fuzz-ball” models are not sufficient. It is imperative that the more detailed signature models be used in all levels of analysis, and higher-fidelity engagement models and simulations are required as well, to ensure valid conclusions and attrition rate assessments in campaign analyses.

The far-term application of advanced techniques for aircraft signature reduction may substantially change the design trade-off between speed and stealth. With these alternative means to absorb and disperse radar RF energy, the signature of the aircraft potentially becomes less sensitive to material and shape and more compatible with high-altitude supersonic to hypersonic flight.

Infrared

The roles, capabilities, and limitations of IR sensors in airborne interception are well understood in the United States and in other countries. Short-range (within visual range) air-to-air missiles (SRAAMs) since the first Sidewinder have used IR seekers. Technology for IR seekers has advanced through about five generations to the imaging IR seekers in use today. Aircraft fighters and interceptors that carry SRAAMs have relied primarily on radars to detect and track the target. The missiles are launched after first acquiring the target with the missile seeker. Some of those aircraft have been fitted with infrared surveillance and tracking sets to aid in the acquisition, identification, and tracking of opposing aircraft.

The roles, capabilities, and limitations of IR sensors in ground-based air defense systems are not so well characterized or understood. While there are some systems equipped with IR sensors, their ability to detect lower-signature vehicles could be degraded by fog, clouds, precipitation, and background conditions, and there may be other reasons for their use.

Examples of IR long-range surveillance and tracking systems have been deployed in some countries. An IR-assisted IADS is still considered well within the technological capabilities of several adversaries and remains a potential future asymmetric threat to the survivability of U.S. aircraft when the atmospheric conditions permit its use.

IR sensors in all three waveband windows of the atmosphere (long wave [LWIR], medium wave [MWIR], and short wave [SWIR]) have made significant advances and are incorporated into a wide range of threat missile systems to provide detection, tracking, and guidance at short range or at very high altitude above the weather and most cloud formations. The more sophisticated and robust applications are multimode, multispectral, and/or have improved counter countermeasures (CCM) capabilities, which improve their lethality.

IR signature continues to be an area that should be considered for increased resources to further the technology development. Additionally, a methodology is needed to evaluate sensor designs and capabilities and how they might be exploited by the enemy. This evaluation should model and evaluate IR sensors and systems in the context of engagements and should consider tapping the expertise of the missile defense community in this area.

Visual Signature

Visual signature sources can provide foreign elements an additional source to enable alert, detection, and cueing. Susceptibility to visual signatures can be significantly impacted by factors such as weather, daytime or nighttime, and viewing aspect. However, in operationally common situations, in favorable environmental conditions, detection ranges can be useful. The visual signature provides both airborne and ground-based threat system operators with valuable knowledge that can then be applied in the effective operation of their systems. This is particularly true in engagement scenarios with airborne interceptors at altitudes above inhibiting weather conditions. The committee believes that the Air Force should hedge against the possibility that future asymmetric threat responses will involve exploitation of visual signatures, by thorough assessment of the potential utility and development of CCM technology and concepts.

Visual signature control continues to be an area that should be considered for future development.

Other Signature Elements: Electronic Emissions and Acoustic Signatures

Electronic emissions will continue to become a more stressing element of signature as the "network-enabled" requirements for more robust data communications become more demanding. Past solutions involving shutting down communications and going silent in the high-threat region will not meet the network-centric GIG connectivity demands of the future operational environment. More in-depth assessment of this type of detectable signature source and the technologies and electronic techniques to control these emissions is needed.

For the operational altitudes currently envisioned for the next-generation strike systems, subsonic acoustic signatures are not currently considered a significant contributor to aircraft susceptibility. However, there is the potential that threat acoustic detection systems could be much more effective against supersonic aircraft that are generating a supersonic boom. Further assessment of this potential threat is merited at all flight speeds.

TECHNOLOGY FEASIBILITY ANALYSIS

Signature Technology Matrix Readiness Versus Speed

The committee assessed the readiness and potential of the technologies that impact signature across a speed regime from subsonic to speeds approaching hypersonic. The technology readiness was assessed in five groupings: airframes, propulsion systems, sensors and apertures, countermeasures and electronic warfare, and weapons.

This assessment was conducted in a three-step process. In the first step, the committee generated a list of the significant technologies that impact the aircraft and weapon system and conducted a baseline assessment of their readiness to support a 2018 IOC (TRL 6 by 2009 SDD milestone) for the next-generation long-range strike system.

In the second step, the committee's baseline assessment was distributed to seven organizations to collect their readiness assessment. The seven organizations included three airframe companies (Boeing, Lockheed Martin, and Northrop Grumman); two engine companies (General Electric and Pratt & Whitney); and two government organizations.

The final step in the assessment process consisted of compiling the data and generating a committee consensus view of the technology readiness. For the majority of the assessed technologies, agreement existed in the technology readiness among the assessing groups. However, divergence in the assessment of the technology readiness was observed in several areas.

There was very good agreement between the committee's baseline assessment and the subsequent assessment of experts in the seven organizations listed above on the high-level readiness assessment of many of the sensors and apertures-related signature technology elements. There was reasonable agreement on most of the remaining technology elements. Technology readiness was judged to be significantly impacted by the speed range. The significant conclusion is that, generally, solutions are considered to exist, but there is uncertainty in the assessment of risk associated with the implementation in the required time frame.

The assessment of the onboard electronic countermeasures and electronic warfare-related signature technologies found very good consensus on all of the technology elements.

There was very good consensus on most of the high-level readiness assessments of the weapons-related signature technologies. There was reasonable consensus on the remaining few technology elements. There were no areas of large variability in the assessments.

SUMMARY OF SIGNATURE TECHNOLOGY READINESS

From a high-level perspective, several general conclusions can be drawn from the assessment, as follows:

- As vehicle Mach number approaches the hypersonic region and temperatures rise, fewer signature control technologies are sufficiently mature to support an air vehicle development program that would meet a 2018 IOC. In the lower supersonic region, there are no major outstanding airframe issues associated with achieving the RCS signature levels required, and the airframe technology is mature enough for a 2018 IOC.
- At high Mach numbers where continuous engine augmenter operation will be required, the higher-temperature materials (both in the propulsion system and some parts of the airframe) needed to control signature require additional developmental investments to support a 2018 IOC.
- The readiness of signature-control technologies required for weapons at higher speeds is generally better than is the readiness of the corresponding technologies for aircraft, due primarily to weapons' single-use, short-life operations.
- The readiness assessment concluded that the following technologies incurred the highest risk in the higher-speed ranges, in support of a 2018 IOC:
  - —High-temperature radar-absorbing structure,
  - —EO[7] apertures, and
  - —Communication system apertures.

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[7] EO includes ultraviolet, visible, and IR.

Achievable Signature Versus Speed

In addition to the technology assessment discussed above, the committee assessed the overall projected signature levels achievable in the future as a function of flight speed compared with the Air Force signature goals and levels achievable today.

The committee initially assessed the achievable signature levels as a function of speed, vehicle aspect, and frequency/wavelength using its own experience and knowledge base together with information provided in briefings to the committee. The committee's assessment focused on demonstration of TRL 6 by 2009 in time for a 2018 IOC. The committee believes that the subsonic RF signature goals could be achieved. The committee believes that the goals for IR signature should be restated in terms related to specific postulated sensors, and in the presence of countermeasures, after further engagement analyses have been carried out to assess the utility of IR sensors with and without countermeasures.

The committee made an assessment of expected signature growth as the Mach approaches the hypersonic region. With increasing speed, this expected signature growth is attributed to higher material temperatures coupled with the need for configuration changes, including those of inlets and nozzles.

ONGOING RESEARCH AND DEVELOPMENT PROGRAMS

Current R&D programs associated with high-speed vehicle development, initiated under the National Aerospace Initiative of the Director, Defense Research and Engineering, were reviewed. These efforts are aimed at maturing hypersonic technologies to support both high-speed missiles and aircraft. Propulsion and airframe technologies to support high-speed missiles operating in the Mach 3 to 7 speed regime will be flight-demonstrated within the next 1 to 4 years.

RESEARCH AND DEVELOPMENT NEEDS AND OPPORTUNITIES

In reviewing the Air Force's current capabilities as well as requirements for platforms that are survivable, responsive, and persistent, the committee identified areas of likely technology needs. These needs, discussed below, are described relative to a time horizon that is both near term (defined as

TRL = 6 in 2009 to support SDD with IOC in 2018) and far term (defined as technologies to support pre-planned product improvement [P3I] programs for the 2018 IOC platform or development of new platforms in 2025 and beyond).

Near-Term Technology Needs

Additional technology efforts are needed in the area of IR/EO and visible signatures as well as countermeasures to sensors operating in these wavelength regions. Fundamental investigations should be pursued into potential techniques for controlling signatures. Technical advances to allow greater utility of active RF sensors without increasing susceptibility should be explored.

Shortfalls exist in propulsion technology in the areas of variable-cycle engines for missions requiring efficient operation over a wide range of operating conditions. Within the VAATE program, funding shortfalls exist that jeopardize planned gains in high-temperature, creep-resistant disk materials; advanced turbine-cooling techniques; thermal management; and power-generation systems.

For sustained flight at supersonic speeds, temperature limits for signature control technologies should be extended. Additional research is needed on RF signature control technologies capable of sustained operation at elevated temperatures for high-temperature leading-edge materials, exhaust coatings, and engine seals.

Additional countermeasure technology efforts are appropriate.

High-speed weapons technologies can be developed in a time frame consistent with a 2018 IOC capability following successful completion of the ongoing flight experiments and demonstration programs. Technologies that should be considered to support the weapons system needs include submunition dispense techniques and the integration of terminal sensors.

Finally, research into robust and accurate techniques for capturing the cognitive limitations inherent in an adversary IADS should be pursued.

Mid- and Long-Term Technology Opportunities

The postulated requirement for an IOC in 2018 with the start of an SDD program in 2009 constrains technologies to ones that are relatively mature and nearly available for transition. A number of technologies have been identified that may significantly impact survivability in the future, but which are not, in the opinion of the committee, likely to be sufficiently mature to support the start of an SDD program in 2009. These technologies may represent opportunities for P3Is or for application in the development of future systems.

A number of promising propulsion technologies warrant investigation for application to future systems. Specifically, combined-cycle propulsion systems, high-temperature materials and structures, and advanced thermal management systems have the potential to significantly expand the operating capabilities of hypersonic platforms. The development of fuels with increased cooling capacity and/or higher energy density will lead to more capable aircraft and more flexible designs.

In the area of airframe technologies, the development of morphing airframe shapes is one potential path to the development of an aircraft system that can operate with high performance in multiple flight conditions. Technologies associated with lightweight actuators and flexible skins may enable entirely new classes of aircraft.

Active flow-control techniques for application to both aircraft and propulsion systems show promise for improving the robustness and performance of existing and advanced systems. These techniques may produce challenges for the LO systems designer, and appropriate design methods must be developed by the LO community.

If future aircraft systems carry advanced directed-energy systems, lightweight power-generation systems and advanced thermal balance techniques beyond the present state of the art will be required.

For weapons, needed areas of investigation include propulsion and airframe miniaturization technologies, novel seekers for enhanced target recognition, and advanced fuels, as well as issues arising from the specific type of warhead carried. These investigations will support future weapons that are smaller, more capable, and more autonomous in their operation.

4

Assessing the Operational Utility of Speed and Observability Trade-offs

Determining a “good balance” between the speed and observability of a future air vehicle logically requires assessing their contributions to the operational effectiveness[1] of the air vehicle. This is a complex analysis process that is confounded by the many other design and operational variables that interact with speed and observability and also affect the vehicle’s operational effectiveness. The complexity of this analysis process is described in Appendix C, along with a framework for a comprehensive, simulation-based analysis methodology that considers this level of complexity. Although the approach is logically sound,[2] its employment as described in Appendix C requires significantly more time and resources than were available to the committee. In the short time available to it, the committee used a historical and experienced-judgment approach for its analysis and focused on aircraft survivability as its utility metric rather than mission effectiveness.

In this chapter, the committee combines the insights that it drew from its analysis of recently published reports in the field, the information provided during the briefings that it received, and its own expertise to arrive at some conclusions regarding the utility of speed, stealth, and other key variables in air vehicle survivability in various operational situations.

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[1] Mission effectiveness and a number of other utility measures are defined in Appendix C, “A Framework for Comprehensive Analysis.”

[2] The methodology considers multiple missions, many interdependent design variables, many operational threats, and mission effectiveness and survivability metrics.

The committee used this approach to define a range of speed and stealth combinations that can provide equivalent survivability. It then overlaid the technical analysis of Chapter 3 on these results to draw conclusions about the feasibility of achieving these combinations in the 2018 initial operational capability (IOC) time frame, with a view to identifying the recommendations for research and development investment presented in the next chapter.

COMMITTEE ANALYSIS OF PREVIOUS STUDIES

A number of studies have been performed over the past few years by industry, federally funded research and development centers, and government agencies to examine various aspects of the speed and observability (and related variables) trade-offs for various existing and notional aircraft. The committee reviewed a number of studies that provided useful insights.[3] A general summary of these follows.

Each of these studies required a large number of inputs and presented many output tables and graphics relating some design variables to various output utility metrics. From these studies the committee has with confidence and clarity shown that, as a function of speed and stealth in terms of radar cross section (RCS), there exist regions of very high survivability. This was done for surface-to-air missiles (SAMs) and airborne interceptors (AIs) separately and in combination for a specific foreign, moderate capability.

The committee assessed aircraft survivability as a function of speed and signature for a current widespread SAM threat, the current stressing SAM threat, and a projected advanced responsive threat.

As the examples above suggest, the studies examined by the committee varied significantly in design variables, parameters, mission vignettes, specific threats, assumptions, and utility metrics considered. In order to assess the commonality of the studies, each was abstracted in terms of its inputs (design variables, design parameters, missions and threats considered, and so on) and outputs (utility metrics, utility results), as well as study observations regarding speed and observability. Examples of the inputs for the seven studies are presented in Table 4-1. Analysis by experienced committee members suggested a number of qualitative and quantitative observations and conclusions, presented in the next section.

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[3] A listing of these studies is given in the classified report.

TABLE 4-1 Summary of Inputs of Relevant Aircraft Studies

Inputs	Study 1	Study 2	Study 3	Study 4	Study 5	Study 6	Study 7
Design variables	• Speed • Vulnerability • Maneuver	• Speed • Stealth • Countermeasures (CM) • Altitude • Situation awareness (SA)	• Speed • Stealth • CM • SA	• Speed • Stealth • CM • Weapons • Payload	• Speed (subsonic to hypersonic) • Stealth	• Speed • Stealth	• Speed • Stealth
Design parameters	• Stealth • Altitude	• Persistency • Platform size and weight • Procurement costs	• Altitude	• Altitude • Weight • Range • Cost • Manned/ unmanned • Weapons • Endurance	• CM • Altitude	• Size/weight due to speed • Affordability • Shape impacts on signature • Technology readiness levels • Range	• Altitude
Systems evaluated	• Notional missile, with speed (subsonic to hypersonic)	• Parametric long-range strike system • Speed (subsonic to hypersonic) • Full attack suite	Unknown	• Notional vehicles (3) • Speed (subsonic to hypersonic)	• F-22 • FA-18G • Cruise missiles	• Speed (subsonic approaching hypersonic) • Stealth (appropriate for systems)	• Parametric aircraft • F-22A • B-1B • B-2 • F-117

SOURCE: Committee-generated abstract of earlier studies.

COMMITTEE OBSERVATIONS AND CONCLUSIONS

Qualitative Observations and Conclusions

Speed and Stealth

The committee's review shows that speed and low signature are both primary factors in determining survivability. When these factors are analyzed independently, it is clear from the committee's review of recent reports that aircraft with hypersonic speed can survive against highly capable current threats because air defenses are not expected to have time to engage them successfully at their achievable observability; it is also clear that very stealthy vehicles can survive because air defenses cannot find them in time to track them and engage them.

In the region between these extremes, balanced speed and stealth solutions can also be robust against the threats posed by air defenses. Improvements in *stealth* reduce the threat's defended area and have a greater utility in defeating SAMs than do increases in speed. Increases in speed and stealth both reduce the exposure time in the threat's defended area; increases in speed have a greater utility in defeating airborne interceptors than do just improvements in stealth alone. However, the committee believes that the analyses available on the impact of speed and stealth on AI threats were quite limited. Furthermore, there was a lack of analysis on the implications of high stealth levels and speed for integrated air defense system (IADS) cueing capabilities.

As discussed in Chapter 3, the long-range strike system might consist of a standoff aircraft armed with fast hypersonic missiles. Missiles traveling at this speed would be capable of striking targets quickly and would likely have a high probability of survival against air defense threats, regardless of the signature level achieved.

Situation Awareness

The level of situation awareness (SA) can significantly impact the use of signature, speed, countermeasures, and tactics for increasing survivability. In addition to the use of sophisticated cyber and information operations techniques, the ability to decrease a weapon system's susceptibility in an adversary's airspace is a result of achieving the right balance of speed and signature reduction, both of which are synergistically enhanced by SA.

Therefore, accurate, current knowledge of threat location and type is important. From mission planning through mission execution, gaining and maintaining SA will provide the weapon system operator an enormous advantage in understanding the battlespace and, therefore, in selecting the appropriate plan of attack and use of *tactics.* High-stealth vehicles will be less dependent on SA than will supersonic higher-signature designs, and therefore the former will be more robust on missions where SA is denied.

Countermeasures

Countermeasures (CM) can enhance the survivability of aircraft, and they offer a significant improvement in survivability in the face of future threat advances. While the utility of specific CM was not assessed in this study, the studies reviewed suggest that CM offers an increase in survivability equivalent to a significant reduction in RCS, and CM appears particularly valuable for aircraft with higher signatures. It also appears that a high level of SA enhances the performance of CM by optimizing their selection and timing. However, poor SA can reduce the effectiveness of CM to zero.

The traditional philosophy has been that CM is designed-in as a kind of "insurance" to maintain the aircraft's level of survivability against uncertainties or improvements in threat capabilities, and this design philosophy continues today. An attractive feature of CM is that they can be adapted or changed to respond to changing threats, such as redesigned IADS electronics, new radar waveforms, and so on. More analysis of the effectiveness of radio-frequency stealth and countermeasures against SAMs would be desirable. Similarly, more analysis is needed on potential electro-optical/infrared (EO/IR) and visual threats that might have to be countered, especially from AIs.

Some Additional Observations

In general, the studies examined by the committee did not consider the interactions among the aircraft design variables. For example, increasing the sustained speed of an air vehicle requires an increase in its size to maintain range and payload, and this in turn affects its signature, not to mention its affordability. It will be important for future comprehensive studies of the type described in Appendix C to take account of these interactions.

The committee is concerned with the level of USAF and industry investigation of the relative merits of speed, stealth, electronic CM, and

SA. There is both a lack of emphasis in past efforts as well as shortfalls in the analysis tools used. *Specifically, before choosing a design point on the speed/stealth performance curve, the USAF needs to conduct rigorous analysis and trade-off studies as a basis for that decision.* These studies need to go beyond susceptibility and survivability metrics and consider higher-level effectiveness measures[4] to assess the impacts of—and trade-offs among—all relevant design variables and their interactions.

However, the committee found that the analytical tools possessed by and used by the community for this task can be improved. Specifically, the tools' fidelity for assessing the effects of aspect and radar frequency upon the ability of an IADS to detect, track, and provide cueing for AI can be improved. Also, the effects of speed are difficult to analyze effectively because models lack fidelity in dealing with the human decision process, command and control, and reaction times. Finally, tools are needed that can deal with the potential EO/IR and visual threat impacts.

Low signature does not guarantee survivability. The survivability of extremely low signature aircraft is sensitive to the number of SAMs fired in an engagement as well as to the SAMs' location areas. The survivability of aircraft also drops steeply with loitering time in the defended area.

For an aircraft with IOC in 2018, system definition and design must be initiated around the 2009 time frame when critical technologies must have achieved TRL 6. Specific near-term changes in emphasis that can be made are discussed at the end of Chapter 3.

Speed and Stealth Requirements for Survivability

The committee has determined with confidence the speed-stealth combinations (at the primary frequency of interest) that would be expected to yield an equivalent high level of survivability against threats of primary concern in the 2018 time frame. The findings represent a composite view of the several studies presented to the committee, combined with a consensus summary of the committee's expert judgment. The results provide the means for the Air Force to carry out trade-off studies to establish a family of baseline configurations for systems that could achieve IOC in 2018. Additional analyses extending the studies presented to the committee will enable the refinement of those baseline configurations.

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[4] These measures are defined in Appendix C.

The committee assessed the variation in results from the wide range of relevant studies that have been carried out and found that the uncertainty band is reasonable. The committee observes that there is no sharp breakpoint (or "knee" in the curve) in the speed-versus-signature relationship, and a trade-off exists over the range of conditions investigated. This data compilation shows a continuous relationship of speed versus stealth in achieving constant survivability.

Speed and Stealth Requirements Versus Feasibility

The achievable levels of stealth discussed in Chapter 3 were compared with the requirements discussed here that were derived from the reports presented. The results show a significant degree of agreement in achievable signature versus speed, with a reasonable spread over most of the speed range from subsonic to approaching hypersonic. Further analyses and configuration refinement will reduce the variation in technology assessment.

The assessment discussed above mainly dealt with fire-control radars. A significant aspect of survivability concerns the detection capability of search radars. While the committee determined the achievable capability of very-high-frequency systems, additional work is needed to determine the requirements.

The committee assessment of achievable signatures leads to the conclusion that, for constant survivability, technologies are available to support multiple solutions at differing speed and signature combinations. In particular, solutions for these combinations exist at both subsonic and supersonic conditions. With multiple solutions potentially available, selection of the "best" option will involve other considerations including costs, schedule risks, robustness to potential countermeasures, and so on.

While one desired outcome of this study was the definition of a "sweet spot" in the range of feasible solutions, the committee did not find this to exist, possibly owing to the spread in requirements derived from existing studies and to variations in available estimates of achievable signature levels. Shortfalls in the analyses and analytic tools identified earlier will need to be resolved in order to further refine the speed-versus-signature assessment. The finding regarding these shortfalls, along with the committee's other overarching findings and recommendations, are presented in the next chapter.

5

Findings and Recommendations

Finding 1: The Air Force Global Strike (GS) Concept of Operations (CONOPS) in high-threat environments determines survivability requirements for the long-range strike system and other systems because it simultaneously stresses range, signature reduction, persistence, timeliness, and payload characteristics.

The Committee on Future Air Force Needs for Survivability concludes firmly that future Air Force requirements and CONOPS will dictate aircraft that are survivable and responsive for timely strike at long range, as well as capable of loiter and persistence in the threat environment. The GS CONOPS stresses long range, speed, and payload, while the Global Persistent Attack (GPA) and the persistent Intelligence, Surveillance, and Reconnaissance (ISR) CONOPS stress long range, loiter, and persistence. Separate platforms for GS, GPA, or persistent ISR may be required. However, the committee concludes that emerging technologies might enable multimission capabilities. These technologies promise both system flexibility and affordability. Following are facts to be considered when evaluating these technologies:

- Range, persistence, and “24/7” (day and night stealth) operations against improved and proliferated threats increase the future survivability challenge.

- Increasing multimission capabilities tend to increase aircraft size and cost.
- Future threat uncertainties call for robust solutions that incorporate speed, stealth, and other important survivability techniques.
- The committee finds that multiple combinations of speed and stealth capabilities provide equivalent levels of survivability against surface-to-air missile (SAM), airborne interceptor (AI), and integrated air defense system threats. These combinations range from very significant stealth at subsonic speeds to moderate stealth at speeds approaching the hypersonic region.

Recommendation 1: The U.S. Air Force should develop and exploit technologies to enable efficient airframe and propulsion operation at both subsonic and supersonic speeds, and at medium and high altitudes, with appropriate levels of signature reduction to enhance survivability against plausible future threats.

Finding 2: The USAF has not completely investigated the combinations of speed, stealth, situation awareness, countermeasures,[1] and tactics to enable a solid judgment as to what level of speed is required for acceptable survivability in the future.

Specifically, neither the Air Force nor industry has invested sufficiently in analysis of the impact of combinations of speed and stealth when employed against postulated future AI and SAM threats. Further in-depth analysis of the potential performance of electro-optical/infrared (EO/IR) and visual sensors based on postulated sensors as well as signatures is needed.

Recommendation 2: Before choosing a design point on the speed-stealth performance curve, the Air Force needs to conduct rigorous analyses and trade-off studies as a basis for that decision. The USAF should carry out the following:

- Perform mission-level analyses (using multiple major combat operation threat baselines and multiple CONOPS) including EO/IR and visual threats, as well as the impact of airborne interceptors;

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[1] The committee considers self-defense technologies to be a subset of countermeasures in this report.

- Conduct trade-off studies constrained by the needed or expected technology capabilities;
- Develop enhanced mission-level analytical tools capable of investigating the subtle but critical aspects of detection, tracking, fusion, and cueing of SAM and AI threats;
- Develop models more accurately representing the human cognitive processes involved in the kill chain command-and-control and decision processes;
- Assess the impact of speed and stealth on the mission-critical sensor suite; and
- Strengthen system design and engineering capabilities in the Air Force and in industry.

Finding 3: Broad selections of speed and stealth combinations that meet the GS CONOPS capability requirements are technically feasible.

The committee finds that the Air Force technology roadmap for radio-frequency (RF) signature reduction is generally adequate (with some exceptions) to enable, with low to moderate risk, platforms with various combinations of speed and stealth with initial operational capability by 2018. Subsonic, supersonic dash, and supersonic cruise, all with appropriate stealth treatments for consistently high levels of survivability, are feasible with increased funding in a few areas. The committee found reasonable consensus on stealth capability achievable at speeds ranging from subsonic to hypersonic.

Based on numerous briefings from government and industry sources, the committee concludes that RF signature-reduction technology development for supersonic designs needs additional emphasis, including technology for designs incorporating a supersonic dash requirement if value or need is determined.

The committee concludes that investment in RF stealth in subsonic regions is currently strong and at the appropriate levels, but that advanced propulsion development is the single technology that can provide the most impact to the success of future aircraft for GS CONOPS. For example, advanced variable-cycle engines could provide the air vehicle with both high speed *and* efficient loiter capabilities, thus adding greatly to its mission flexibility.

Recommendation 3: The USAF should balance its research efforts between speed and stealth to bring advances in various speed regimes:

- Improve the balance across the speed range by preserving current subsonic programs while increasing funding for supersonic aircraft technology;
  - —Analyze the extent to which all-aspect, RF stealth performance is required for supersonic aircraft and the ability of technology to provide that performance;
  - —Provide additional investment in technologies that enable supersonic operations to support fielding in 2018 if required. One such technology is high-temperature radar-absorbing structure materials;
- Fully fund the Versatile Affordable Advanced Technology Engines program to original program levels for both subsonic and supersonic applications, including increased hot-section capability, improved materials, and thermal-management system technologies;
- Establish a variable-cycle engine demonstration program to achieve technology readiness level 6 by 2009 in a supersonic cruise aircraft; and
- Investigate the feasibility of adaptable airframe/skin technology, including morphing technology, to support multimission capabilities.

Finding 4: The design balance of speed and stealth will depend on the quality of available friendly and adversary situation awareness (SA).

Several presentations to the committee emphasized qualitatively the very significant potential of SA to improve vehicle survivability. The question, to what extent does SA impact overall survivability? needs additional analysis. There is no definitive conclusion on the relative effects of speed, stealth, and size on the benefits of situation awareness. With the available test results and current modeling and simulation tools, the incremental impact of SA on overall survivability is not quantifiable. The committee also notes that the relative contribution of onboard and offboard sensors to SA remains unresolved.

Recommendation 4: The USAF should include SA as a high-priority requirement for all platforms, and include in the design, from the beginning, the essential sensors, apertures, and data links. In addition, it should do the following:

- Improve modeling, simulation, and analysis tools to enable the development of insight into the trade-offs among speed, signature reduction, and SA in future CONOPS scenarios; and
- Assess the best mix of onboard and offboard sources for derived SA based on trade-offs of risk and complexity.

Finding 5: Countermeasures will continue to have the capability to enhance the survivability of aircraft and offer a significant hedge against future threat advances.

There are other techniques, technologies, and subsystems that can complement signature reduction and offer additional survivability improvements in their own right, including: electronic attack, electronic countermeasures, information warfare, EO/IR countermeasures, RF countermeasures, and self-defense weapons (air-to-air missiles and directed energy). The committee believes that there is insufficient effort on high-speed penetration aids.

Recommendation 5: The USAF should continue to implement countermeasure improvements, and:

- If the Air Force concludes after further trade-off studies and evaluation that *sustained* supersonic cruise is essential to GS CONOPS, it should implement a high-speed penetration aid effort compatible with contemporary stealth signature levels.
- The Air Force should evaluate the relative effectiveness of self-defense weapons and define requirements for any new or upgraded capability for next-generation aircraft.
- This committee urges that, to the maximum extent possible, the basic weapon system be designed with the capability to complete its assigned mission without relying upon countermeasures. In other words, although countermeasure systems can significantly enhance the survivability of a weapon, they should be hedges against future threat evolution and improvement and not a requirement for the baseline. The same holds for SA and tactics.

Finding 6: Hypersonic missiles with ranges comparable to those of current missiles could increase targeting timeliness and flexibility and thus increase operational utility in the 2018 time frame. It is not clear, however, whether a hypersonic cruise aircraft (other than a missile) designed for long-range flight and recovery offers unique capability and operational utility. Furthermore, it is unlikely that such an air-breathing hypersonic platform, other than a missile, will be available in the near term.

The committee believes that hypersonic missiles available in 2018 could be based on either chemical rocket or air-breathing propulsion. An attempt to field a hypersonic cruise aircraft by 2018 would be very high risk.

Recommendation 6: The USAF should increase the investment in hypersonic missile propulsion, materials technologies, and sensor and seeker apertures to be carried on both current and future platforms for long-range strike and begin development as soon as possible, if warranted. It should also conduct a study to determine the technical feasibility, operational utility, and affordability of a hypersonic cruise aircraft with appropriate sensors and weapons. If warranted by the results of the study and the readiness level of the technology, the USAF should begin development of a hypersonic aircraft.

Appendixes

Appendix A

Biographical Sketches of Committee Members

Leslie Kenne, *Chair*, currently provides consultancy services as LK Associates. She retired from the U.S. Air Force in 2003 as Deputy Chief of Staff for Warfighting Integration, Headquarters U.S. Air Force, Washington, D.C. She was responsible to the Secretary of the Air Force and the Chief of Staff for forming and executing policy and strategy to integrate command, control, communications, computers, intelligence, surveillance, and reconnaissance capabilities to enable more effective employment of air and space power in support of national objectives. General Kenne provided guidance and direction to four field operating agencies: the Air Force Command and Control & Intelligence, Surveillance and Reconnaissance Center; the Air Force Communications Agency; the Air Force Frequency Management Agency; and the Air Force Agency for Modeling and Simulation. General Kenne entered the Air Force in 1971 as a distinguished graduate of Auburn University's ROTC program. She served as a flight-line maintenance officer in operations, and attended the U.S. Air Force Test Pilot School in 1974. After school, she served as a test-and-evaluation project manager and in test-and-evaluation supervisory positions. General Kenne served in two other Pentagon staff positions, first as a division chief, and during a second tour as a deputy director in the Office of the Assistant Secretary of the Air Force for Acquisition. She has directed three major programs: the Low Altitude Navigation and Targeting Infrared System for Night, the F-16, and the Joint Strike Fighter. She served as vice commander both of the Aeronautical Systems Center at Wright-Patterson Air Force

Base, Ohio, and of the Sacramento Air Logistics Center at McClellan Air Force Base, California, and commanded the Electronic Systems Center, Hanscom Air Force Base, Massachusetts. In addition to her management of major Air Force aircraft acquisition programs, General Kenne led a division of the Special Projects Office of the Air Force that managed low-observable research and applications.

Seth Bonder *(NAE)* was the founder and CEO of Vector Research, Incorporated (VRI) for 31 years, a company recognized for its quality and innovations in applying operational research and management science to public- and private-sector enterprises. Throughout his distinguished career, Dr. Bonder has been a leader in applying operations research to national defense planning and policy issues, and subsequently to health care delivery reengineering and disease-management practices. Dr. Bonder made major contributions to the operations research profession. He served as 27th president of the Operations Research Society of America and the Military Operations Research Society and as vice president of the International Federation of Operational Research Societies. He has received numerous awards, including the Patriotic Service Award from the Secretary of the Army, the George E. Kimball Medal, and the Institute for Operations Research and Management Sciences President's Award. He is a member of the National Academy of Engineering.

John J. ("JJ") Campbell is the director of proprietary programs, Military Systems Organization at General Electric Aviation. He directs the conduct of advanced research projects dealing with the control of signature for current and future weapons systems. His work includes highly classified activities in materials, manufacturing processes, conceptual designs of propulsion solutions, and new advanced cycle approaches. He manages the company funding and roadmaps targeted to this technology for subsonic and supersonic applications. He has more than 20 years of experience in the development, subsequent establishment, and execution of advanced technology programs within government and industry channels. He has an extensive background in conventional and nuclear survivability studies.

Bennett M. Croswell is the vice president of Military Development Programs for Pratt & Whitney with responsibility for the development of advanced gas turbine engine products and technologies. In this position, Mr. Bennett is responsible for new and derivative products, unmanned air vehicle and advanced programs as well as small turboshaft and turbofan propulsion systems. He began his career with Pratt & Whitney in 1979 as an analytical engineer specializing in engine performance and modeling. He held positions of increasing responsibility, including the engineering manager position for the Navy A/F–X (1991-1993). In 1995, he was appointed JSF119 model manager responsible for developing the propulsion system to power the Lockheed Martin Joint Strike Fighter (JSF) Concept Demonstrator Aircraft. He left the JSF program in 1997 when he was selected for the position of assistant to the president, Large Military Engines. Mr. Bennett returned to the JSF program in 1999 and was appointed JSF119 Engineering and Manufacturing Development (EMD) program director in December 2000. As EMD director, he was responsible for all aspects of the JSF119 EMD program including definition of the engine configuration, planning the program, and managing the EMD proposal. In November 2001, Mr. Bennett was named director of the F119/F/A-22 program and became vice president of that program in 2003. He earned a B.S. degree in mechanical engineering from the University of Tennessee in 1979 and an M.B.A. in aviation from Embry Riddle Aeronautical University in 1989. He is also a graduate of the Defense Systems Management College, Fort Belvoir, Virginia (1993). Mr. Bennett has authored several papers published by technical societies and has lectured at the University of Tennessee Short Course on Propulsion and the Purdue University Short Course on Winged Flight Vehicles. He is also a member of the University of Tennessee Aerospace Advisory Board and the Air Force Association. In 2001, he was part of the team awarded the Collier Trophy for the development of the Integrated Lift Fan Propulsion System for the JSF program.

Alec Gallimore is currently with the Plasmadynamics and Electric Propulsion Laboratory at the University of Michigan. His primary research interests include electric propulsion, plasma diagnostics, space plasma simulation, electrode physics, and hypersonic aerodynamics and plasma interaction. He has extensive design and testing experience with a number of electric propulsion devices, including Hall thrusters, ion engines, arcjets, 100-kW-class steady magnetoplasmadynamic thrusters, and multimegawatt pulsed coaxial plasma accelerators. He has implemented a variety of probe, microwave, and optical/laser plasma diagnostics, and has graduated 15 Ph.D. students and 11 M.S students in the field of electric propulsion. Professor Gallimore has more than 170 archival journal articles and conference papers and 2 book chapters in electric propulsion. He is also director of the NASA-funded Michigan Space Grant Consortium and is an adviser to the U.S. Air Force Scientific Advisory Board.

Charles L. Guthrie is the director of Advanced Capabilities Development for Northrop Grumman's Western Region within the Integrated Systems Sector. He is responsible for all future-systems programs that include the topics of space systems, future strike systems, missile defense systems, and naval system integration. Some of his previous positions include director of unmanned systems rapid prototyping and advanced concepts at Boeing Phantom Works; director of the joint strike fighter air vehicle integrated product team for Boeing Military Aircraft and Missiles; and director of air vehicle advance design for the Phantom Works. He was a Boeing technical fellow, and was named manager of the year in 1993 and 1994 by North American Aircraft and the Southern California Area Council, respectively, and engineer of the year in 1987 and 1988 by North American Aircraft/Rockwell. In addition to earning a B.S. in aerospace engineering from the University of Kansas, Mr. Guthrie has completed many technical short courses in topics such as radar, aircraft design, and engine-airframe integration, and employee development courses. He works to support the California Polytechnic State University San Luis Obispo School of Engineering, the University of Kansas Aerospace Department, the Naval Postgraduate School, and California State University, Long Beach, by providing industry feedback, serving on advisory boards, and conducting guest lectures. He is a senior member of the American Institute of Aeronautics and Astronautics and has served on its Aircraft Design Technical Committee. He is also a senior member of the Association for Unmanned Vehicle Systems International and a member of the National Management Association.

Neil G. Kacena was named vice president, Advanced Development Programs at Lockheed Martin Aeronautics–Palmdale in March 2005. He is responsible for directing all Advanced Development Programs activities, leading more than 1,400 people in the pursuit of advanced concepts, product improvements, derivatives, technology development, mission area architecture, and prototyping. Mr. Kacena also acts as chair of the Lockheed Martin corporate-wide Low Observables Technology Focus Group, working across business areas and company lines to address critical technologies for applications to advanced projects. Previously, Mr. Kacena was the director of Advanced Development Program's Technology Development and Integration organization. Prior to that, he served as the director of Signature Management Systems and deputy director, Advanced Development Programs. In 1998, Mr. Kacena joined the Skunk Works after a 25-year career in the Air Force, where he achieved the rank of colonel. His Air Force experience included service as a fighter pilot in the F-4 Phantom and F-15 Eagle aircraft; Fighter Weapons School instructor; 9th Fighter Squadron commander; chief, U.S. Liaison Office in Doha, Qatar; and culminated as director of Special Programs in the office of the Assistant Secretary of the Air Force for Acquisition. Mr. Kacena received a Masters of Science degree in management from Troy State University. He attended Iowa State University where he graduated with a B.S. degree in industrial engineering. He is affiliated with various organizations, including the Air Force Association, Order of the Daedalians, the Iowa State University Alumni Association, National Defense Industrial Association, Veterans of Foreign Wars, and the Association of Old Crows.

Gregory S. Martin retired from the Air Force Materiel Command, Wright-Patterson Air Force Base, Ohio, as commander on September 1, 2005. He oversaw the research, development, and testing and evaluation, and provided the acquisitions management services and logistics support necessary to keep Air Force weapon systems ready for war. He earned a B.S. degree from the U.S. Air Force Academy in 1970 and a master's degree in business management from Central Michigan University in 1977. He entered the Air Force in June 1970 with a commission from the U.S. Air Force Academy. In addition to flying 161 combat missions in Southeast Asia, he commanded the 67th Tactical Fighter Squadron, the 479th Tactical Training Wing, and the 33rd and 1st Fighter Wings. He also served as vice director of the Joint Staff's Force Structure and Resources Directorate, director of Operational Requirements for the U.S. Air Force, and principal deputy to the Assistant Secretary of the Air Force for Acquisition. Before assuming his last position, General Martin served as the commander of U.S. Air Forces in Europe and Allied Air Forces Northern Europe. He is a command pilot with more than 4,600 flying hours in various aircraft, including the F-4, F-15, C-20, and C-21.

Jesse T. (Tom) McMahan has more than 35 years of experience in aerospace activities in government and industry, specializing in advanced technologies such as stealth and counterstealth. He spent 25 years in the Air Force and had oversight responsibility for all Air Force special access programs at the time of his retirement in 1993. He is an acknowledged, national-level expert in mission-level modeling and simulation of advanced aeronautical and defense systems. Mr. McMahan serves on numerous senior advisory boards for both government and industry. Along with the other co-president of Modern Technology Solutions, Inc. (MTSI), he is responsible for the overall technical, financial, and business management of the corporation. He has specialized expertise in low-observable and counter-low-observable technology and electronic countermeasures. MTSI is currently serving a number of government and industry clients in tasks including operational analyses of modern low-observable and counter-low-observable weapons systems, red teaming of proposals, analysis of technology investment plans, and advising on and preparing flight test plans and procedures. MTSI also supports the Missile Defense Agency in technology planning, system requirements analysis, and sensor integration and evaluation. He is a specialist in mission- and scenario-level computer modeling of complex integrated air defense systems and their response to reduced-observable vehicles and is significantly involved in analyzing the potential impact of coordinated stealth and information warfare and electronic warfare on modern air defense and command systems.

Robert A. Moore is a consultant at DST, Inc. His early career was in the aerodynamic design and development of tactical aircraft and high-speed cruise missiles at McDonnell Aircraft, beginning with the F-3H, F-4, F-101, and the Triton hypersonic missile. With the beginning of the manned space program, he worked on the reentry thermal protection problem for Mercury and then on electric propulsion for space travel. He then moved to the intercontinental ballistic missile program, where he assisted the Air Force and Navy in the management of reentry physics, penetration aids, and reentry vehicle technology programs. He then joined government in the Defense Advanced Research Projects Agency (DARPA) and managed advanced technology programs for future strategic offensive and defensive systems. He also originated and managed antisubmarine warfare programs. He became director of the Tactical Technology Office at DARPA and directed programs in air vehicle technology and observables, stealth aircraft, armored vehicle and antiarmor technology, undersea warfare technology, and sensor systems. Later he was deputy director of DARPA. During the Carter Administration, Mr. Moore was appointed to the executive position of Deputy Undersecretary of Defense for Tactical Warfare

Programs and was responsible for planning and oversight of acquisition of all defense systems for land, sea, and air warfare. He returned to industry at the Lockheed Martin Corporation Skunk Works. Next he established a consulting company in which he continues to be active, providing advice to major aerospace and defense companies in the areas of systems analysis and engineering, systems management, research and technology, program development, and proposal preparation. He participates in corporate strategic planning efforts and has served on numerous corporate boards of directors and advisory boards. He serves on government and military advisory panels and is a member of the Army Science Board. He was a charter member of the Senior Executive Service (SES), received the SES Presidential Rank Award and the Secretary of Defense Meritorious Civilian Service Medal. Mr. Moore received B.S. and M.S. degrees in mechanical engineering with concentration on studies in fluid mechanics, aerodynamics, thermodynamics, plasma physics, and heat transfer.

David M. Van Wie is an aerospace engineer in the field of aerospace vehicle design and development with emphasis on propulsion systems and advanced aerodynamics for supersonic and hypersonic flight vehicles. He has been with the Johns Hopkins University Applied Physics Laboratory since 1983 and is currently a member of the principal professional staff and director of the Precision Engagement Transformation Center. Dr. Van Wie also holds appointments as research professor in the Department of Mechanical Engineering at the Johns Hopkins University and lecturer in the Department of Aerospace Engineering at the University of Maryland. Dr. Van Wie attended the University of Maryland between 1976 and 1986 and received B.S., M.S., and Ph.D. degrees in aerospace engineering. He was also awarded an M.S. degree in electrical engineering from the Johns Hopkins University in 1998, with an emphasis on radar and communication systems. He was awarded the Gene Zara Award for outstanding contributions to the National Aerospace Plane (NASP) program in 1989 and 1992. Dr. Van Wie was a member of the USAF Scientific Advisory Board's (SAB's) Committee on Hypersonic Airbreathing Vehicles (1991), a member of the National Research Council's Committee on the Assessment of the Air Force Hypersonic Technology Program (1987), and member of the USAF SAB 2000 Summer Study on Air Force Hypersonics.

Alan R. Wiechman is vice president, Advance Global Strike Systems, within Advanced Systems for Integrated Defense Systems (IDS), of the Boeing

Company. He was also responsible for East operations, which include Mesa, Arizona; Huntsville, Alabama; St. Louis, Missouri; and Philadelphia, Pennsylvania. This responsibility includes future military fighters, bombers, directed energy efforts, hypersonics, survivability, and several proprietary efforts for Phantom Works. From 2000 to 2004, Mr. Wiechman was the division director and manager for proprietary programs within IDS. Prior to that, from 1992 to 2000, he was director of Signature/Design Applications, Advanced Military Aircraft, and Missiles Phantom Works. He joined McDonnell Douglas in 1981 as a section chief assigned to develop future low-observables technology. From 1977 to 1981 he worked in the Skunk Works at Lockheed Martin on a variety of advanced programs that included Sea Shadow, Proto Type Pre-F-117 and F-117A. Mr. Wiechman holds a bachelor's degree in electrical engineering from California Polytechnic State University San Luis Obispo in 1972.

Michael I. Yarymovych is president of Sarasota Space Associates, an aerospace consultancy, with clients in the government and the aerospace industry. Until the end of 2003, he served on the board of trustees of the ANSER Corporation in Arlington, Virginia, and was also its chief scientific adviser. In 1998 Dr. Yarymovych retired from the Boeing Company, where he most recently served as vice president for international technology of the Information, Space and Defense Systems Group. He was responsible for the assessment of technology capabilities of international and domestic enterprises for partnership and business development opportunities. Prior to this assignment and the merger of Boeing with the aerospace portion of Rockwell, he was vice president and associate director of Rockwell's Systems Development Center, responsible for the early phases of missile defense systems development, strategy and policy analysis, concept formulation, technology assessment and long-range planning for the center, located in Seal Beach, California. It was created in 1986 to focus the corporation's high-technology resources and capabilities on selected major growth opportunities that required the core competencies, skills, and resources of multiple divisions. In addition to his responsibilities in industry, Dr. Yarymovych has had an active role, which continues in the present, on many scientific advisory committees, including the Air Force Scientific Advisory Board, the Science Council of the NASA Institute for Advanced Concepts, the NASA Advisory Council Task Force on Space Goals, the Stanford University Industrial Affiliates Advisory Board, Defense Science Board studies, and the Space Panel of the National Research Council's Naval

Studies Board. From 1997 to 2003, Dr. Yarymovych was president of the International Academy of Astronautics, and from 1996 to 2000 he served as chairman of the NATO Research and Technology Organization, which is the successor to the Advisory Group for Aerospace Research and Development (AGARD) and the Defense Research Group. He was U.S. national delegate to AGARD from 1991 and its chairman from 1994. He is a fellow of the American Institute of Aeronautics and Astronautics and was its president from 1982 to 1983. Dr. Yarymovych has been widely recognized for his accomplishments in engineering, research, and management. He is a four-time recipient of the Air Force Exceptional Civilian Service Award, and he also received the Energy Research and Development Administration Distinguished Service Award in 1977.

Appendix B

Committee Meetings

MEETING 1, ROSSLYN, VA, NOVEMBER 29-30, 2005

Tuesday, November 29, 2005

8:00 a.m.–10:00 a.m.	Closed Session—Committee Members and National Research Council (NRC) Staff Only
10:00 a.m.–5:00 p.m.	Data-Gathering Session Not Open to the Public

Wednesday, November 30, 2005

8:00 a.m.–1:00 p.m.	Closed Session—Committee Members and NRC Staff Only
1:00 p.m.–5:00 p.m.	Data-Gathering Session Not Open to the Public

MEETING 2, ROSSLYN, VA, DECEMBER 8-9, 2005

Thursday, December 8, 2005

8:00 a.m.–9:00 a.m.	Closed Session—Committee Members and NRC Staff Only
9:00 a.m.–3:30 p.m.	Data-Gathering Session Not Open to the Public
3:30 p.m.–5:15 p.m.	Closed Session—Committee Members and NRC Staff Only

Friday, December 9, 2005

8:00 a.m.–3:00 p.m.	Closed Session—Committee Members and NRC Staff Only

MEETING 3, ROSSLYN, VA, JANUARY 18-20, 2006

Wednesday, January 18, 2006

8:00 a.m.–9:45 a.m.	Closed Session—Committee Members and NRC Staff Only
9:45 a.m.–1:30 p.m.	Data-Gathering Session Not Open to the Public
1:30 p.m.–5:15 p.m.	Closed Session—Committee Members and NRC Staff Only

Thursday, January 19, 2006

8:00 a.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

Friday, January 20, 2006

8:00 a.m.–10:15 a.m.	Data-Gathering Session Not Open to the Public
10:15 a.m.–3:00 p.m.	Closed Session—Committee Members and NRC Staff Only

MEETING 4, ROSSLYN, VA, FEBRUARY 13-16, 2006

Monday, February 13, 2006

1:00 p.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

Tuesday, February 14, 2006

8:00 a.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

Wednesday, February 15, 2006

8:00 a.m.–10:00 a.m.	Open Session Briefing
10:00 a.m.–3:00 p.m.	Data-Gathering Session Not Open to the Public

Thursday, February 16, 2006

8:00 a.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

MEETING 5, ROSSLYN, VA, MARCH 8-10, 2006

Wednesday, March 8, 2006

8:00 a.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

Thursday, March 9, 2006

8:00 a.m.–1:00 p.m.	Closed Session—Committee Members and NRC Staff Only
1:00 p.m.–2:00 p.m.	Data-Gathering Session Not Open to the Public
2:00 p.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

Friday, March 10, 2006

8:00 a.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

MEETING 6, ROSSLYN, VA, APRIL 5-6, 2006

Wednesday, April 5, 2006

8:00 a.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

Thursday, April 6, 2006

8:00 a.m.–5:00 p.m.	Closed Session—Committee Members and NRC Staff Only

Appendix C

A Framework for Comprehensive Analysis

In addition to asking for an initial analysis to estimate speed and observability trade-offs for the next-generation long-range strike system (LRSS), Task 2 of the statement of task requested that the committee outline a framework for a more comprehensive analysis that might subsequently be performed by the U.S. Air Force. This appendix outlines one such framework, not only to meet the statement of task, but also to serve as a guidepost for the analysis performed by the committee (described in Chapter 4). The appendix begins with a description of the complexity of the analysis problem: that is, the identification of a good balance between speed and observability for a future air vehicle. Then the committee presents a methodology (via a sequence of analytic tasks) for a comprehensive utility analysis that addresses the full complexity of speed and observability trade-offs.

COMPLEXITY OF THE ANALYSIS PROBLEM

Speed and observability both affect the operational utility of air vehicles, but any analysis of their trade-offs is confounded by many other *design and operational variables* that interact with them and also affect the operational utility of the air vehicle. Some of these design variables are listed below and defined in the Glossary in Appendix D:[1]

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[1] The reader is referred to Robert E. Ball, *The Fundamentals of Aircraft Combat Survivability Analysis and Design*, Second Edition, American Institute of Aeronautics and

- Speed,
- Signature and/or observability,
- Countermeasures,
- Situation awareness,
- Range,
- Persistence,
- Altitude,
- Maneuverability,
- Payload,
- Weapon lethality, and
- Tactics and rules of engagement.

The utility of an air vehicle depends on the *operational missions* that it may be called on to perform in the future. From today's planning perspective, these are uncertain dimensions. The three focus missions for this study are (1) Global Strike, (2) Global Persistent Attack, and (3) Space and Command, Control, Communications, and Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR), as discussed in Chapter 2. For analysis, air vehicle missions can be evaluated in 1-on-1, 1-on-*N*, *M*-on-*N* (where *M* and *N* represent the number of attacking and defending air vehicle systems in a particular engagement, respectively), or campaign contexts.

Many *threat dimensions* affect the operational utility of air vehicles while they are performing a mission. These include the following:

- *Threat type* (airborne interceptor/air-to-air missile, anti-aircraft artillery, surface-to-air missile, directed energy, and so on);
- *Threat ordnance* (missiles, kinetic energy rounds, high explosive rounds, and so on);
- *Threat sensors* (radio frequency, infrared, acoustic, visual);
- *Command and control* (single site, networked sites, integrated air defense systems); and
- *Degree of cueing available.*

The utility of an air vehicle also depends on the *target type* specified for the mission (hard and deeply buried target, weapon of mass destruction

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Astronautics Education Series, 2003, for a more complete listing and discussion of relevant aircraft design variables.

[WMD], others), the time-sensitivity of the targets (mobile, moving), and the environmental conditions, such as the weather, daylight, and terrain.

It is convenient for subsequent discussions to refer at times to the set of threat dimensions, target types, environmental conditions, and missions as the *operational situation* (Ops Sit) within which the utility of an air vehicle is to be evaluated and analyzed. These dimensions are *uncertain* as the Air Force plans for a future air vehicle, and most are *uncontrollable* by U.S. planners and operational commanders. Although not part of the utility analysis, the following dimensions need to be considered in assessing the overall value of an air vehicle:

- *Costs* (science and technology, R&D, procurement, operating and supportability); and
- *Risks* (technological and/or performance risks, time to field, cost).

Given the multidimensional nature of the problem, the analysis of speed-and-observability trade-offs on the bases of their contribution to the utility of air vehicles is a complex activity. Fortunately, there are methodological approaches used in the Department of Defense (DOD) that can reasonably and appropriately consider this level of complexity in assessing weapons system design trade-offs on the basis of the forecasted operational utility of the system. One such approach is outlined in the following section.

SUGGESTED FRAMEWORK FOR COMPREHENSIVE ANALYSIS

The framework is presented by summarizing a sequence of major tasks in the approach.

Task 1: Define Proxies for the Utility of an Air Vehicle

The utility of any system in general, and the LRSS in particular, is its raison d'etre—the objective that it was designed to achieve. In conducting analysis, it is difficult to determine the objectives and appropriate proxy metrics (that indicate the degree to which objectives are achieved) from the customer because these objectives are rather subjective. They vary depending on whether the customer is a component designer, an aircraft designer, a planner, or an operating commander, and they vary with the level of the individual within the organization—for example, flight leader, wing commander, or Air Force commander. Under this first task, appropriate utility metrics need to be defined.

As a general rule, utility metrics need to be defined at a level higher than all the decision variables in a decision problem in order to capture all of the interactions and interdependencies among the decision variables. In the air vehicle problem, the decision variables are the aircraft's design variables, with particular emphasis on speed and observability. A number of utility proxies have been used in—or proposed for—analysis of aircraft strike systems.

Aircraft susceptibility is a commonly used utility proxy that is affected by a number of design variables. It is defined as the "inability of the aircraft to avoid being hit by threat ordnance along a mission flight path." Some proposed metrics of susceptibility include these:

- *The time required to fly the mission flight path:* presumably more time results in more hits, but this metric ignores other design variables that can reduce susceptibility (e.g., increased speed, low observability, countermeasures, and so on);
- *The expected number of shots fired at the air vehicle:* ignores design variables that can prevent hits by fired shots (e.g., countermeasures, maneuverability); and
- *The probability of being hit by at least one round during the mission flight path:* only this metric logically considers all of the design variables that affect susceptibility and can be computed in 1 on 1, 1 on N, and M on N mission profiles.

Susceptibility is deficient as an air vehicle utility measure because it does not consider design variable interactions, design effects, and threat dimensions that affect the *vulnerability* of the aircraft, which is defined as "the likelihood that the aircraft will be killed if hit by threat ordnance."[2] As an example of design variable interaction, significant increases in speed will likely require an increase in aircraft size with current engine technologies, which will require more fuel to maintain range or persistency. The additional fuel could make the air vehicle more vulnerable. Many studies inappropriately use susceptibility as a measure of an air vehicle's survivability.

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[2] Ball (see footnote 1) describes methods and models for calculating vulnerability metrics such as vulnerable area and the probability that the aircraft is killed when it is hit—Pr [aircraft kill | hit].

Survivability, as a proxy of air vehicle utility, is defined as "the ability of the air vehicle to avoid being killed as it transits a complete mission flight path." It incorporates decision and design variables that affect both susceptibility and vulnerability metrics. Some appropriate survivability metrics used in studies include the following:[3]

- *Pr* [an aircraft survives one mission | Ops Sit].
- *Pr* [an aircraft survives *N* missions | Ops Sit].
- *E* [number of sorties the aircraft can fly | Ops Sit].
- Sortie loss rate.

Although purportedly used in many aircraft-planning studies, survivability too is deficient as a utility proxy, in that it does not consider design and operational decision variables that affect accomplishing the mission objectives (e.g., destroying a WMD site), such as sensor capabilities, number of weapons, lethality of the ordnance, and employment tactics. A number of these design variables have second- and third-order interactions with speed and signature.

Operational mission effectiveness is an appropriate utility proxy that is defined as "the ability of the air vehicle to accomplish the mission objectives *and* avoid being killed while doing so." This metric includes both the ability of the aircraft to defend itself against the threat ("survivability") *and* the "offensive (end game) ability" to accomplish the mission objectives (e.g., destroy a WMD site or hold a threat force at risk). Some example mission effectiveness metrics include the following:

- *Pr* [Destroy target and survive | Ops Sit].
- *E* [Number of missions air vehicle can successfully perform | Ops Sit].
- *E* [Number of critical targets destroyed by air vehicle in a campaign | Ops Sit].
- Force exchange ratio in an air-land campaign involving significant numbers of the air vehicles.

Air vehicle effectiveness measures need to be defined consistent with the level of operational missions used in the study: 1 on 1, 1 on *N*, *M* on *N*, air-land campaign, and so on.

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[3] Here *Pr* stands for probability, and *E* stands for effectiveness.

Obviously, the two components of effectiveness (survivability and offensive capability) are interdependent phenomena and are often traded off during operations (e.g., deliver ordnance on targets at nonoptimal altitudes to enhance survivability). Perhaps more importantly for the air vehicle case, they are both affected in the design process when trade-offs are made among design variables that affect susceptibility, vulnerability, and lethality of delivery means. These trade-offs should be made consciously and explicitly in the comprehensive study.

Task 2: Identify Criteria and Transformation of Models to Conduct the Study

Conducting the study will require the use of simulation models and analytic methods that can be used efficiently to relate air vehicle design capabilities (speed, observability, countermeasures, sensor suite, weapons lethality, and so on) to the selected effectiveness and survivability measures for different relevant missions or vignettes and operational situations (threats, targets, environments). Said symbolically, analysts need to identify the function

$$\begin{array}{l}\text{Mission}\\ \text{Utility}\\ \text{Measures}\end{array} = f_i \left\{ \begin{array}{l}\text{Air Vehicle}\\ \text{Design}\\ \text{Capabilities}\end{array} \;\middle|\; \begin{array}{l}\text{Mission and}\\ \text{Operational}\\ \text{Situation}\\ \text{Descriptors}\end{array} \right\} \tag{1}$$

where f_i represents the simulation models and methods that describe the *i*th mission and relevant utility measures are effectiveness and/or survivability. For a given set of Ops Sit descriptors and mission, the study will search over the air vehicle design capabilities to identify (within a cost constraint) air vehicle designs that maximize mission effectiveness, trading off survivability with the offensive (end game) part of the mission. Given the criticality of aircraft survivability, a more reasonable criterion would be to search for air vehicle designs that maximize effectiveness subject to a constraint on achieving a desired level of survivability, for example, $Pr[\text{survivability} \geq .98]$.

Designing an air vehicle to maximize mission effectiveness subject to cost and survivability constraints for a fixed operational situation is the classic cost-effectiveness criterion most frequently used to develop systems and forces in the DOD. If uncertainty regarding future missions and operational situations is large, one alternative criterion that might be considered is to identify air vehicle design capabilities that maximize the versatility[4] of an air vehicle across missions and Ops Sits, subject to effectiveness, survivability, and cost constraints. Symbolically, it develops the inverse of equation (1):

$$\begin{array}{l}\text{Mission and}\\ \text{Operational}\\ \text{Situation}\end{array} = f_i^{-1}\left\{\begin{array}{l}\text{Air Vehicle}\\ \text{Design}\\ \text{Descriptors}\end{array}\middle|\begin{array}{l}\text{Effectiveness \&}\\ \text{Survivability}\\ \text{Constraints}\end{array}\right\} \quad (2)$$

Designing an air vehicle using this criterion maximizes the number of missions it can perform at the desired level of effectiveness and provides commanders and pilots with a flexible response capability in downstream operations. The versatility planning approach has been used in studies for the Supreme Allied Commander Europe[5] and the Commander in Chief, U.S. Army Europe.[6]

Some available models and methods that might be used to conduct the comprehensive study are noted below:[7]

- Extended Air Defense Simulation (EADSIM) (mission level),
- Suppressor (mission level),
- Thunder, Storm (campaign level),
- Radar Directed Gun Simulation (RADGUNS) (engagement level), and
- Brawler (engagement level).

Note, however, that in the committee's view, these models require improvements in their ability to handle track fusion and the human decision-making process.

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[4] For a description of versatility planning and some of its applications, see S. Bonder, *Versatility Planning: An Idea Whose Time Has Come—Again!,* Steinhardt Lecture presented at the Institute for Operations Research and Management Science Conference, Salt Lake City, Utah, May 9, 2000.

[5] Vector Research, *Multinational Forces in NATO, Quick Response Analysis of Rapid Reaction Forces,* Final Report, VRI-G-91-25, Ann Arbor, Mich., 1991.

[6] G. Miller and C. Johnston, *Analysis of Alternative Structures for U.S. Army Forces in Europe,* Proc. of the 33rd U.S. Army Oper. Res. Symposium, Ft. Lee, Va., November 7-9, 1994.

[7] An extensive discussion of available models is contained in Ball (see footnote 1), p. 141.

Task 3: Develop Experimental Designs for Simulation Runs

Conceptually, one would like to examine the effectiveness and survivability impacts for all combinations of air vehicle design variables over their feasible ranges (with consideration given to their engineering interactions) to identify designs that maximize effectiveness and survivability in important missions and operation situations. Even for a "comprehensive study," the combinatorics make this infeasible. Instead, the committee suggests the following process:

- **Task 3a:** Based on previous study results and experience, select a set of air vehicle design capabilities as "primary variables" for the experiments. This should likely include the following:
  —Aircraft speed,
  —Observability,
  —Countermeasures (active and passive),
  —Situation awareness,
  —Payload, and
  —Weapon lethality.

These variables should be varied over ranges based on the development feasibility analyses and their engineering interactions.

- **Task 3b:** Set the remaining relevant air vehicle design variables as "parameters" for the analysis. These should be fixed for all the runs except where engineering and operational interactions suggest that they change with changes in primary variables. For example, altitude as a parameter would likely change with speed for operational efficiency. Persistence and vulnerability parameters might change owing to engineering interactions as speed is varied.

- **Task 3c:** Select relevant missions or vignettes and Ops Sits (threats, targets, and so on) for the analysis. The committee suggests that these be "stressful" so that insights regarding less stressful missions would be gained by interpolation rather than extrapolation.

- **Task 3d:** Develop appropriate experimental designs for efficient conduct of the simulation-based experiments and specify how the

simulated outputs would be analyzed. In addition to all the combinations of primary variables, the design should include runs of
—Current systems versus current threats, and
—Current systems versus future threats.

These can be used as baselines to compare with runs involving simulated future air vehicles.

Task 4: Set Up, Conduct, and Analyze Initial Simulation Runs

Although many design variables impact on the survivability and effectiveness of potential air vehicles, a major focus is to identify a good balance between speed and observability capabilities for different levels of other design parameters, missions, and Ops Sits. Toward this end, analysis of simulation results should try to identify functional input-output relationships such as:

$$\begin{array}{l}\text{Mission}\\ \text{Effectiveness}\end{array} = f_i \left\{ \begin{array}{l|lcl} \text{-Speed} & \text{fixed} & & \text{Mission} \\ \text{-Observability} & \text{parameter} & , & \text{Operational} \\ \text{-Countermeasures} & \text{values} & & \text{Situation} \end{array} \right\} \tag{3}$$

and

$$\begin{array}{l}\text{Aircraft}\\ \text{Survivability}\end{array} = g_i \left\{ \begin{array}{l|lcl} \text{-Speed} & \text{fixed} & & \text{Mission} \\ \text{-Observability} & \text{parameter} & , & \text{Operational} \\ \text{-Countermeasures} & \text{values} & & \text{Situation} \end{array} \right\} \tag{4}$$

for each of *i* missions. These relationships could be portrayed graphically through the use of scatter plots, some examples of which are shown in Figures C-1 and C-2.

Task 5: Some Analysis Thoughts

- In reviewing the simulation outputs, it is important to look for knees in the effectiveness and survivability functions to identify good speed and observability pairs. For “robust” air vehicle capabilities, one should design away from inflection points so that the operating point is out along flat parts of the curve.

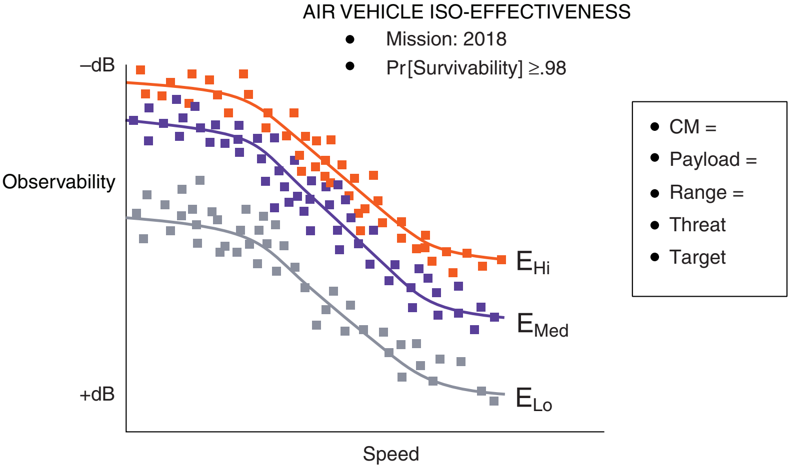

FIGURE C-1 Conceptual simulation results showing speed and observability combinations that yield iso-effectiveness or constant effectiveness (*E*) of the air vehicle at high, medium, and low levels, given a particular mission and specified probability of survival. Bulleted variables are treated as parameters in the simulation.

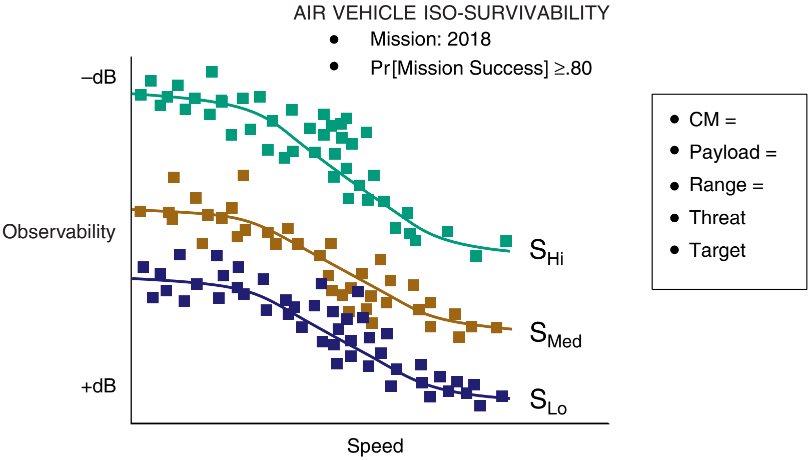

FIGURE C-2 Conceptual simulation results showing speed and observability combinations that yield iso-survivability or constant survivability (*S*) of the air vehicle at high, medium, and low levels, given a particular mission and specified probability of mission success. Bulleted variables are treated as parameters in the simulation.

- One should look for changes in design parameters and/or tactics that might provide equal survivability and effectiveness levels with less costly or risky speed and observability pairs.
- One should look for design parameter and/or tactics changes that might enhance effectiveness and survivability for the same speed and observability pair.
- It is important to conduct sensitivity analyses on operational situation dimensions (threat, targets, environment) to assess the impact of (1) uncertainties in these dimensions and (2) threat countermeasures on effectiveness and survivability and the speed and observability balance. One should develop and analyze potential design and/or operational counters to threat countermeasures.
- One should continually assess the engineering "feasibility" associated with high-utility (effectiveness and survivability) pairs.

Appendix D

Glossary

Altitude: Altitude can be measured in several meaningful ways. One is the height of the air vehicle above mean sea level, measured along the line between the air vehicle and the center of Earth. Another is the density altitude, which is the equivalent altitude under standard conditions of pressure and temperature at the existing air density outside the air vehicle. In considering the kinematics of a threat missile, it is the density altitude that is important.

Countermeasures: Countermeasures refer to a wide range of devices (both active and passive) aimed at defeating the ability of an enemy's sensor system to find, fix, track, or engage friendly forces. Countermeasures include both radio-frequency (RF) systems (e.g., jammers and so on) and infrared systems (i.e., flares, chaff, and so on) and may be either onboard or offboard systems.

Lethality: Weapon lethality must be defined specifically for each class of weapon or munition and each class of target. That said, lethality is expressed as the probability that the desired effects on a target will be achieved by a munition for the conditions of employment. The metric usually used is $Pr[\text{kill} \mid \text{hit}]$, where a hit can be by a contact or proximity fuzed munition. For the U.S. munitions inventory, the Joint Munitions Effectiveness Manual is an authoritative source of lethality information.

Maneuverability: Air vehicle maneuverability refers to the acceleration capability of the vehicle in a plane normal to the vehicle velocity vector. Acceleration is generally quoted in terms of "G's" where 1 g = 9.8 m/s^2. Maneuverability is a function of the vehicle shape, mass, orientation, speed, and altitude.

Payload: Payload refers to a device or devices carried by the air platform for the purpose of meeting the mission objectives. For intelligence, surveillance, and reconnaissance (ISR) platforms, payload refers to the sensor suite carried. For attack air platforms, payload refers to the munitions that can be deployed. For munitions, payload refers to warhead or submunitions carried. The payload is specified in terms of its impact on the air vehicle by parameters such as mass, volume, power, interface, and so on. The required payload is set by the definition of the mission requirements and can have a significant impact on air vehicle shape and size.

Persistence: Persistence refers to the time period that an attacking or ISR platform can engage a target within its window of vulnerability. For air platforms, persistence is measured as time on station. Note that persistence in an attack role can be achieved in three ways: (1) by loitering over the vicinity of a potential target and delivering a gravity bomb, (2) by standing off and using a high-speed weapon to attack within the target's time of vulnerability, or (3) by standing off at a distance and repeatedly dashing into the battlespace to attack.

Range: Range is a distance measurement usually quoted in terms of the relative distance between two points on the surface of Earth. Several range measurements are of importance when considering survivability. The combat range of an aircraft is generally defined as half of the maximum distance (i.e., combat radius) that an aircraft can cover between in-flight refueling operations. Detection range is the maximum linear distance between an air vehicle and the sensing system used to detect the air vehicle at the lowest threshold of the detection system. The weapon range is the maximum distance that a weapon can transit between its carrier platform and target.

Signature and/or observability: The general definition of the signature of an air vehicle is any direct or indirect measure of its characteristics or effects. In the context of this study, the most common signature measurement for

RF systems is the radar cross section (RCS, or σ), usually quoted as a $\log_{10}$ of the cross section measured in square meters (dBsm). The RCS of an air vehicle is a function of the RF wavelength and the vehicle shape, size, materials, and orientation. For infrared systems, the signature of a vehicle is quoted in terms of radiant intensity in the waveband of the sensor system of interest and is usually quoted in watts per steradian. The optical signature is a function of the vehicle size and shape, the surface temperature and emissivity, and the exhaust plume.

Situation awareness: Situation awareness refers to one's understanding of the current state of the battlespace. Situation awareness addresses both the knowledge of physical properties of entities within the battlespace (i.e., the position and velocity vector of air vehicles, state of communications systems, location of enemy forces, and so on) and the cognitive understanding of the dynamically evolving environment. As such, the ability of a human to process and act on data and information is an important aspect of situation awareness. Situation awareness is important for both the attacking forces (i.e., knowledge of surface-to-air missile system locations, targets, defensive doctrine, and so on) and the defensive forces (i.e., targeting and tracking of attacking systems, determining intent, weapon-target pairing, and so on).

Speed: The normal definition of speed is the instantaneous magnitude of the velocity vector. The speed of an air vehicle represents the relative motion of the air vehicle with respect to the air mass surrounding it. This vector is normally not coincident with the axes of the vehicle, which results in an angle-of-attack or angle-of-yaw with respect to its direction of motion. The normal way to express speed for modern military aircraft and missiles is Mach number, M, which is the ratio of air vehicle speed to the local speed of sound in the air mass. (Since the sound speed is a function of temperature, the sound speed is generally taken to be with respect to the standard atmosphere unless otherwise noted.) The Mach number is used to characterize speed ranges or regimes: subsonic ($M < 1$); transonic ($M \sim 0.8$-1.1);[1] supersonic ($1 < M < 4$); and hypersonic ($M > 4$). Mach number is an important similarity parameter regarding the aerodynamics of the vehicle. When tied to a specific altitude, Mach number can also be used to define the aerothermal environment that the air vehicle must oper-

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[1] Strictly speaking, the transonic regime, which begins when $M = 1$, is first reached somewhere on the vehicle, usually at the maximum thickness point on the wing.

ate within. Air vehicle block speed, V_{block}, is also an important parameter for analysis. Block speed is defined as the distance covered along a ground track divided by the flight time. Block speed is sometimes quoted in terms of a Mach number, but Mach number is ambiguous in this context, since altitude (and hence temperature and speed of sound) can vary throughout a trajectory. Within this report, Mach number used to denote a block speed is defined as the block speed divided by the standard-day sea-level sound speed. The design speed of an air vehicle system strongly impacts air vehicle and propulsion system requirements.

Survivability: In terms of combat, survivability refers to the capability of an aircraft to avoid a man-made hostile environment. Survivability is defined as the probability that an air vehicle is not killed during its mission. Survivability consists of susceptibility and vulnerability. Within this report, the focus is on the susceptibility portion of aircraft survivability.

Susceptibility: Susceptibility is a measure of the probability that an air defense system can physically make contact with the air vehicle. With a hit-to-kill interceptor system, susceptibility defines the probability that a portion of the interceptor actually impacts the air vehicle. With an interceptor system using a blast-fragmentation warhead, susceptibility defines the probability that a warhead fragment impacts the air vehicle.

Tactics: Tactics are the processes that are executed to achieve the desired mission results and typically are designed to synergistically maximize capabilities and strengths and to minimize weaknesses. An example is a fighter that has a speed advantage against a threat, but also has a turn-rate disadvantage. This fighter would generally be deployed with tactics that utilize high-speed "blow through" techniques while taking shots of opportunity, as opposed to tactics that utilize a low-speed "dogfight" approach with a steady-state weapons engagement zone as the goal. The functional components of tactics include available assets, support assets, associated capabilities, timing synchronization, threat environment, weather, terrain, fuel, communications, weapons, operator experience, and mission objectives. Key trade-offs include the ability to achieve surprise versus the capability to execute, comprehensive planning versus the ability to dynamically respond, risk versus value of mission accomplishment, risk versus assets committed, and risk versus timing.

Threat: Threat is a general term that can be applied to the enemy systems and subsystems that impact the detectability, susceptibility, and ultimately, the survivability of U.S air vehicles. The term is applied, for example, to an enemy integrated air defense system, early warning sensors, acquisition sensors, surface-to-air missiles, and air-to-air missiles.

Vulnerability: Vulnerability addresses the response of the air vehicle after it is hit by an interceptor system. Vulnerability is defined as the probability that the air vehicle is killed once it is impacted by an interceptor system. (Note that the vehicle's mission could well be compromised prior to this kill if it were forced to maneuver or turn back to avoid the threat.)