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[illegible] Design and Technological Uncertainties Create Significant Risk

GAO United States
General Accounting Office
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Information Management and
Technology Division

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February 19, 1992

The Honorable John Conyers, Jr.
Chairman, Legislation and
National Security Subcommittee
Committee on Government Operations
House of Representatives

Dear Mr. Chairman:

This report discusses the impact of including or excluding integration capabilities for space-based interceptors into the missile defense system architecture. The report further discusses the need for solidifying the organization's system architecture and the significant technological challenges that the organization must overcome.

As arranged with your office, unless you publicly announce the contents earlier, we plan no further distribution of this report until 30 days from the date of this letter. We will then send copies to other appropriate congressional committees; the Director, Strategic Defense Initiative Organization; the Director, Office of Management and Budget; the Secretary of Defense; and other interested parties.

This report was prepared under the direction of Samuel W. Bowlin, Director for Defense and Security Information Systems, who may be reached at (202) 336-6240. Other major contributors are listed in appendix III.

Sincerely yours,

Ralph V. Carlone

Ralph V. Carlone
Assistant Comptroller General

Executive Summary

Purpose

In 1983, President Reagan launched a multibillion-dollar program to develop a system for protecting America against ballistic missile attacks. Known as the Strategic Defense Initiative (SDI), the program is now nearing the end of its first decade of research and development. During this time, with billions of dollars having been spent, SDI has undergone repeated changes in its objectives and design. The current SDI system is intended to defend against a limited ballistic missile attack from any country and is estimated to cost $46 billion (in fiscal year 1991 dollars). In response to a request from the Chairman, Legislation and National Security Subcommittee, House Committee on Government Operations, GAO reviewed the status, challenges, and risks associated with the Strategic Defense Initiative Organization's (SDIO) current system and its automated data processing and communications technologies.

Background

SDIO has changed its approach to ballistic missile defense several different times, consuming billions of dollars along the way. Program objectives shifted in 1987 from defending the United States against a massive Soviet attack to the goal of deterring such an attack. In 1990, the introduction of Brilliant Pebbles, a new space-based interceptor that SDIO hoped would increase system survivability and reduce cost, caused SDIO to change direction again. Because of this constant change, GAO concluded in July 1990 that the architecture should be stabilized before proceeding with system development. An architecture defines the system's functions and the relationships among components. It also provides a road map identifying the technologies that will be needed to complete the system.

In January 1991, the program's objectives changed once more as President Bush directed that SDI provide protection from limited ballistic missile attacks originating from any country in the world. This change came about because of a perceived lessening of the Soviet threat and the emergence of tactical ballistic missile threats from Third World countries such as Iraq. To meet program objectives, SDIO is advocating an integrated system that includes both ground- and space-based interceptors. This system is known as GPALS —Global Protection Against Limited Strikes.

GPALS has three segments, two ground- and one space-based. One of the ground-based segments would have sensors and interceptors to protect U.S. military forces overseas, along with friends and allies, from missile attack. Another ground-based segment would protect the United States itself from accidental or limited attacks of up to 200 warheads. The third segment, a space-based defense, would help detect and intercept missiles and warheads launched from anywhere in the world. According to SDIO, all three segments will be integrated to provide mutual, coordinated support. This approach requires that all segments be designed to work together using automated data-processing and communications networks.

The Missile Defense Act of 1991, which establishes a national goal for missile defense, was enacted in December 1991. The act's goal is to deploy a missile defense system to protect the United States, its forward deployed troops, and its friends and allies against limited missile attacks.

Results in Brief

The goal of the Missile Defense Act of 1991 includes the deployment of both national and theater ground-based defenses; the act depicts space-based interceptors as a possible future option. However, the act does not address whether integration capabilities for space-based interceptors should be included in the missile defense system architecture.

SDIO is continuing to design GPALS—whose cornerstone is space-based interceptors. According to the Director of SDIO, integration capabilities for space-based interceptors are being included in the missile defense system. Including or excluding integration capabilities for space-based interceptors in the missile defense system architecture has significant design and cost implications, but to what degree is unknown. If integration capabilities for space-based interceptors are included in the missile defense system architecture but they are never deployed, then unnecessary systemwide costs will be incurred. On the other hand, if integration capabilities for space-based interceptors are not included but are later deemed necessary, costly reengineering will be required.

To proceed with a system that uses both ground- and space-based interceptors, SDIO must overcome tremendous technical challenges. Such a system will push the cutting edge of technology. SDIO must rely on some technologies that are as yet unproven, and learn how to integrate them into a reliable system. Designing, developing, and deploying a system with these uncertainties increases the risk that the system will not provide the level of protection SDIO currently promises.

Principal Findings

Uncertainties Could Adversely Affect System Design and Cost

The Missile Defense Act of 1991 does not address whether integration capabilities for space-based interceptors should be included in the missile defense system architecture. However, the act authorizes $465 million for research and development on space-based interceptors and states that they could support some future system. Defense and the Director of SDIO state that SDIO is continuing to design GPALS; integration capabilities for space-based interceptors are being included in the missile defense system architecture. Further, they state the system will be ready to incorporate space-based interceptors if national decisionmakers decide to include them.

Proceeding with an architecture with or without integration capabilities for space-based interceptors raises two concerns. First, if integration capabilities for space-based interceptors are included in the architecture but they are never deployed, system design and engineering costs may be wasted. Any hardware, software, and communications capabilities included in the other subsystems specifically needed for interacting with space-based interceptors would be superfluous. Second, if such integration capabilities are not included in the missile defense system architecture but space-based interceptors are later deemed desirable, costly redesign or reengineering will be necessary to integrate them into the existing system. For example, ground-based subsystems would not have been designed and developed with the hardware, software, and communications capabilities needed to interact with space-based interceptors. To preclude costly redesign or reengineering and to ensure compatibility, all potential segments, subsystems, and their respective integration capabilities need to be included in the architecture.

Further, SDIO has introduced additional risk into GPALS' design and development. SDIO has distributed integration responsibilities among different contractors without identifying the exact subsystems to be included in GPALS' two ground-based segments. Consequently, the risk is increased that the GPALS subsystems will not be compatible. Without a well-defined architecture describing how and which subsystems will work together, developers may interpret their integration functions incorrectly, which increases the risk of subsystem incompatibility. Indeed, officials at two Defense organizations, including the Army Strategic Defense

Command's Chief of the Battle Management Division, stated that confusion and duplication of effort could already be occurring.

Unprecedented Technical Challenges Increase Risk

If the Congress and SDIO decide to design, develop, and deploy a space- and ground-based system, tremendous technological challenges must be overcome. GPALS stretches the capabilities of today's technology. For the system to succeed, significant advances must be made over the next several years in critical areas, such as software engineering and space-to-space communications. If these advances are not achieved, schedule delays, escalating costs, and performance problems could occur.

The technical complexity of integrating GPALS' segments and subsystems is unprecedented. Its functions will be distributed among hundreds of computers located in space and throughout the world. The system must operate in real time, in a hostile environment, and with a dynamic configuration of sensors, targets, and interceptors. The communications and data processing must be highly reliable and secure. Given the short time to react to an attack—35 minutes for an intercontinental missile and far less for a tactical one—critical data must be received, analyzed, and acted on almost instantaneously. And because processing and communications components could malfunction or be destroyed during battle, the links among subsystems must accommodate change. The critical hardware and software technologies needed to perform these functions are in various stages of maturity; some are already being used while others are still being researched.

Even if the technologies needed become available, SDIO still faces the enormous challenge of integrating them into a cohesive system. This challenge stems not only from inexperience with the individual technologies but also from a lack of knowledge about how these new technologies will interact.

Recommendations to the Secretary of Defense

Because of the design and cost implications of including or excluding integration capabilities for space-based interceptors in the missile defense system, GAO recommends that the Secretary of Defense provide the Congress with an analysis of the design and cost implications of (1) including integration capabilities for space-based interceptors in the architecture but never deploying them and (2) excluding such integration capabilities from the architecture but incorporating space-based interceptors later.

Subsequently, GAO recommends that the Secretary of Defense develop and submit with its next appropriation request an implementation plan that (1) clearly lays out system and integration architectures and (2) describes technology availability schedules, plans for inserting demonstrated technologies, and contingencies when technologies are not available (see ch. 4).

Agency Comments

The Department of Defense generally concurred with GAO's recommendation to the Secretary of Defense concerning the development of an implementation plan and with the report's findings. However, it did not concur with GAO's depiction of the complexity of the GPALS system and the immaturity of some needed critical technologies. Defense did not offer convincing evidence to dispute the facts presented in the draft report. Additionally, in commenting on a draft of this report, Defense and the Director of SDIO state that SDIO is continuing to design GPALS and will include integration capabilities for space-based interceptors in the missile defense system described in the Missile Defense Act of 1991. Because including or excluding such integration capabilities will have a significant impact on system design and cost, GAO redirected the draft report's recommendation from the Congress to the Secretary of Defense. Specifically, GAO now recommends that the Secretary of Defense provide the Congress with an analysis of these cost and design implications. See chapter 4 for a detailed evaluation of Defense's comments.

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Abbreviations

BM/C3	Battle Management/Command, Control, and Communications
GAO	General Accounting Office
GPALS	Global Protection Against Limited Strikes
IMTEC	Information Management and Technology Division
NORAD	North American Aerospace Defense Command
NSA	National Security Agency
SDDS	Strategic Defense Development System
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization

Introduction

Since 1984, the Department of Defense, through its Strategic Defense Initiative Organization (SDIO), has received about $25 billion for research and development of a ballistic missile defense system. During this time the program's objectives and the system being designed and developed have changed several times. Currently, SDIO would like to deploy a system to protect the United States from ballistic missile attacks of up to 200 warheads, and to protect U.S. forces deployed overseas and our friends and allies. The President's fiscal year 1992 budget estimates this system's acquisition cost to be $46 billion in fiscal year 1991 dollars.

SDIO's Ballistic Missile Defense Program

On March 23, 1983, President Reagan called for a comprehensive scientific research effort to develop a system that would render nuclear ballistic missiles impotent and obsolete. In January 1984, Defense established the Strategic Defense Initiative (SDI) as a research and technology development program. SDI's goal was to provide the basis for an informed decision on whether to develop and deploy a defense system to shield the United States against a massive Soviet ballistic missile attack. In April 1984, Defense formally chartered SDIO as the agency responsible for managing the program.

What Is Ballistic Missile Defense?

In 1983, President Reagan directed that an intensive analysis be conducted to identify what new technologies could be used to counter a ballistic missile attack. This analysis became known as the Fletcher study.[1] The study contained three conclusions that affected the design of all ballistic missile defense architectures.

First, it concluded that an effective defense system must be designed to intercept ballistic missiles in any of the three flight phases—boost, midcourse, and terminal. The Fletcher study's second conclusion was that an effective architecture would include both ground- and space-based interceptors and sensors. Third, the study concluded that an effective defense system would have only three basic functions—sensing, interception and destruction, and battle management/command, control, and communications (BM/C3).

The sensing function of a ballistic missile defense system would be conducted by both ground- and space-based sensors, whose purpose would be to determine the characteristics of an attack—that is, to locate the missiles and warheads, discriminate the missiles from the decoys, and

[1]Eliminating the Threat Posed by Nuclear Ballistic Missiles, James C. Fletcher, October 1983.

determine where the missiles are going. Once the sensors collect targeting information, the information can be used by whatever weapons systems are available to intercept and destroy the targets. Finally, the BM/C3 system, with its hardware, software, and communications links, supports information exchange, coordinates actions, and facilitates human command and control. To date, all of SDIO's proposed architectures have been based on the Fletcher study's layered defense concept and have incorporated the three basic functions defined in the study.

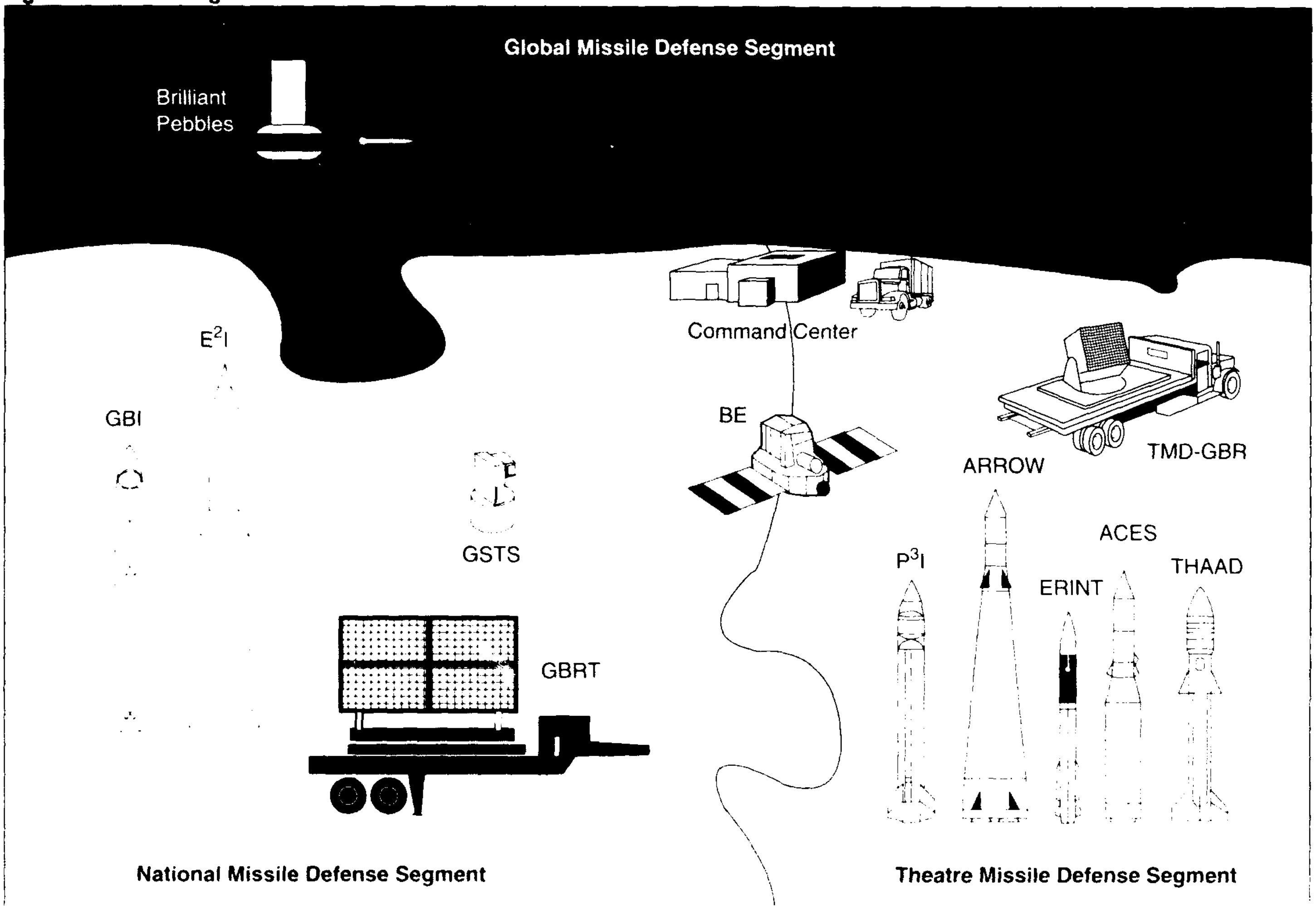
Ballistic Missile Defense Objectives and System Design Have Undergone Significant Change

SDIO has refocused its program several times to accommodate changing program concepts and objectives, emerging technologies, and changes in perceived threat. The initial objective in 1983 was to provide the basis for an informed decision on whether to design, develop, and deploy a system to defeat a massive Soviet attack on the United States. The system was to include space-and ground-based weapons and sensors, including exotic directed energy subsystems such as lasers and particle beams. In 1987 the focus shifted from defeating a Soviet attack to a less ambitious goal of deterrence. SDIO decided to develop and deploy the system in phases. The objective of the first phase (known as Phase I) was to defend against a certain classified percentage of incoming warheads. More exotic weapons and sensors would be developed and deployed in later phases to provide a more complete defense. Then, in January 1990, the inclusion of a new space-based interceptor—Brilliant Pebbles—resulted in major changes that reduced, changed, or eliminated the need for some of the space-based subsystems in the Phase I design. In January 1991, another major change occurred when President Bush directed the program to shift its objective from deterrence to protection from limited ballistic missile strikes originating anywhere in the world. This change came about because of a perceived lessening of the Soviet threat and the emergence of tactical ballistic missile threats from Third World countries such as Iraq.

SDIO's System

In response to the President's direction, SDIO has proposed the development and deployment of a ballistic missile defense system, Global Protection Against Limited Strikes (GPALS), meant to protect against up to 200 warheads of any range originating anywhere in the world. This would include accidental or limited attacks on the United States as well as attacks on U.S. forces, friends, and allies overseas. SDIO calls for GPALS to include three interoperable segments—a theater missile defense segment, a national missile defense segment, and a global missile defense segment. Figure 1.1 depicts the three GPALS segments.

Figure 1.1: Three Segments of GPALS



Legend

ACES	Advanced Component Evaluation System	GBRT	Ground-Based Radar Terminal
BE	Brilliant Eyes	GSTS	Ground Surveillance and Tracking System
E^2I	Endo-Exoatmospheric Interceptor	P^3I	Improved Patriot
ERINT	Extended Range Interceptor Technology	THAAD	Theatre High Altitude Area Defense
GBI	Ground Based Interceptor	TMD-GBR	Theatre Missile Defense Ground-Based Radar

Source SDIO Program Office

GPALS: What Is It?

While the precise makeup of GPALS has not yet been solidified, it currently calls for (1) surveillance satellites and sensors for detecting, discriminating, and tracking missiles and warheads; (2) space- and ground-based interceptors for destroying them; and (3) a sophisticated BM/C3 system for integrating the sensors and interceptors into a working unit. SDIO refers to the separate sensor and interceptor subsystems as elements. See appendix I for a description of candidate elements for GPALS.

The elements of GPALS are to be configured into the three segments. The theater segment is being designed to protect U.S. forces deployed overseas, as well as our friends and allies, against tactical ballistic missile threats such as those experienced in the Persian Gulf. The elements in the theater segment will include transportable ground-based radars and interceptors, and will receive early launch detection and missile tracking information from space-based sensors.

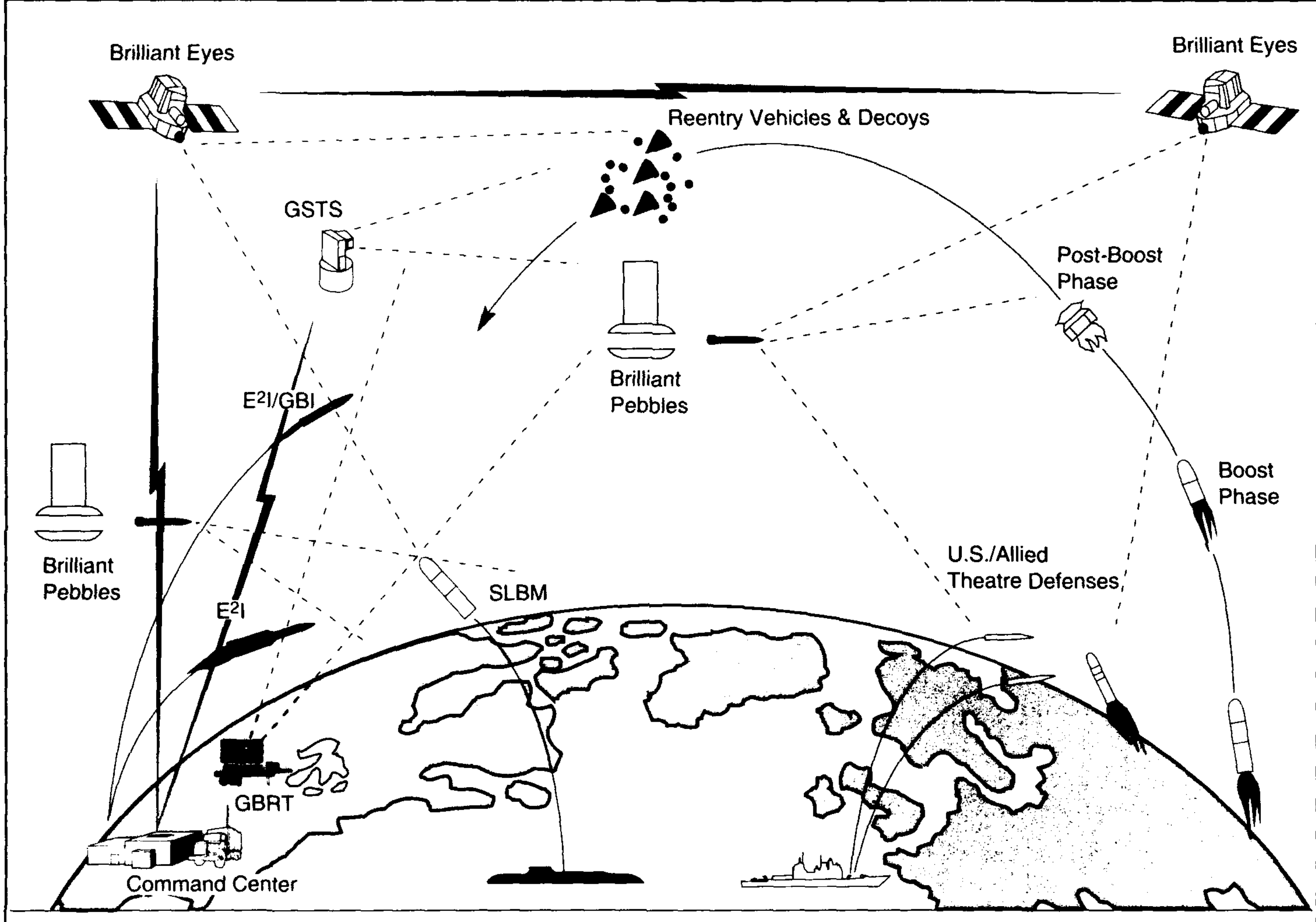
The national segment is to protect the United States against intercontinental ballistic missiles. It will consist of ground-based elements strategically located across the United States. Orbiting surveillance satellites (currently called Brilliant Eyes) are to detect missiles and warheads early in their flight and track them through the midcourse phase. This information will be provided to space- and ground-based interceptors to assist them in acquiring and intercepting their targets.

The global missile defense segment is to provide defense against ballistic missiles of any range launched from anywhere in the world. It will consist of a combination sensor and interceptor element (currently called Brilliant Pebbles), hundreds of which will orbit the earth. The global, space-based segment will augment the other segments by providing detection and interception capability in the boost and midcourse phases of flight, thus providing the layered defense advocated by the Fletcher study. All segments will rely on a distributed command center element that will perform functions, such as communications and data processing, and will direct the use of sensors and interceptors during battle.

GPALS: An Interdependent System-of-Systems

As shown in figure 1.2, GPALS will protect against ballistic missiles launched from anywhere in the world. Accordingly, the diversity of threats, along with the operational environment, creates a unique and demanding challenge. First, the space-based elements will have to almost immediately detect and begin tracking missiles launched from anywhere in the world, and intercept and destroy some of them. Short- and medium-range (including tactical) missiles will have to be intercepted either during the brief time in which they are outside the earth's atmosphere or after reentry. Long-range (intercontinental) missiles that are not destroyed will release warheads, possibly along with decoys intended to confuse the system. At this point, space-based elements will have to detect which targets are warheads and which are decoys, and intercept and destroy more warheads. Space-based elements will continue tracking the surviving missiles and warheads and provide targeting information to the ground-based elements. The ground-based elements then have to detect, track, and intercept all remaining warheads before they hit their targets.

Figure 1.2: Integrated GPALS Defense Scenario



Legend

E^2I	Endo-Exoatmospheric Interceptor
GBI	Ground-Based Interceptor
GBRT	Ground-Based Radar Terminal
GSTS	Ground Surveillance and Tracking System
SLBM	Submarine-Launched Ballistic Missile

Source: SDIO Program Office

To accomplish this feat, all elements must be tightly coordinated, and the processing and transmission of data must occur in real time. GPALS will have less than 35 minutes—the flight time of an intercontinental ballistic missile—to intercept and destroy such missiles and warheads, and even less time for tactical missiles. Further, the system might have to operate amidst nuclear warheads exploding in space and during enemy attempts to disrupt communications and computer operations. The formidable task of integrating and coordinating the diverse GPALS elements falls to one of GPALS' systems—battle management/command, control, and communications (BM/C3).

The Importance and Complexity of Battle Management/ Command, Control, and Communications (BM/C3)

BM/C3 has been characterized as the "long pole in the tent," "the paramount strategic defense problem," and "the pivotal element of the Strategic Defense System."[2] The BM/C3 system will need to coordinate and manage the diverse elements of a ballistic missile defense system by quickly analyzing sensor data and directing interceptors to destroy incoming missiles. The functions needed to do this include (1) automated battle management functions, such as assigning interceptors to targets; (2) human command and control, including automated decision support; and (3) communications among the system's elements. A detailed blueprint of BM/C3 functions, including the required technologies, interfaces, and location of the functions, is referred to as the integration or BM/C3 architecture. This architecture serves as a guide for implementing the BM/C3 system.

BM/C3 Integrates GPALS Into a System-of-Systems

GPALS is a system-of-systems in that the three segments, as well as the elements within the segments, need to work together. Although the segments are to be interdependent, SDIO hopes to increase system survivability by designing GPALS so that each segment can work independently if necessary. SDIO is also attempting to design the elements within segments to be as independent as possible. GPALS' system performance and effectiveness, however, are maximized by sensor and interceptor coordination between, among, and within segments.

Between segments, for example, early warning of launches and accurate tracking data from the space-based segment could enhance the theater segment's effectiveness by facilitating earlier intercepts than would be possible using only theater elements. Within the same segment, communication between ground-based sensors and interceptors is necessary for updating targeting information as the interceptor approaches the target. SDIO's major system acquisition policy for managing the design, development, and deployment of large complex systems

[2]Fletcher Study; Summer Study 1985: A Report to the Director, Strategic Defense Initiative Organization, Eastport Study Group, Dr. Danny Cohen, Study Chairman, December 1985.

endorses identifying the pieces of the system architecture early in the design process. Because of the kinds of interdependencies discussed above, it is very important that all system segments and elements be identified early so that the BM/C3 architecture can be defined.

A well-defined, integrated BM/C3 architecture provides a blueprint for developers by ensuring that interfaces, interdependencies, and common functions are identified and used to design and develop the various parts of the system. Given this blueprint, each developer understands what its role is and how its work fits into the overall system. After the BM/C3 architecture has been solidified, the hardware and software technologies needed for its implementation can be determined, and reasonable implementation plans and schedules can be formulated. For these reasons, if any segment or element is added later, software and hardware must be adjusted or systems replaced to accommodate the change. This rework is known as reengineering and its cost is a function of the significance of the change. On the other hand, if an element or segment is planned for but not deployed, some systemwide design and development cost will be wasted.

National Goal for Ballistic Missile Defense

This past December, the Missile Defense Act of 1991, which for the first time establishes a goal for missile defense, was enacted. The act directs the Secretary of Defense to deploy a missile defense system by the mid-1990s. Specifically, the act states:

(a) MISSILE DEFENSE GOAL.—It is a goal of the United States to—

(1) deploy an anti-ballistic missile system, including one or an adequate additional number of anti-ballistic missile sites and space-based sensors, that is capable of providing a highly effective defense of the United States against limited attacks of ballistic missiles;

(2) maintain strategic stability; and

(3) provide highly effective theater missile defenses (TMDs) to forward-deployed and expeditionary elements of the Armed Forces of the United States and to friends and allies of the United States.

Additionally, the act accelerates the development of both theater and national missile defense systems. However, despite the mid-1990s deployment goal, the Missile Defense Act's conferees agree that there is no commitment to procure national systems or components for deployment before the technology for these systems or components is ready.

Prior GAO Report Highlights Concern Over Unstable Architecture

In July 1990, we reported that SDIO's approach for building a missile defense system, then known as Phase I, was in a state of flux.[3] This was primarily because Brilliant Pebbles, a new space-based interceptor, was added to the system architecture that was intended to increase system survivability and reduce cost. Brilliant Pebbles significantly changed the Phase I design and highlighted the instability of SDIO's approach to missile defense. Instead of a highly integrated, interdependent architecture envisioned for Phase I, Brilliant Pebbles was to provide more autonomy and require less interdependence among the system's other sensors and interceptors.

The inclusion of Brilliant Pebbles rippled across the entire system causing major restructuring of the architecture. Much of the data and analyses conducted on the previous design was no longer relevant. Surveillance, tracking, and communications functions and responsibilities had to be reallocated, and the types and numbers of the space- and ground-based sensors and interceptors changed. For example, by introducing Brilliant Pebbles, two space-based sensors and a space-based weapon have been eliminated.

The importance of a stable architecture cannot be overstated. An architecture that is not well-defined runs the risk that system interdependencies will not be identified, requirements will not be met, and the system will not perform as intended. We cautioned that unless the respective elements are designed, developed, and tested as an integrated system, significant integration problems and costs could emerge.

Objectives, Scope, and Methodology

The Chairman, Legislation and National Security Subcommittee, House Committee on Government Operations, asked that we review SDIO's plans for developing the BM/C3 capabilities needed to integrate and operate GPALS. Specifically, our objectives were to (1) report on the status of SDIO's ballistic missile defense system and BM/C3 architectures and (2) identify the automated data processing and communications technology challenges and risks for designing and developing GPALS' BM/C3 capabilities.

At the time of our review, the program was undergoing significant change as SDIO's ballistic missile defense objectives moved from deterring a massive Soviet attack to protecting against a limited attack from anywhere in the world. SDIO is currently in the process of defining its GPALS and BM/C3

[3] Strategic Defense System: Stable Design and Adequate Testing Must Precede Decision to Deploy (GAO/IMTEC-90-61, July 6, 1990).

architectures. We conducted our review under the assumption that GPALS, or some similar variation, would be SDIO's ballistic missile defense system.

We reviewed and analyzed criteria on the importance of a well-defined BM/C3 architecture, identified and determined the status of selected BM/C3 technologies, and interviewed a wide range of officials involved in the SDI program. To understand the importance of BM/C3, we analyzed cornerstone reports such as the Fletcher study. We interviewed and obtained documentation from ballistic missile defense experts, including officials from the Defense Advanced Research Projects Agency, the Army's Strategic Defense Command, and the Air Force's Electronic Systems Division.

To identify and determine the status of the automated data processing and communications technologies needed for GPALS, we reviewed SDIO's Program Management Agreements, which specify who is to perform what work on the BM/C3 technologies. Because of the large number of technologies needed to implement the BM/C3 for GPALS, we decided to focus primarily on selected software issues and on parallel computing. SDIO has identified six engineering areas: algorithms, software engineering, networking, communications, security, and processors. Software applies to all engineering areas and must have unprecedented characteristics. These include trust[4] and parallelism.[5] To quantify the relative maturities of trust and parallel processing, we developed a technology matrix. We asked experts from the Defense Advanced Research Projects Agency, the National Security Agency, the Army Strategic Defense Command, and the National Institute of Standards and Technology to complete the matrix, applying the National Aeronautics and Space Administration's Maturity Index, and interviewed these officials to ensure our understanding of their responses.

Further, we reviewed and analyzed key documentation on trusted systems, parallel processing, and software engineering. These included the National Security Agency's Rainbow Series on trusted computing bases, the Institute for Defense Analyses' report on software research and development for SDI, Defense's 1991 Critical Technologies Plan, and the

[4]As presented in Defense's standard Department of DefenseTrusted Computer System Evaluation Criteria, trust technology is the systematic application of computer science and engineering to the protection of information in automated systems.

[5]Parallel computing involves two or more processors working together to solve a problem; serial computing uses a single processor to solve a problem. Software for parallel processing has different characteristics from software for serial processors.

Software Engineering Institute's Maturity Assessment Model for software development.

We interviewed officials involved in the Strategic Defense Initiative program, including (1) the system architect, (2) project integrators and engineers, (3) system integration and command and control officials, and (4) architecture integration study officials. We also met with Army and Air Force officials involved in ballistic missile defense research and development programs. Additionally, in concert with our Office of General Counsel, we obtained and analyzed relevant documentation on the Missile Defense Act of 1991.

Our work was conducted from September 1990 through February 1992 at SDIO Headquarters, Washington D.C.; Electronic Systems Division, Boston, Massachusetts; and the Army Strategic Defense Command, Huntsville, Alabama. We conducted our review in accordance with generally accepted government auditing standards.

Uncertainties Continue to Surround Missile Defense System Architecture

Eight years and $25 billion into the SDI program, the Missile Defense Act of 1991 establishes the goal of deploying a highly effective missile defense system. The goal of the act includes the deployment of both national and theater ground-based defenses; space-based interceptors are characterized as a potential future option. However, the act does not address whether integration (BM/C3) capabilities for space-based interceptors should be included in the missile defense architecture.

For the past year, SDIO has been pressing forward with a $46 billion system— GPALS—to address the change in program focus from deterrence to protection. However, the GPALS architecture has not been solidified. Without a stable system and BM/C3 architecture that describes the segments and elements and how they will work together, the risk increases that the system will not work as intended. Every time the system architecture is changed, BM/C3 is significantly affected.

Including or Excluding Space-Based Interceptors Has Significant Design and Cost Implications

Significant design and cost implications could emerge if integration capabilities for space-based interceptors are included or excluded in the missile defense system described in the Missile Defense Act of 1991. The goal of the act includes deploying highly effective missile defense systems to defend the United States, U.S. forces deployed overseas, and our friends and allies from limited missile attacks. The act characterizes space-based interceptors as a promising technology and authorizes $465 million for their continued research and development in fiscal year 1992. Further, the act states that space-based interceptors could be a future option to support ground-based defenses. However, the act does not address whether integration capabilities for space-based interceptors should be included in the missile defense system described in the act.

SDIO is continuing to design GPALS—whose cornerstone is space-based interceptors. According to its director, SDIO is including integration capabilities in its missile defense system, and the system will be ready to support all segments whenever they are incorporated into the architecture. Including or excluding integration capabilities in the missile defense architecture for meeting the goal of the act raises two concerns from a system-of-systems perspective.

First, if integration capabilities for space-based interceptors are included in the missile defense architecture but they are never deployed, then design and development costs for including space-based interceptors will have been wasted. Any hardware, software, and communications capabilities included in the system's other elements which would facilitate integration specifically with Brilliant Pebbles would be superfluous. For example, the space-based sensors' battle management, command and control, and communications software would have been written to provide launch and targeting information to Brilliant Pebbles. Additionally, the space-based sensors' hardware, (e.g., computers and antennae) would have been designed to support the additional requirements placed on them by Brilliant Pebbles.

Second, if integration capabilities for space-based interceptors are not included in the elements of the missile defense system architecture, and an exclusively ground-based missile defense system is deployed, but the space-based interceptors are later deemed desirable, then costly redesign or reengineering will be required.

Under this second scenario, the national and theater segments would have been designed, engineered, and deployed without the hardware, software, and communications capabilities needed to integrate specifically with Brilliant Pebbles. For example, space-based sensors, costing billions of dollars, would have been built to process and send sensing, tracking, and targeting information to ground-based interceptors only. Likewise, the ground-based interceptors would have computers and communications links designed and built to receive and handle information from the space-based sensors included in the architecture—not from Brilliant Pebbles or some other space-based interceptor. Consequently, the ground-based system's hardware and software would have to be redesigned or reengineered to handle increased processing and communications requirements.

Changes in Architecture Significantly Hinder BM/C3 Development

In January 1991, when the President changed the focus from deterrence to protection, SDIO was faced with the enormous task of reassessing its system and BM/C3 architectures. As a result, in February 1991, SDIO initiated a multi-million dollar architecture integration study to address program changes and to guide GPALS and BM/C3 design and development. According to the statement of work, the objective of the study is to define a system architecture for GPALS that could evolve from an initial theater missile defense system to a full GPALS system, and possibly beyond to a system capable of thwarting a massive attack. The study is to look at the time phasing of GPALS, taking into consideration the availability of technology and affordability. It is also to completely describe the BM/C3 system; analyze trade-offs among the system's elements in terms of performance, cost, schedule, and risk; and describe how GPALS and its elements will function. Additionally, the study is to provide enough detail to guide element design, prioritize the technologies needed to field the system, and determine when the technologies are needed.

The study has not been completed. According to the study director, the study group is still considering many different sensor and interceptor combinations for GPALS; exactly which elements will comprise GPALS has not been decided. Until SDIO at least identifies the pieces of GPALS and their functions with some degree of certainty, it is unclear how a BM/C3 architecture can be defined, thus making it impossible to provide the BM/C3 developers the guidance they need.

Even though the system and BM/C3 architectures have not been solidified, SDIO has distributed BM/C3 research and development. However, without a clear understanding of BM/C3 responsibilities, the risk increases that BM/C3 development may not be relevant, or elements will be incompatible and thus unable to operate as a single working unit. Officials at two Defense organizations, the Army Strategic Defense Command and the Air Force Electronic Systems Division, have expressed concern over the extensive distribution of BM/C3 research and development without a well-defined architecture.

Army Strategic Defense Command officials, including the Chief of the Battle Management Division, believe that the large number of BM/C3 developers will ultimately result in greater cost and complexity, duplication of effort, increased schedule risk, interface problems, and poor performance. Furthermore, they contend that numerous developers and decentralized BM/C3 development responsibilities increase the complexity of the program and its management. These Army officials conclude that the least understood and potentially most difficult piece of a ballistic missile defense system —BM/C3 design and development—is being fragmented and complicated. They strongly recommend a single BM/C3 architecture and one technical authority that has responsibility for integration. Air Force officials at the Electronic Systems Division share these concerns.

Several examples show how an unstable architecture is causing confusion and duplication of effort. Air Force officials responsible for the Command Center element stated that they have no idea what technologies will be required because SDIO has not defined the BM/C3 architecture. Air Force officials had developed a series of tests for analyzing ballistic missile attack response options and question why SDIO's integration contractor has similar tests. Further, according to Army officials, including the Technologies Section Chief, Battle Mangement Division, SDIO has not funded fault-tolerance technology research for the Strategic Defense Command because fault tolerance was being researched under SDIO's trusted software effort. However, the National Security Agency (NSA) official responsible for SDIO's trusted software activity sees fault tolerance as a hardware issue, and did not consider fault tolerance in his definition of trust. These same Army officials asked a contractor to conduct a BM/C3 function analysis because SDIO's integration contractor had not completed the same type of analysis. However, the Architecture Integration Study statement of work indicates that study contractors are also performing this analysis.

Resolving BM/C3 Technology Challenges Is Essential to Successful GPALS Development

If a decision is made to design, develop, and deploy a global, multi-segment system such as GPALS, significant technological challenges must first be overcome. SDIO believes these technology challenges are not insurmountable and, therefore, would like to continue to design and develop GPALS. However, counting on technologies that are currently not proven or available can result in schedule delays, increased cost, or poor system performance.

BM/C3 System Is Extraordinarily Complex

GPALS' BM/C3 system will be one of unprecedented complexity. Although SDIO will try to make the elements and segments as independent as possible, the BM/C3 functions must be distributed among hundreds of computers located in space and throughout the world. Some will probably require advanced parallel processing designs. To solve complex problems, some processors may require information from multiple data bases. This introduces the need for distributed data base management. The computers and their associated data bases will be linked by a complex communications network consisting of telephone lines, satellite links, fiber optics, and microwave media. Algorithms (detailed descriptions of solutions to problems) will be needed to perform GPALS' automated functions, including sensor and interceptor operations, communications network management, and battle management.

Other complicating factors include real-time operation in a hostile environment and a dynamic system configuration. The flight of an intercontinental ballistic missile would last only about 35 minutes, and the flight of a tactical ballistic missile only several minutes. During this time, the BM/C3 system will have to direct and coordinate the detection, tracking, interception, and destruction of up to 200 warheads with sufficient accuracy to preclude any of them from reaching their targets. Additionally, critical information will have to be processed and shared among many—possibly hundreds—of different computers operating in a changing configuration. The system configuration will be changing because system elements, such as satellites and interceptors, will be in constant motion. Those destroyed in battle or failing to function as intended will necessitate a reconfiguration of the communications network.

In response to the challenges discussed above, SDIO has identified critical advances in software and hardware technology required to implement a BM/C3 system. Some of the more challenging technology requirements are the capability to build trusted software, software for parallel processors, tools and techniques for effective software engineering, space-to-space communications, and parallel processing for ballistic missile defense. These technologies are all being researched; none is sufficiently mature to support GPALS' BM/C3 system.

Successful BM/C3 Development Requires Significant Software Advances

The BM/C3 software for GPALS will be the most complex and difficult of any military or civilian software developed and implemented to date. Much of the critical BM/C3 software will require a level of trust never before achieved. It may have to operate on parallel processors, and it will require a highly sophisticated software engineering and development environment that is not currently available. Compounding these challenges is that the state-of-the-practice for any technology, including those for software, generally lags well behind the technology's state-of-the-art. In other words, researchers may understand the underlying principles for a technology; however, it will be some time before the technology is proven well enough to be commercially available.

Trust for GPALS Software Currently Undefined

According to senior SDIO officials, to help minimize BM/C3 development risk, software must be trusted when necessary. However, trust technologies are the most immature of all the technologies needed for GPALS' BM/C3. The traditional definition of trust involves information security. According to officials at the National Security Agency (NSA), Defense's executive agent for developing information security standards, trust includes data confidentiality, integrity, and availability. Data confidentiality means that only authorized access to data will be possible; integrity means that information is protected from unauthorized modification or destruction; and availability means that system access for authorized users is ensured, i.e., that the system cannot be rendered ineffective by malicious attacks. These three components all deal with thwarting unauthorized and malicious attempts to access or destroy the information. Confidentiality in an information system is the best understood of the three, but is not yet a solved problem. Technologies to ensure integrity and availability are just now emerging.

Yet BM/C3 software for GPALS requires more. In addition to the traditional definitions of confidentiality and integrity, BM/C3 software must be highly reliable or correct. This means that the software will do only what it is supposed to do and nothing else. The implications for human safety, national defense, and international relations are too significant to risk incorrect software. Further, BM/C3 software must support system availability, e.g., be fault-tolerant. A fault-tolerant system provides continuing processing capability in the event of software or hardware failure or degradation. Engineering tools and approaches for ensuring confidentiality, integrity, availability, and correctness in large complex software are in various stages of development.

NSA is managing the Trusted Software Program, which SDIO has established to address trust for GPALS' software. NSA officials are defining what trust means to SDI, developing criteria for evaluating trust in BM/C3 components (such as data bases, networks, and system and application software), and identifying the technologies needed to implement trust. Consequently, the policies, guidance, and understanding of the implications of building and fielding trusted software for GPALS are only recently becoming known. Further, some trust technologies needed to implement GPALS are either in their infancy, or have yet to be proven in an operational environment.

For example, a trusted distributed operating system for scheduling parallel and distributed processing is currently being researched. However, according to its developer, it will be at least 2 to 3 years before it is commercially available and accepted by NSA. It is also unclear whether the operating system will be able to handle real-time processing. Trust in data base management systems is also extremely important. Without correct and available data, operational errors could occur and the system could experience catastrophic failure. However, SDIO and NSA have only just begun to address the question of what is required for GPALS' trusted data base management systems. Finally, some of the technologies for trusted applications software are in their infancy. For example, mathematical models for formally verifying the integrity of applications software are just emerging. Without trust and the models to verify the correctness of software, there are no assurances that the system will do only what it is supposed to do, and be protected from unauthorized access.

Tools for and Experience in Parallel Processing Are Limited

Although SDIO officials differ on whether GPALS will require parallel processors (yet another indication of the immaturity of this program), many experts believe that GPALS cannot achieve the performance required, at a manageable cost and with room for growth, without using parallel processors for some BM/C3 functions. To effectively use parallel processing, compatible computer languages, compilers, and operating systems must be used. However, some of the required parallel technologies are either still in research or in limited use in environments that are much simpler than that in which GPALS must operate.

SDIO has been researching how existing battle management, message routing, and other algorithms specifically written for serial machines can be reused in a parallel processing environment. However, SDIO researchers have found it extremely difficult to translate structured, sequential serial code into parallel code that can perform the task or tasks on a number of processors. If serial code cannot be reused, new parallel code must be created. This will present SDIO with a major challenge. First, there are few engineers with experience developing parallel code, none of it as complex as BM/C3 software. An entire generation of software engineers has been designing, developing, testing, and maintaining serial-based software, again none of it as complex as that required for GPALS, and have found the transition to a parallel environment very difficult. Second, computer-aided software engineering tools (programs that assist engineers in software requirements-setting, design, development, and testing) for parallel processing are just emerging.

BM/C3 Software Dependent on Immature Software Engineering Environment

Software engineering could be the most challenging and critical BM/C3 technology issue. According to the Software Engineering Institute,[1] "the quality of a software system is governed by the quality of the process used to develop and evolve it." In 1989 the Institute, using a maturity assessment model it developed, reported that 86 percent of Defense software developers it assessed were at the initial, or "ad hoc and chaotic," level in terms of process maturity. Specifically, most of the developers did not have a standard software development process.

The production and integration of a large amount of high-quality, reliable software is critical to the success of the GPALS mission. The BM/C3 software will consist of millions of lines of code developed by scores of contractors. Further, the software must include trusted characteristics that have never been accomplished before and, most likely, will have to be developed for parallel processors. For these reasons a comprehensive, software engineering environment is imperative to ensure the efficient development, production, integration, and validation of trusted GPALS software. To address this challenge, SDIO has tasked the Institute for Defense Analyses[2] to help apply the Software Engineering Institute's maturity model to all software developers and is developing a software

[1]The Software Engineering Institute at Pittsburgh's Carnegie-Mellon University is a federally funded research and development center sponsored by Defense to provide leadership in advancing the state of the practice of software engineering to improve the quality of systems that depend on software.

[2]The Institute for Defense Analyses is a federally funded research and development center that provides technical evaluations, analyses, and support to U.S. government agencies.

engineering environment called the Strategic Defense Development System (SDDS).

According to SDIO officials, SDDS is to provide a comprehensive software engineering environment. SDDS is supposed to be available by the mid-1990s to support GPALS' software development. It will provide SDIO contractors with a common software engineering environment for developing, testing, and integrating software code. While contractors will be encouraged to use SDDS, they will be allowed to use whatever specific tools they choose. SDDS is also to be used for the larger task of integrating all the software developed by the various contractors. SDDS is to provide a central data base for storing developed software, to ensure consistency and completeness in the requirements-setting process, and to assist in implementing trusted software characteristics. SDIO plans to have a first version of SDDS available for release early in 1993; however, according to the program manager for software engineering, it will only have rudimentary capabilities. Further, SDDS may have to use a highly sophisticated data base that is still being researched.

Critical BM/C3 Hardware Still a Challenge

Generally speaking, hardware technologies appear to be advancing fairly rapidly. Most challenges involve using the technology, rather than understanding the underlying principles of it. Two examples are (1) space-to-space communications and (2) parallel processors for ballistic missile defense.

The communications links needed among the space-based elements of a ballistic missile defense system have always presented a formidable challenge to Defense. SDIO is currently assessing whether GPALS will require extremely high radio frequency communications, laser communications, or both, to meet space-to-space communications needs. While extremely high radio frequencies and laser communications for space-to-space cross-links are still not available, the basic technologies are proven. The difficulty is not so much in understanding the basic technological principles as in implementing them in space on board small, lightweight satellites. For such space applications, some of the engineering challenges include developing reliable, lightweight components[3] with low power requirements, and ensuring that satellites can accurately exchange necessary information among other continually moving satellites.

[3]Components are all of the parts that make up the satellites including processors, power sources, antennae, propulsion systems, etc.

Parallel processing hardware has been available for years; however, the tools and experience for developing complex parallel software have lagged behind. Parallel processing can help meet Defense's real-time processing requirements by using several interconnected processors to work on a task, or many tasks, simultaneously. Parallel processors are highly desirable because of their capability to handle enormous amounts of data simultaneously, their capability for increased capacity, their decreasing costs, and because of the projected physical limitations of serial processors. For these reasons, differing and competing design philosophies have recently emerged, and many different models and types are now commercially available. However, implementing parallel processors on board small, lightweight spacecraft will be difficult because of size, weight, and power constraints. SDIO has conducted and plans to continue conducting tests intended to demonstrate this capability.

Integration of Immature Technologies Required for BM/C3 Greatly Exacerbates Existing Complexities

Individual technologies alone cannot support GPALS BM/C3. If and when each technology is proven, SDIO will be faced with the enormous challenge of integrating them to provide the data processing and communications capabilities needed. For simpler systems such as the North American Aerospace Defense Command's (NORAD) Tactical Warning and Attack Assessment System at Cheyenne Mountain, Colorado, integrating subsystems is a technically demanding endeavor.[4] In the case of BM/C3, the difficulty lies not only in the integration task itself, but also in the lack of experience with individual technologies, compounded by a lack of knowledge of the interactions among them. For example, there is no real understanding of what it means to build software that is simultaneously trusted, correct, and fault-tolerant; trusted components for real-time parallel processors are an object of ongoing research; technologies for formally verifying large-scale serial software are still unsophisticated despite years of research; and technologies for formally verifying parallel software are only now being addressed.

Besides the complexity of the interactions among the various technologies, trade-offs must also be made. For example, building trusted systems may mean sacrificing system performance. This degradation in performance results from the checks the system must perform before allowing access to the processor, data base, or network. SDIO and NSA are determining what effect implementing undefined trusted concepts could have on system performance.

[4]Attack Warning: Better Management Required to Resolve NORAD Integration Deficiencies (GAO/IMTEC-89-26, July 7, 1989).

Correct Selection of BM/C3 Technologies Is Critical

Prematurely committing to inadequate existing technologies, or depending on the future success of immature or unavailable technologies, increases the risk that GPALS will not work as intended, or will not be able to easily evolve. For example, if SDIO decides to use only serial processors in its BM/C3 architecture, but additional requirements are levied on GPALS that necessitate high performance parallel processing, potentially millions of lines of computer code would have to be reengineered. Reengineering this code from serial to parallel applications would be difficult and costly. Equally dangerous is counting on technologies that may not be available, may not perform as required, or may not be sufficiently reliable.

A technology road map that defines what technologies are needed and when, and what the interdependencies are, is essential. Also important are plans for transitioning from existing to emerging technologies, plans for inserting technologies as they become available, and plans for contingencies if a technology is not ready when needed.

Conclusions and Recommendations

The Missile Defense Act of 1991 establishes for the first time a national goal of deploying highly effective missile defenses in the mid-1990s. The act is the culmination of years of debate and the billions of dollars spent on various ballistic missile defense system proposals. Approximately one year prior to the act, SDIO proposed its GPALS approach to missile defense and is currently proceeding with its design and development.

Each segment of GPALS, in and of itself, is highly complex; integrating these segments would be one of the most technologically complex undertakings the nation has ever faced. A decision to include or exclude the integration capabilities for space-based interceptors in the system architecture will have significant design and cost implications, although the extent is not known. Identifying which sensors and interceptors will be integrated is very important so that interactions, such as what data needs to be shared among them, can be planned and included in the subsystem designs. Without a stable system and BM/C3 architecture that describes the subsystems and how they will work together, the risk increases that the system will not work. Furthermore, major shifts in the architecture (such as including or excluding integration capabilities for space-based interceptors at a later date) can be costly, time-consuming, and disruptive. This was demonstrated last year as SDIO changed its program focus from deterrence to protection, requiring a year-long, multi-million dollar study to develop new system and BM/C3 architectures.

BM/C3 is the most important and least understood of any of the basic ballistic missile defense functions (sensing, interception and destruction, and BM/C3). BM/C3 would be required for GPALS, or any missile defense system, to perform as a tightly coordinated unit—without it, sensors and interceptors would be useless. The BM/C3 architecture describes how this coordination would occur, and serves as a guide, or blueprint, for developing the BM/C3 system. Because SDIO has not solidified its architectures and also distributed BM/C3 responsibilities among developers, the risk increases that system elements will be incompatible.

Distributing BM/C3 responsibilities among developers is not, in and of itself, a high-risk approach to BM/C3 development. However, the larger and more distributed the effort, the more important well-defined system and BM/C3 architectures become. Otherwise, there is a potential for wasted efforts and integration problems. Equally important, without a stable system and BM/C3 architecture, it is impossible for SDIO to know precisely which supporting technologies will be required.

Further, a space- and ground-based system such as GPALS faces enormous technical challenges. Critical yet immature BM/C3 software and hardware technologies must be available to successfully develop and integrate such a missile defense system. To mitigate the risk of committing to the development of the system before these technologies are sufficiently mature, SDIO must have a comprehensive understanding of the status and interdependencies among all technologies and precisely what role each plays along the critical path of development.

Recommendations to the Secretary of Defense

Because of the design and cost implications of including or excluding integration capabilities for space-based interceptors in the missile defense system, we recommend that the Secretary of Defense provide the Congress with an analysis of the design and cost implications of (1) including integration capabilities for space-based interceptors in the architecture but never deploying them and (2) excluding such integration capabilities from the architecture but incorporating space-based interceptors later.

Subsequently, we recommend that the Secretary of Defense develop an implementation plan for missile defenses. The details of this plan should be provided with Defense's next appropriation request for missile defenses and include, but not be limited to,

- a stable, well-defined missile defense system architecture;
- a well-defined, integrated BM/C3 architecture sufficient in detail to provide the guidance and direction needed by developers to carry out their BM/C3 responsibilities; and
- a comprehensive BM/C3 technology plan describing reasonable technology availability schedules, plans for insertion of improved or advanced technologies as they become available, and contingency plans for dealing with situations when technologies are not available, including the ramifications of such contingencies on system performance.

Agency Comments and Our Evaluation

The Department of Defense generally concurred with our recommendation to the Secretary of Defense concerning the development of an implementation plan and with the report's findings. However, it did not concur with our depiction of the complexity of the GPALS system and the immaturity of some needed critical technologies. Defense did not offer convincing evidence to dispute the facts presented in the draft report.

Additionally, in commenting on a draft of this report, Defense and the Director of SDIO state that SDIO is continuing to design GPALS and will include integration capabilities for space-based interceptors in the missile defense system described in the Missile Defense Act of 1991. Because including or excluding such integration capabilities will have a significant impact on system design and cost, we redirected the draft report's recommendation from the Congress to the Secretary of Defense. Specifically, we recommend that the Secretary of Defense provide the Congress with an analysis of these cost and design implications.

Evolution of the Strategic Defense Initiative Program

Defense states that the SDI program objective has remained fairly constant, that is to "direct a research program that will provide the basis of an informed decision regarding the feasibility of eliminating the threat posed by ballistic missiles...." While this broader objective may not have changed, more specific objectives, including system concepts, designs, and missions have undergone major change. For example, the original concept of defending against a massive Soviet ballistic missile attack was changed to deterring such an attack, and now to protecting against limited attacks originating anywhere in the world.

In 1983 the Strategic Defense Initiative began as a research program but transitioned into Defense's formal acquisition process in 1987. This transition required SDIO to develop a system architecture. Since then, SDIO's program and system architecture have been in a state of flux. The 1987 architecture has undergone major revisions because of changing concepts, designs, technologies, and mission objectives. For example, the introduction of Brilliant Pebbles in late 1989 precipitated change requiring SDIO to spend more than a year revising the system architecture. Before the changes resulting from Brilliant Pebbles were completed, President Bush refocused the program from a deterrence to a protection mission, requiring more time to reassess and redesign the system architecture. To accomplish this, a study was initiated in February 1991, and SDIO has yet to complete this effort. If SDI had remained a research program and had not entered the formal acquisition process, the impacts of changing concepts, designs, technologies, and objectives would have been far less disruptive and costly.

BM/C3 Development

According to SDIO, BM/C3 development is being suitably addressed. Nevertheless, the lack of a stable architecture causes confusion. While SDIO has been reviewing the system and BM/C3 architectures, developers have continued to work on their components, including the BM/C3 requirements. As we reported, officials at two Defense organizations expressed concern over proceeding with their BM/C3 efforts without a well-defined architecture.

While SDIO states that a single system engineer and integration contractor has been assigned BM/C3 system-level responsibilities, this alone does not mitigate the risk. Until the architecture is solidified, the system engineer and integration contractor will not be able to provide the system-level guidance necessary to avoid the potential problems cited by Army and Air Force officials.

Technology Challenges

Defense disagrees with our depiction of the complexity of GPALS' BM/C3 subsystem and the statement that significant technological challenges must be resolved to successfully develop GPALS. However, Defense did not provide convincing evidence to dispute the facts presented in the draft report. According to Defense, it is working to minimize the complexity of the BM/C3 subsystem for GPALS. For example, Defense states that the BM/C3 subsystem is being designed so that only modest amounts of data will be transferred among subsystems. Defense also states that no shared data processing or distributed data base concepts will be involved or required. Whether or not such distributed processing concepts are used, the BM/C3 subsystem will still be of unprecedented complexity. GPALS may be more autonomous and may have to contend with fewer numbers of warheads than previous system designs, but BM/C3 will have to coordinate—in real time—diverse subsystems widely distributed on the ground and in space. Experts in the field said that there are major challenges in the area of real-time distributed processing. In fact, the official from the National Security Agency who completed our technology maturity matrix stated that many of the parameters of real-time distributed processing are poorly understood, at best.

Defense states that there is little basis for asserting that software safety, correctness, and fault tolerance are more demanding for GPALS than for nuclear reactors, medical systems, or aircraft flight control systems. Further, Defense noted that large software systems can and do operate reliably with minor errors or weaknesses. But GPALS cannot be compared to existing systems. The consequences of an operational software failure with GPALS could be catastrophic. The Patriot missile defense system—whose supporting software is much smaller and far less complex—failed to engage an incoming missile during the Persian Gulf resulting in the deaths of 28 Americans. If GPALS fails to engage, millions of people could be killed.

GPALS will involve an interconnection of sensors, weapons, communications, and decision-making subsystems. Software must meet highly stringent requirements for security and safety and must operate in a hostile environment. These critical requirements must be supported by processes and technology that can provide high levels of assurance of correct behavior. The need for such software processes and technologies, coupled with the characteristics of the GPALS architecture, make BM/C3 software for GPALS a formidable challenge.

Defense also states that it has many trusted and secure computing and command systems that GPALS can use. We did not assert otherwise. However, according to Defense documentation and statements of Defense officials, GPALS' BM/C3 software requires a level of trust not yet achieved. We collected and analyzed data from officials from the Army's Strategic Defense Command, the Defense Advanced Research Agency, the National Security Agency, and the National Institute of Standards and Technology that all corroborated our findings. Defense itself has initiated a Trusted Software Program to address critical trust issues for GPALS.

Technology Integration

Defense states that a transition plan and technology road map will be used and that technologies are sufficiently mature to begin developing GPALS BM/C3. By recommending that the Secretary of Defense develop a transition plan and technology road map, we are not implying that SDIO was not intending to develop them. Further, as our evidence indicates, some of the required technologies are immature, which introduces risk; integrating such technologies into a coherent system compounds this risk. Our concern is that the complexity, cost, and technological risks associated with this system are unprecedented; hence, we believe comprehensive plans need to be developed as soon as possible to identify, control, and mitigate these risks.

Candidate Elements for GPALS

Arrow and ACES: A theater ballistic missile defense interceptor concept being jointly developed with the Israeli government. ACES is a follow-on to the Arrow, with a defense range significantly greater than the Patriot.

Brilliant Eyes (BE): Space-based satellite sensors for surveillance, tracking, and discrimination during late boost and midcourse phases. Brilliant Eyes is intended to support space-and ground-based interceptors.

Brilliant Pebbles (BP): A distributed, autonomous, space-based interceptor and sensor system. It is being designed to collide with and destroy enemy missiles during the early phases of the missiles' flight. Brilliant Pebbles is intended to intercept any ballistic missile above the earth's atmosphere with a range in excess of several hundred miles.

Command Center Element (CCE): A distributed system of facilities, equipment, communications, personnel, and procedures that supports decision making, battle planning, and execution of the missile defense mission.

Endo-Exoatmospheric Interceptor (E2I): A U.S. ground-based interceptor that uses the atmosphere for discrimination of warheads from decoys; E2I can also intercept in late midcourse (i.e., can intercept both inside and outside the atmosphere).

Extended Range Interceptor (ERINT): A theater missile defense interceptor that works with the Patriot launch system, providing greater firepower and destroying targets in the low atmosphere by colliding with them.

Ground-based Interceptor (GBI): A U.S. ground-based interceptor designed to engage warheads outside the atmosphere (exoatmosphere) during midcourse.

Ground-based Radar-Terminal (GBR-T): A U.S. ground-based sensor that provides search, tracking, and discrimination capabilities for U.S. ground-based interceptors. TMD-GBR is the theater version of this radar capability and will support theater ground-based interceptors.

Ground Surveillance and Tracking System (GSTS): A U.S. ground-launched suborbital rocket surveillance system that uses sensors to perform tracking and discrimination of midcourse objects.

Patriot Preplanned Product Improvement (P3I): An enhancement to the Patriot missile defense system. The Patriot's velocity will be increased; the system will also be supported by a more sophisticated fire control radar.

Theater High-Altitude Area Defense (THAAD): A theater ground-based interceptor that is to destroy theater/tactical ballistic missiles at high altitudes. THAAD is to provide a large area defense capability and support other interceptors such as Patriot and ERINT.

Comments From the Department of Defense

DEPARTMENT OF DEFENSE
STRATEGIC DEFENSE INITIATIVE ORGANIZATION
WASHINGTON, DC 20301-7100

January 17, 1992

Mr. Ralph V. Carlone
Assistant Comptroller General
Information Management and
Technology Division
U.S. General Accounting Office
Washington, D.C. 20548

Dear Mr. Carlone:

This is the Department of Defense (DoD) response to the General Accounting Office (GAO) draft report, entitled "STRATEGIC DEFENSE INITIATIVE: Changing Design and Technological Uncertainties Create Significant Risk," dated December 1991 (GAO code 510620), OSD Case 8889. The Department partially concurs with the draft report.

The original mission and program objective of the Strategic Defense Initiative Organization has not changed since its inception. It is defined in the DoD Directive as "...direct a research program that will provide the basis of an informed decision regarding the feasibility of eliminating the threat posed by ballistic missiles...." As early as 1984, DoD direction was, "The program shall protect U.S. options for near-term deployment of limited ballistic missile defenses." In 1991, in light of the emerging post Cold War world, the program was refocused to a Global Protection Against Limited Strikes. Changes to the overall architecture over the past years have been in response to changes in projected threats and improving technology. The changes have resulted in an improved, more affordable, and responsive Strategic Defense System architecture and program.

The acquisition strategy of the Strategic Defense Initiative has been to develop ballistic missile defense technology as it matures and, as it is proven, to move to deploy it in an evolutionary manner. Since the initiative has been largely a research program, many different technologies, many different architectures, and many different program responses to changes in threats and national needs have been investigated.

The development, testing, and deployment strategy for a Global Protection Against Limited Strikes follows an evolutionary and integrated approach. It is evolutionary, because it initially develops a system that relies on proven technology and research (the initial National Missile Defense) and builds upon it. It is integrated, because from the onset, the DoD has been planning for an architecture that will maximize a Global Protection Against Limited Strike capability, particularly from the Battle Management/Command, Control and Communications perspective.

Battle Management/Command, Control and Communications have evolved and changed with the system architecture design. In fact, changes and evolution of the system architecture have clarified and simplified Battle Management/Command, Control and Communications. The goal has been and still is to deploy practical, demonstrable ballistic missile defenses in a phased or segmented approach, with the ability to add greater capabilities and systems in the future. That means that Battle Management/ Command, Control and Communications must be adaptable and updated to technology innovations and architectural design changes.

The DoD acquisition policies and procedures call for early identification and resolution of critical risks. Demonstration and validation is the phase in which a program is required to demonstrate critical technologies. The selection of appropriate Battle Management/Command, Control and Communications technologies on which to proceed will be reviewed by the Department, before beginning the engineering and manufacturing development stage (Milestone II).

The detailed DoD comments on the report findings, recommendation, and matter for Congressional consideration are provided in the enclosure. The Department appreciates the opportunity to comment on the draft report.

Sincerely,

HENRY F. COOPER
Director

Enclosure:
As Stated

GAO DRAFT REPORT - DATED DECEMBER 24, 1991
(GAO CODE 510620) OSD CASE 8889

"STRATEGIC DEFENSE INITIATIVE: CHANGING DESIGN AND TECHNOLOGICAL UNCERTAINTIES CREATE SIGNIFICANT RISK"

FINDINGS, RECOMMENDATION, AND MATTER FOR CONGRESSIONAL CONSIDERATION

DEPARTMENT OF DEFENSE COMMENTS

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FINDINGS

o <u>FINDING A</u>: <u>Evolution of the Strategic Defense Initiative Program</u>. The GAO reported that, although the Strategic Defense Initiative was originally conceived as a defense against a massive Soviet missile attack, the current version of the system is intended to defend the U.S. and its allies against a limited ballistic missile attack from any country in the world. The GAO found that change has been a constant element of the Strategic Defense Initiative since 1983. For example, the GAO reported that, in July 1990, the system then known as Phase I, was in a state of flux, primarily because Brilliant Pebbles was added to the architecture, causing a major restructuring. The GAO indicated the DoD is currently advocating a system that integrates ground-based defenses with space-based interceptors, and would like the system deployed by the year 2000. The GAO noted, however, that the Missile Defense Act of 1991, which is the first bipartisan consensus on missile defenses since the debate began 25 years ago, establishes goals based on ground-based interceptors, accelerates development of missile defense systems, and authorizes $465 million for research and development of space-based interceptors, even though the Act excludes space-based interceptors from the architecture. The GAO also reported that the President's FY 1992 budget estimates the acquisition cost at $41 billion (in 1988 dollars). (pp. 2-3, pp. 10-19/GAO Draft Report)

<u>DoD RESPONSE</u>: Partially concur. The overall objective of the program has remained fairly constant, with near term deployment of limited ballistic missile defenses envisioned. The Strategic Defense Initiative Program has adjusted both to the changing geopolitical situation and advances in ballistic missile defense technology. The research and development strategy throughout the life of the program has been to improve the performance and autonomy of the system elements associated with ballistic missile defense, while reducing the cost and complexity. At the same time, the Strategic Defense Initiative Organization is conducting research into new promising systems and technologies.

The GAO example of the Brilliant Pebbles addition placing the system architecture in a "state of flux" is not accurate. Brilliant Pebbles combines the functions of ballistic missile detection, tracking and interception into a single space-based element. The introduction of Brilliant Pebbles simplified the design of the initial architecture while retaining its functionality by eliminating the dependence of space-based weapons on a Boost Surveillance and Tracking System. In addition, it significantly reduced the costs of a Strategic Defense System. As promising concepts such as Brilliant Pebbles are identified, changes in the design of the Strategic Defense System have been made. The purpose of these changes is to provide a more effective, affordable, and survivable defense against ballistic missiles.

- FINDING B: <u>The Congress and the DoD Differ on Inclusion of Space-based Interceptors</u>. The GAO reported that the Strategic Defense Initiative has had to accommodate shifting international threats, changing concepts and designs, and continuing debate between the Administration and the Congress on the program mission and objectives, --and, that absent agreement, the DoD has pursued several different approaches consuming billions of dollars along the way. The GAO found that, for the past year, the DoD has been pressing forward with a missile defense system, referred to as Global Protection Against Limited Strikes, consisting of a National and Theater-based segments and one space-based segment. The GAO noted that each of the segments would have its own sensors and interceptors and could operate independently; however, the GAO indicated it is the DoD view that all three must be integrated to provide mutual, coordinated support--an approach that requires the segments to work together, using automated data processing and communication networks.

  The GAO reported that the Congress and the DoD differ on how to provide the most effective defense. The GAO found that, while the Act supports deployment of ground-based defenses, it excludes space-based interceptors from the system architecture, but leaves the option open to include them later. The GAO indicated that, if the Congress subsequently agrees with Defense that space-based interceptors should be included, significant re-engineering will be required to include them in the system and Battle Management/Command, Control and Communications architectures. Further, the GAO pointed out that, without a stable system and architecture, the risk that the system will not work as intended increases greatly. The GAO concluded that adding space-based interceptors at a later date would have a significant impact on the ground-based system--potentially costing hundreds of millions of dollars. (pp. 23-25/GAO Draft Report)

DoD RESPONSE: Partially concur. The Global Protection Against Limited Strikes concept represents an orderly evolution from the previous Phase I Strategic Defense System. The Global Protection Against Limited Strikes objective is protection from limited strikes, rather than the Phase I concept of deterring massive, deliberate attacks by the Soviet Union. Protection against limited strikes was a sub-goal of the previous Phase I system.

As previously noted, the instability (to which the GAO has alluded) relates to evolvable changes to improve the effectiveness and cost of a Strategic Defense System throughout its development. Battle Management/Command, Control and Communications is not simply driven by individual sensor and weapon technology; rather, it is a critical architectural function which all segments must rely on. The greatest risk of failure is to not address adequately Battle Management/Command, Control and Communications capabilities and trade-offs as part of a long range plan. The Global Protection Against Limited Strikes is establishing a Battle Management/Command, Control and Communications structure that supports all system segments whenever they are incorporated into the system architecture.

The Department supports the Missile Defense Act of 1991. The Global Protection Against Limited Strikes is a system that allows for segmented growth, as required, and is designed to evolve as threats and national requirements change. Space sensors play key roles in both national and theater segments. Space-based interceptors also have important roles, especially for longer range missiles. The system design is specifically intended to be flexible and may incorporate a space-based segment as national decision makers may decide. The National Defense Segment or Theater Defense Segment will not have to be redesigned for a space-based segment. In addition, there is no significant cost impact of "hundreds of millions of dollars" in re-engineering costs to add a space-based segment at a later date. Indeed, with appropriate planning (and depending on when space-based interceptors are added), there may be substantial reductions in the cost of providing a given desired level of protection and coverage.

o FINDING C: Changes in Architecture Significantly Hinder Battle Management/Command, Control and Communications Development. The GAO reported that the DoD, faced with the enormous task of reassessing its system and architectures in January 1991, initiated an architecture integration study to address program changes and to guide Global Protection Against Limited Strikes and Battle Management/Command, Control and Communications design and development. The GAO found that the study, which was scheduled to be completed in

September 1991, will not be completed until early 1992. The GAO also found that the DoD is still considering many different sensor and interceptor combinations for Global Protection Against Limited Strikes, and that the Battle Management/Command, Control and Communications architecture, which has not been solidified, has been distributed among several contractors for research and development, thereby exacerbating the risk of system incompatibility and duplication of efforts. (pp. 25-28/GAO Draft Report)

DoD RESPONSE: Partially concur. While the DoD continues to perform Strategic Defense System studies, Battle Management/Command, Control and Communications development is being suitably addressed. Battle Management/Command, Control and Communications planning and evolution have proceeded vigorously as an integral part of the overall system architectural evolution. Changes and evolution of the system architecture have clarified and simplified Battle Management/Command, Control and Communications concepts, and have been incorporated after ample system testing.

The Architecture Integration study was created to analyze and evaluate architectures to protect against limited strikes, define defense mission and goals and architecture variations for alternative futures, provide a rationale and road map for the architectures, and identify interactions and interfaces with other elements of U.S. and allied security policies. The first phase of the study was completed in September 1991, and it was extended to perform cost and operational effectiveness analyses; particularly to account for the Missile Defense Act of 1991.

In addition, the Strategic Defense Initiative Organization assigned to a single System Engineer and Integration Contractor the responsibility to produce controlled, integral top-level building block designs to integrate segments without a duplication of effort into a Global Protection Against Limited Strikes system. Thus, Battle Management/Command, Control and Communications is being designed at the system level and not the segment or element level. That approach is aimed at reducing the risk of system incompatibility and duplication of efforts.

o FINDING D: Resolving Technology Challenges Is Essential To Successful Global Protection Against Limited Strikes Development. The GAO reported that the complexity of the Battle Management/Command, Control and Communications system for Global Protection Against Limited Strikes is unprecedented. The GAO explained that the system will have to operate in real time in a hostile environment in a constantly changing configuration. The GAO found that (1) the Battle Management/Command, Control and Communications functions must be distributed among hundreds of computers located in space and throughout the world, (2) some computers will probably require advanced parallel processing designs, and (3) many processors will require information from multiple data bases, thereby introducing the need for distributed data base management. In response to those challenges, the GAO noted that the DoD has identified critical advances in software and hardware technology required to implement the system, such as trusted software, software for parallel processors, tools and techniques for effective software engineering, space-to-space communications, and parallel processing for ballistic missile defense.

The GAO found that the required technologies are all objects of current research and none is yet sufficiently mature to support the Global Protection Against Limited Strikes Battle Management/Command, Control and Communications system. The GAO explained that the software will require a level of trust never before achieved; i.e., it may have to operate on parallel processors and it will require a highly sophisticated software engineering and development environment that is not currently available. The GAO indicated that state-of-the-art practice generally lags well behind the technology state-of-the-art; therefore, it will be some time before the technology is proven well enough to be commercially available. The GAO also found that hardware technologies appear to be advancing fairly rapidly and that parallel processing hardware has been available for years. The GAO concluded, however, that implementing parallel processors on board small, lightweight spacecraft will involve packaging challenges to meet size, weight, and power constraints. (pp. 29-36/GAO Draft Report)

DoD RESPONSE: Nonconcur. The GAO states that the Battle Management/Command, Control and Communications system has "unprecedented complexity," that "enormous amounts of information will have to be processed and shared -- possibly among hundreds -- of different computers" and that a "distributed data base is essential." The GAO further states that the Battle Management/Command, Control and Communications software "...is the most complex and difficult of any military or civilian software developed and implemented to date."

The Strategic Defense Initiative Organization is designing the Battle Management/Command, Control and Communications system for data processing simplicity, such that only modest amounts of data are transferred to coordinate and control Global Protection Against Limited Strikes elements. The information handled by each computer is tightly constrained, as is its functionality in the system. Although data exists in multiple locations for redundancy and robustness, during operation no shared data processing or distributed data base concepts are involved or required.

There is little basis for asserting that software safety, correctness, and fault tolerance are more demanding for a Global Protection Against Limited Strikes than for nuclear reactors, medical systems, or aircraft flight control systems. Large software systems can and do operate reliably with minor errors or weaknesses. The trusted operating system and trusted data base system under research by the National Security Agency and the Defense Advanced Research Projects Agency represent work to explore new concepts and implementation methods that could provide general capabilities. Success of a trusted system does not depend on having mature and general solutions. The DoD already has many trusted and secure computing systems and command centers and the Global Protection Against Limited Strikes system will utilize proven existing systems enhanced by applicable technologies emerging from current research.

- FINDING E: Integration of Required Immature Technologies Greatly Exacerbates Existing Complexities. The GAO reported that individual technologies alone cannot support Global Protection Against Limited Strikes Battle Management/Command, Control and Communications, and that the Strategic Defense Initiative Organization will be faced with the enormous challenge of integrating the technologies to provide the data processing and communications capabilities needed. The GAO explained that the difficulty lies not only in the integration task itself, but also in the lack of experience with individual technologies, compounded by a lack of understanding of the interactions among them. The GAO further explained that, besides the complexity of the interactions of the technologies, tradeoffs must also be made. The GAO concluded that prematurely committing to inadequate existing technologies, or depending on the future success of currently immature or unavailable technologies, increases the risk that Global Protection Against Limited Strikes will not work as intended, or will not be able to easily evolve. The GAO further concluded that (1) a technology road map that defines what technologies are needed and when, and what the interdependencies are, is essential, and (2) plans for transitioning from existing to emerging technologies, inserting technologies as they become available, and for contingencies if a technology is not ready, are also needed. (pp. 37-38/GAO Draft Report)

DoD RESPONSE: Partially concur. A transition plan and technology road map will be utilized. As previously stated, current mature technologies are sufficient to begin developing a Battle Management/Command, Control and Communications system for a Global Protection Against Limited Strikes. The DoD continues to pursue research and development in order to improve solutions that may be needed.

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RECOMMENDATION

o RECOMMENDATION 1: Because of technological uncertainties, the GAO recommended that the Secretary of Defense develop an implementation plan for ballistic missile defenses. The GAO further recommended that the details of the plan be provided with the next DoD appropriation request for missile defenses and include, but not be limited to:

-- a stable, well-defined ballistic missile defense system architecture;

-- a well-defined, integrated Battle Management/ Command, Control and Communications architecture, sufficient in detail to provide the guidance and direction needed by developers to carry out their responsibilities; and

-- A comprehensive Battle Management/Command, Control and Communications technology plan describing reasonable technology availability schedules, plans for insertion of improved or advanced technologies as they become available, and contingency plans for dealing with situations when technologies are not available, including the ramifications of such contingencies on system performance. (p. 41/GAO Draft Report)

DoD RESPONSE: Partially concur. The Department agrees that the described information should be provided to the Congress, but does not agree a separate plan is necessary. Instead, the DoD will provide the information as part of the President's FY 1993 budget, the Report to Congress on the Strategic Defense Initiative, and such other congressional submissions, as required. The Department is committed to providing the Congress all the information necessary for a complete and thorough review of the Global Protection Against Limited Strikes program.

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MATTER FOR CONGRESSIONAL CONSIDERATION

o MATTER 1: Since the Congress has left the option open for space-based interceptors, the GAO recommended that the Congress authorize the DoD to include space-based interceptors in the missile defense system architecture to minimize risks and the need for potential re-engineering. (pp. 40-41/GAO Draft Report)

DoD RESPONSE: Concur. Space-based interceptors allow for a continuous global capability in ballistic missile defense. In concert with surface-based defense deployed nationally or in theaters of operation, it would assure high-confidence protection against limited ballistic missile strikes.

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