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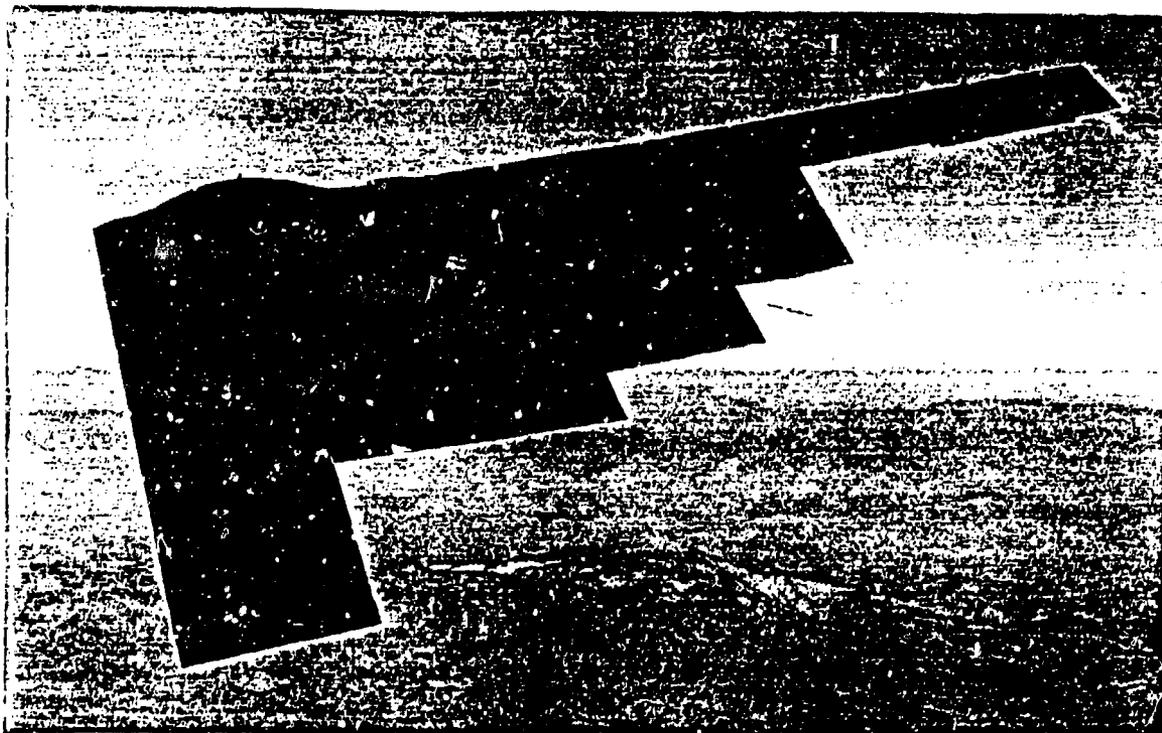
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1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE March 1990	3. REPORT TYPE AND DATES COVERED White Paper/Final
4. TITLE AND SUBTITLE B-2 Survivability Against Air Defense Systems			5. FUNDING NUMBERS
6. AUTHOR(S) SAF/AQ			8. PERFORMING ORGANIZATION REPORT NUMBER None
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) SAF/AQ The Pentagon Washington, DC 20330-1000			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) SAF/PANS Pentagon (Room 4A120) Washington, DC 20330-1000 POC: Lt Col Warden/DSN 225-3063			10. SPONSORING/MONITORING AGENCY REPORT NUMBER None
11. SUPPLEMENTARY NOTES None			
12a. DISTRIBUTION/AVAILABILITY STATEMENT Previously released to news media and community leaders. Public domain.			12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) Paper begins with a short general discussion on stealth and counter-stealth activities. The main sections of this paper then analyze the capabilities of conventional and unconventional air defense systems to defend against stealth aircraft. The paper then concludes with a short commentary on the value of a vigorous U.S. program in counter-stealth air defense approaches.			
14. SUBJECT TERMS Air Defense. Strategic Bomber. B-2. Stealth.			15. NUMBER OF PAGES 13
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

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B-2 SURVIVABILITY AGAINST
AIR DEFENSE SYSTEMS

MARCH 1990



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I. INTRODUCTION

Incorporating "stealth" technologies that reduce its signature in a wide array of spectra, the B-2 now stands poised to enter operational service within the next few years as the cornerstone of the Air Force's modernized bomber fleet. The military value of the B-2 hinges directly on the survivability provided by its stealth capabilities. The purpose of this paper is to provide interested readers with an unclassified overview of the B-2's current and long-term survivability when penetrating air defense systems--an issue that has become the subject of much misinformed controversy.

B-2 survivability raises many complex technical topics that directly affect the lives of U.S. aircrews--accordingly, some details relating to survivability must remain classified. Despite this limitation, this paper discusses the technical and operational issues involved in air defense against stealthy aircraft to provide an informed and accurate unclassified assessment of B-2 survivability. Because this discussion is unclassified, the presentation of quantitative results is severely limited, and some questions are necessarily addressed by assertions that these concerns have been investigated and satisfactory answers obtained.

This paper begins with a short general discussion on stealth and counter-stealth activities. The main sections of the paper then analyze the capabilities of conventional and unconventional air defense systems to defend against stealth aircraft. The paper then concludes with a short commentary on the value of a vigorous U.S. program in counter-stealth air defense approaches.

II. THINKING ABOUT STEALTH AND COUNTER-STEALTH

Maintaining a viable military capability in any particular area typically involves an action-reaction sequence. Submarines offer a useful, long-standing example to guide our thinking about stealth platforms, counter-stealth defenses, and the action-reaction cycle.¹ Modern nuclear

¹ Interestingly, the history of the action-reaction cycle involving submarines features the first use of stealth technology to defeat radars. During World War II, the Allies severely degraded German U-boat activities by employing land-based, long range maritime patrol aircraft to catch U-boats operating on the surface while recharging their batteries. In response, the *Kriegsmarine* developed the snorkel, an apparatus

submarines depend almost totally on stealth for survival. The United States has deployed these types of submarines for many years and has devoted substantial financial resources to their development, procurement, operation, and improvement. Concurrently, we have invested substantial effort and resources in a counter-stealth activity--anti-submarine warfare (ASW). The Soviets also field many submarines and aggressively pursue substantial ASW activities.

Soviet ASW activities do not seriously question the U.S. commitment to submarines, which we continue to rely on for many vital military capabilities. Nor does the vigorous U.S. ASW program provide a reason to question our commitment to submarines. U.S. policy instead strives for substantial superiority over the Soviet Union and other nations in submarine and ASW technologies and capabilities--an approach that has served the United States very well for many decades.

In the case of the B-2 and other stealthy aircraft, we have a dramatic lead in this particular set of technologies and the potential to sustain that lead for many years. At the same time, we are aggressively pursuing counter-stealth air defense programs because--as with the case of submarines--it is reasonable to assume that potential adversaries will quickly recognize the benefits of stealth aircraft and begin fielding such systems in future decades.

Developing an informed and mature view of the survivability of stealthy aircraft is necessary as we pursue these stealth and counter-stealth activities. For example, during test activities, air defense sensor components will occasionally detect stealthy air vehicles, and, with sufficient coverage density and at short ranges, perhaps even track them for short periods of time. But this by itself is not a cause to question our commitment to stealth. What is important is the quantitative extent of the detection or short duration tracking and the "real world" effectiveness of potential defense systems that employ this detection or tracking to defend against a stealthy target.

In the case of submarines, no one suggests that a 560 foot long, 17,000 ton metallic object is "invisible" even under water. Similarly, no one argues

which permitted a submarine to use its diesel engines for battery recharging while cruising underwater. The Allies in turn developed air-borne radars which could detect the snorkel. To counter this threat, the Germans developed and installed a rubbery coating over the snorkel which degraded the effectiveness of allied radars.

that the 170 foot wingspan, 350,000 pound B-2 is "invisible" as it passes overhead at low altitude. What can convincingly be argued and supported by tests, however, is that neither the submarine nor the B-2 can be *consistently* detected, tracked, or engaged at military useful ranges in typical operational scenarios--in short, both types of systems are highly survivable. This paper provides evidence to support this survivability assessment of the B-2 bomber.

III. STEALTH SURVIVABILITY INVESTIGATIONS

Since the early days of the stealth program, the Air Force has conducted, and continues to conduct a broad range of investigations of potential air defense counters to stealthy air vehicles. These ongoing studies have explored the capabilities of potential air defenses against a wide range of air vehicles (such as cruise missiles, fighters, and bombers) with the objective of finding an "Achilles' heel" that could provide a means to effectively counter stealth technologies. A talented cadre of Ph.D. level scientists, engineers, and analysts--aided by the contributions of many additional talented staff from government, industry, and academia--has been given direct access to data on various stealth programs and sufficient funding to conduct major experiments. These researchers have operated independently of stealth program managers and industrial contractors. Their findings have been reported directly to the Air Force leadership.

Substantive experiments in areas where knowledge was uncertain or the interactions very complex were (and remain) key features of these investigations. Such experiments guard against drawing the wrong conclusions from oversimplified or inaccurate views of the interaction between air defenses and stealthy air vehicles. This experimental approach guides and provides confidence in Air Force survivability assessments.

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IV. AIR DEFENSE VS. STEALTH--GENERAL OBSERVATIONS

All air defense systems employ three inter-related functions:

- 1) *Surveillance* is the mechanism that searches broad volumes of air space to locate the target.
- 2) *Fire Control* involves tracking the target to establish its current position and potential future position, identifying the target as hostile or threatening, and guiding some form of weapon to the target's immediate vicinity.
- 3) *Kill* involves bringing a weapon close enough to the target to allow the weapon's fuze to detect the target and then fire the warhead within lethal range.

These three fundamental functions are tightly interwoven and controlled by some form of a command, control, and communication network. Capable air defense systems must be able to accomplish these three main functions reliably against all potential threats. For example, if these three functions were each carried out with a 50% probability of success, the overall kill rate of the air defense system is only 12.5%. If an overall kill probability of about 50% is desired, each task must typically be carried out with an 80% probability of success. If any one function is done poorly, the net overall effectiveness is very low. For example, 80%, 20%, and 80% success rates in each function yield only a 13% probability of overall success.

Compounding matters, air defense systems must also be able to:

- 1) Survive direct attacks
- 2) Successfully resist a wide variety of countermeasures and tactics such as electronic jamming and low altitude flight.
- 3) Function in a full range of the highly variable natural environment: wind, rain, snow, clouds, fog, sunlight, night, clutter from ground, sea, birds, insects, weather, meteors, aurora, and electrical noise (galactic, lightning induced, seismic, cosmic ray).

The third requirement is often the limiting factor, particularly in the case of proposed unconventional air defense schemes. The approach of "hiding in the natural background clutter" is not new. Animals and plants have used it for millions of years to survive--many living species have developed protective colorations and changeable colorations to hide in the clutter from their enemies. In a similar vein, military forces have employed a wide range of camouflage schemes to enhance survivability both on the ground and in the air. Naturally occurring effects often have dramatic impact on the operability of systems that initially appear to offer a potential to counter stealth vehicles. For example, infrared radiation from a target will not pass through clouds and will also be attenuated by water vapor and other constituents in clear air. This tends to dramatically reduce the potential role played by infrared sensors in air defense systems. Infrared systems can be important adjuncts to the all-weather, long-range capabilities of radar, but still cannot be considered a viable substitute.

Developing a confident physical model of this background interference phenomena is very challenging--even more challenging is devising methods to electronically mitigate the effect of the interference on surveillance, tracking, and kill systems. For example, a typical look-down radar on a modern fighter aircraft needs to reduce the magnitude of the radar return from the earth (radar clutter) by a factor of about *one hundred million* before it can detect a small, low-flying air vehicle like a cruise missile.

Stealthy aircraft dramatically reduce the effectiveness of all three basic air defense functions--surveillance, fire control, and kill--to enjoy greatly enhanced survivability. Stealth reduces the size of signals available to the defense sensors which in turn:

- Reduces the probability that surveillance, fire control, and kill will successfully occur, and if they occur, reduces the range at which they happen. A reduction of an aircraft's radar signature by a factor of 10 reduces radar detection range to one third its original value; a factor of 100 signature reduction reduces radar coverage area to one-tenth its original value.

- Weakens the defense system's ability to cope with interference from ground clutter, man-made noise, and false targets such as birds.
- Weakens the defense system's capability to cope with an adversary's tactics, such as flying at low altitudes or employing electronic countermeasures. This is an important additional attribute of stealth. Electronic jamming, for example, becomes considerably easier and more effective when combined with stealth airframes. As the aircraft signature is reduced, the required jammer power and size is also reduced in proportion.

Overall, these effects on air defense systems provide stealth aircraft with a very high degree of survivability. Stealth aircraft are neither invisible or immortal, but pose so many challenges to air defense systems that their survivability is much greater than conventional aircraft.

V. CONVENTIONAL AIR DEFENSES

Most conventional air defenses use radar as the principal sensor. Radars can search large areas, day or night, in all weather conditions to provide accurate location of targets and guide interceptor aircraft or missiles to the target. To deal with stealthy air vehicles such as the B-2 would require substantial improvements in a typical air defense radar. Radar sensitivity must be enhanced to detect the much weaker radar returns from the stealthy target. Clutter rejection capabilities must be dramatically improved to prevent the weak target return from being lost amidst a multitude of other radar returns from the ground, birds, weather, etc. And the radar's resistance to electronic countermeasures must also be improved for the same reason.

If the required improvements in sensitivity, clutter rejection, and countermeasures resistance only involved a tripling or quadrupling of capabilities, this would be a difficult, but not overwhelming task. But the required improvements will typically be much greater.

Designers of the typical ground radars used for surveillance and/or fire control could, if provided with sufficient funds, approach this problem

by building a much bigger antenna and transmitter. Fixed sites with such improvements would, of course, become lucrative defense suppression targets; improved mobile units could become more restricted in terms of movement and thus more vulnerable. Although ground-based radars can accommodate the much bigger hardware, aircraft and satellites typically cannot because of size limitations. Air defense kill mechanisms--typically a guided missile--encounter similar problems. These missiles usually house a nose-mounted antenna as part of the guidance system. Such antennas are strictly limited in size by the diameter of these slender missiles. The designer has little freedom to increase the antenna size and consequently the missile seekers are often the greatest challenge to overcome in defending against stealth aircraft.

The physical constraints influencing air- or space-borne radars greatly enhance the survivability of the B-2. The greatest threat to penetrating bombers today are airborne defenses that combine airborne early warning platforms (such as the USAF's E-3A or the Soviet Mainstay) and look-down, shoot-down fighters. Such defenses can detect low-flying conventional aircraft out to ranges of up to 250 miles. The location of these defenses at any moment in time is unpredictable, making evasive routing difficult. But stealth technology essentially takes these airborne air defense threats out of the picture.

Ground-based systems can be larger. Radar ground stations do not suffer the same physical limitations as air or space platforms and large surface-to-air missiles, for example, have the edge over air-launched missiles, which are typically smaller. But the B-2 poses an array of additional challenges to ground defenses. Many radar systems cannot accommodate the very substantial upgrades to detect the B-2 and their coverage zones are too small to support successful defense against this bomber. Some big powerful radars, though, do have a useful detection capability. In response, the B-2 could employ evasive routing, fly low to reduce coverage, and/or employ stand-off weapons to attack targets in the vicinity of these radars. Some of the larger capable radars could be mobile. But the B-2's crew could detect the radiation from these radars long before the radar detects the bomber (a simple matter of physics) and then avoid the threat.

Some critics argue that stealth is not as effective against Very High Frequency (VHF) radars as against higher frequency radars. When the B-2 was designed, the Soviets already had deployed about 2000 VHF surveillance radars, which were clearly a well recognized part of the air defense threat that challenged the B-2's designers. The B-2's design can deal with this class of radar. In any case, VHF is not a particularly effective surveillance tool for air defense systems. Although generally low in cost, VHF radars have serious problems in detecting low flyers and coping with man-made interference and jamming.

To measure the B-2's capabilities against these varied air defense systems, the Air Force and its independent investigations have employed calculations and computer models, all backed up by actual field experiments. Special radars, infra-red systems, and other sensor systems were built where adequate equipment did not exist. The resulting experimental data allows engineers to characterize the performance of a wide range of sensors with substantial confidence. The B-2 will fly against these and many other sensors to confirm its survivability. Before the availability of a B-2 airframe for testing, hundreds of flight tests were run with F-117 stealthy fighter aircraft and other classified air vehicles against the AWACS and F-15 airborne systems, the improved HAWK ground-based SAM, and numerous other sensor and weapons systems. As a result of these years of experimental work, survivability prediction capability is quite good.

In summary, overall survivability is not seriously threatened by occasional detections or sporadic tracking. Successful air defenses need to consistently detect, track, and kill targets. It is a tall order to accomplish all three of these functions with conventional air defenses in the face of the B-2's stealth technologies. That leaves the matter of unconventional air defenses.

VI. UNCONVENTIONAL AIR DEFENSES

Many fertile and inventive minds in the U.S. and elsewhere have taken up the challenge of projecting or imagining numerous unconventional air defense schemes. All of these assert to show that the B-2 aircraft can be detected--that it is not invisible.

The B-2 is obviously not invisible. But what is needed for successful air defense against the B-2 is detection, tracking, and kill capabilities at relatively long operating ranges (e.g., 25 to 200 miles depending on the style of defense). At such ranges, the various signals available from the B-2 are generally very weak, and easily lost in the noisy background or obscured by ground clutter, weather, clouds, and other phenomena.

Some 50 or so unconventional air defense concepts have been proposed. All of these have been analyzed, some in substantial detail, and some have even been tested experimentally. The details of these investigations are classified, but we can list below some of the concepts that have been investigated over the years:

- Acoustic Systems
- Bi-static Radar Systems
- Infrared Detection Schemes
- Corona Discharge Detection
- Interaction with Cosmic Rays
- Passive Coherent Detection Schemes
- Radar Shadow Detection
- Land Mines
- Magnetic Disturbance Detection
- Hybrid Bi-static Space Radar
- High Frequency Surface Wave Radar
- Detection of Aircraft Emissions
- Radiometric Detection
- Air Vehicle Aerodynamic Wake Detection
- Ultra Wideband (Impulse) Radar

Examining one of these approaches--acoustic systems--provides an instructive illustration of the difficulties of turning an intuitively attractive idea into a viable unconventional air defense system. An acoustic detection scheme offers many attractions: large aircraft emit lots of acoustic energy (noise) and the basic detectors of this energy (microphones) are simple and cheap. Each detection sensor might be a simple array of perhaps five microphones with the capability to detect a B-2's acoustic signal out to a range of about five miles and make a crude estimate of the direction of

arrival of the signal. Signals from such a sensor could then send detection and direction information to a central facility for processing.

Employing such sensors, a Soviet air defense system designer would need to build a "fence" of sensors to cover all possible B-2 routes into the Soviet Union. Such a fence would be roughly 14,000 miles long² thus requiring about 1400 sensors. Such a "fence" could warn of passage of any aircraft through its coverage. So far, this is a simple system as air defenses go.

This system, however, has many shortcomings. A momentary or short detection sequence is not enough to stop a stealthy aircraft: the system needs to track and kill for successful defense. Designers would need to expand the width of the "fence" to track the B-2 and guide interceptors for the kill. To track the B-2 with acoustic sensors would require a "deep" fence capable of keeping the B-2 in track for a sufficient period for an interceptor to close and kill--say fifteen minutes. In fifteen minutes, a B-2 flying at, say Mach 0.8, would traverse about 150 miles, thus requiring the sensor fence to be of a similar depth. Such a fence would cover 2.1 million square miles. Each acoustic sensor with a 5-mile range could cover about 78 square miles, so 27,000 stations would be required. As can be seen, the need to detect, track, and kill turns this simple concept into a far more complex and costly system than first envisioned.

Tactics, countermeasures, and other architectural problems would also reduce this acoustic system's effectiveness:

- If a B-2 crossed the fence at high altitude, the acoustic signals would be very weak
- Soviet aircraft would ring the fence alarm as well as U.S. aircraft
- A few U.S. cruise missiles intentionally flying along the fence would ring many of the alarms.
- The United States could destroy one or a few small segments of the fence or move a penetrating bomber force through only a few places to saturate the air defense interceptors which must necessarily cover the entire fence.

² A similar fence around just the Continental United States would be about 7000 miles long; a fence around all of North American about 10,000 miles long.

Fielding such a system also poses many formidable technical challenges:

- Acoustic sensors are severely degraded by wind noise.
- Atmospheric propagation effects can cause "quiet" zones where microphones cannot hear very well (much as layers of differing temperatures in the ocean provide hiding places for submarines).
- Snow, ice, and rain could degrade the operability and reliability of the microphones (a particular problem for the Soviets since the most important part of this fence would be close to the Arctic Circle).
- The interceptors would still have a very difficult job of detecting, tracking, and killing the B-2 as explained earlier in the section on conventional defenses.

The shortcomings of this hypothetical air defense system do not necessarily mean that acoustic sensors are useless for air defense. But the problems do illustrate the potential complexities of such a system and raise questions about its overall viability.

The analysis illustrated above has been highly simplified. The real Air Force investigation involved a comprehensive experimental examination of aircraft acoustic signatures, acoustic propagation, and background interference phenomena. Actual field tests were run employing state-of-the-art acoustic detectors, electronics, and advanced signal processing schemes. Engineers and analysts developed a realistic view of available detection ranges for differing aircraft flying various speeds at high and low altitudes.

In a similar fashion, the assessment teams subjected all the other unconventional air defense techniques to intense investigation. Many could be shown to lack any serious merit very quickly; some, like the acoustic approach, required substantial field testing. To date, these investigations have not found an unconventional air defense approach that would provide a robust air defense capability against the B-2. This is not to say that more effective approaches may not be developed in the future. The Air Force

believes that a continuing and vigorous search for unconventional defense ideas (including ideas from the full U.S. scientific community) is needed and the more promising concepts subjected to field experiments to confidently assess their viability.

VII. THE ROLE OF THE U.S. COUNTER-STEALTH PROGRAM

The final measure needed to maintain a credible assessment of stealth air vehicle survivability is a vigorous U.S. program in counter-stealth technology. We cannot expect that the Soviet Union, or other nations, will allow the United States to be the sole practitioner of these technologies. The competition for foreign military sales alone could force major arms-producing nations to aggressively pursue stealth technology. U.S. forces must be prepared to deal with attacks by stealthy anti-ship missiles, cruise missiles, and aircraft. In the future, such sophisticated weapons might even be in the hands of third world nations. These factors provide strong incentives to aggressively pursue vigorous research into the counter-stealth area.

We are currently well situated for such research. The United States has developed an extensive data base of design and performance information on a variety of stealthy air vehicles. Our stealth survivability investigations have sorted through numerous defense schemes to identify the most promising and avoid wasting talent and money on unworkable ideas.

Counter-stealth research also serves well as the audit on B-2 survivability assessments. If the counter-stealth effort quickly recognized and developed a simple but robust defense response to stealth, then the whole B-2 survivability assessment process would be suspect. If, on the other hand, the counter-stealth team has to work hard to develop solutions and employ high-risk, expensive technology and futuristic electronics in their selected approaches, B-2 survivability assessments are valid and reliable. The latter case is the situation today--the counter-stealth program is finding no effective, affordable way to defeat stealth.

VIII. CONCLUSIONS

Survivability has been the cornerstone of the B-2 program since its inception. A continuous activity aimed at understanding and auditing the survivability of stealthy air vehicles against a wide variety of possible current and future air defenses, both conventional and unconventional, has been underway for many years. At this time, the net assessment is that the B-2 is, and will remain, highly survivable. In the more distant future the situation may change, but the United States already has in place the right kind of national activities--namely, strong industrial teams in stealth technology, a vigorous Air Force survivability assessment activity, and a counter-stealth program--to stay ahead of our adversaries in this critical area. Finally, in anticipation of the "action-reaction" cycle, the designed-in growth capabilities of the B-2 will allow it to remain resilient to future technological advances in air defenses.