Next Generation Missile Defense Systems including the Golden Dome*

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Abstract

The Strategic Defense Initiative (SDI), later coined ”Star Wars”, was introduced by former President Ronald Reagan in his address to the nation [1] on March 23, 1983 to replace the Mutual Assured Destruction (MAD) doctrine. MAD is a national security policy doctrine that seeks nuclear peace, based on the theory of rational deterrence, which holds that the threat of using (nuclear) weapons against the enemy prevents the enemy's use of those same weapons. In the case of an attack though, the U.S. President is left with two terrible options, either to immediately counterattack or to absorb the attack while in the best case maintaining offensive dominance. On the other hand, in essence, SDI proposed to develop and deploy a missile defense system, the Strategic Defense System (SDS), to protect the U.S. from ballistic nuclear missile attacks by the former Soviet Union, and in theory, making nuclear weapons useless. For that purpose, the Strategic Defense Initiative Organization (SDIO), a DoD agency, was formed in 1984 to oversee the associated developments before related efforts were refocused and the agency was renamed to become again the Ballistic Missile Defense Organization (BMDO) in 1993. Among others, the former Soviet Union had been dissolved on December 26, 1991 and insufficient scientific and technological knowledge at that time contributed to that refocus, in particular pertaining Directed Energy Weapons (DEW), as documented e.g, in an APS report in 1987 [2]. Figure 1 shows President Reagan addressing the nation from the White House during his televised SDI speech [1]. He supported his assertions in the middle with a comparison between the narrative ”approximate parity of forces continue to exist” versus the crude reality ”definition of parity is a box score of 1300 (intermediate range warheads) to nothing in their favor” as well as evidence as documented in satellite imagery ”this Soviet intelligence collection facility less than a 100 miles from our Coast is the largest of its kind in the world”, and sharing with the nation the anticipated increase in defense spending from a low 23% to a still low 28% of the budget due to his SDI proposal. In 2002, the BMDO was renamed the Missile Defense Agency (MDA) [3].

*This abstract has been granted permission for public release. The author is the youngest individual ever awarded the IEEE Fellow ('Nobel' Prize in Engineering) worldwide for his pioneering space robotics accomplishments in flown NASA-ESA-DLR mission [4], launched and headed a world-leading Elsevier Science AI/ML journal for 15 years [5]. Dr. Sánchez has been designing and building to date next-gen space robotics, satellites, space launch vehicles, missile defense systems for decades [6–12], some within NASA and DoD classified programs, most recently for NASA JPL and the U.S. Space Force.

Figure 1: Strategic Defense Initiative (SDI) ”Star Wars” [1]

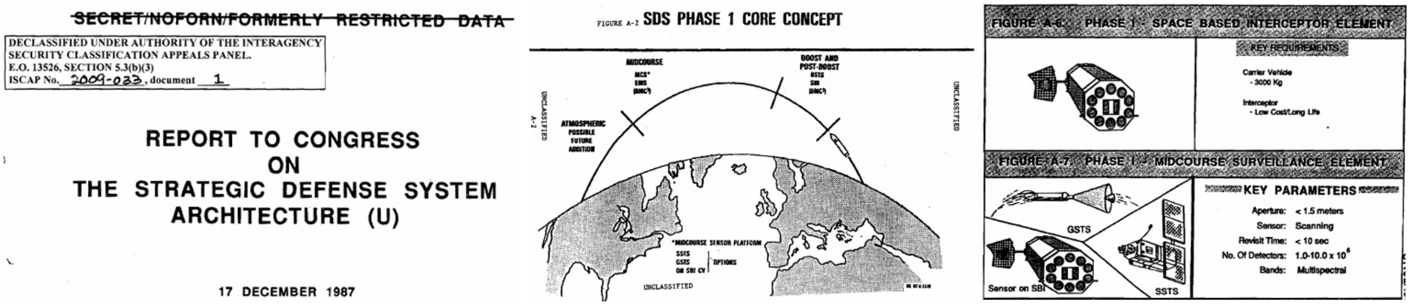


Figure 2: Strategic Defense System (SDS) Phase I Core Architecture [13]

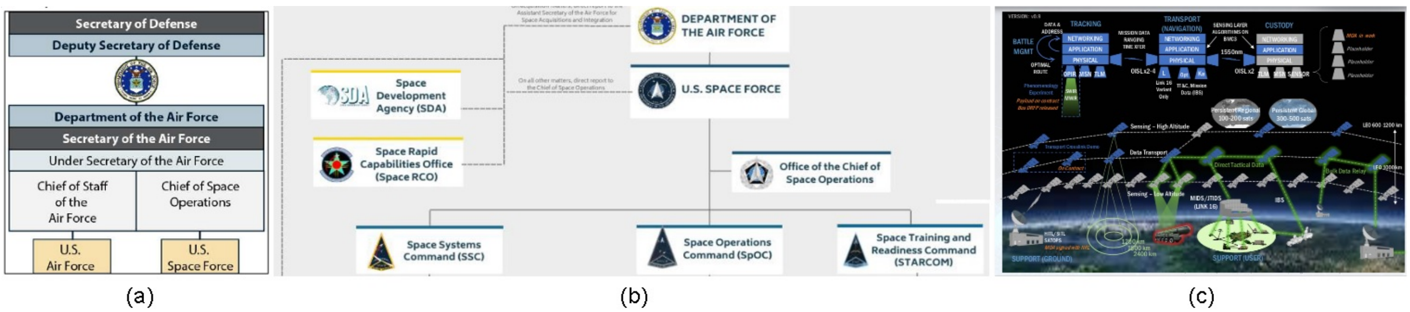


Figure 3: United States Space Force (USSF) (a) within DoD (b) Org Chart (partial, only top part displayed here) (c) Space Development Agency (SDA) Architecture Overview

According to the original SDI considerations, each SDS deployment phase fulfills 3 objectives: (i) perform the required defensive mission (ii) compel favorable changes, operational or technical, in the Soviet ballistic missile force, and (iii) lay the foundation for the improved, follow-on deployment phases. Figure 2 shows the SDS Phase I core architecture and some of its key elements as presented by the SDIO to the U.S. Congress on December 17, 1987 [13]. The trajectory of a ballistic missile is composed of four phases: boost, post-boost, midcourse, and terminal. The Phase I SDS contains two tiers of defense: one space-based and the second one primarily ground-based, which engage ballistic missiles during their boost/post-boost and midcourse phases respectively. The boost/post-boost tier elements include a Boost Surveillance and Tracking Satellite (BSTS) in near geosynchronous orbit and a constellation of Space Based Interceptors (SBIs, key requirements top right of the Figure, together with the Carrier Vehicle (CV)). The midcourse tier elements include exoatmospheric interceptors launched from the ground, supplemented by space-based interceptors, and target acquisition/tracking capabilities provided by multiple elements. The key parameters of the midcourse surveillance element are summarized at the bottom right of the Figure including for the sensor on the space-based interceptor (SBI), the Ground Based Surveillance and Tracking System (GSTS), and the Space Surveillance and Tracking System (SSTS). The Battlement/Command, Control, and Communications (BM/C3) element is the mechanism designed to orchestrate the utilization of all SDS assets incluing sensors, weapons, and others. In particular, the defensive tiers would be under positive man-in-the loop command and control from designated centers in the U.S., all the elements being linked through the BM/C3.

The Space Development Agency (SDA) was formed on March 12, 2019, tasked with deploying disruptive space technology, one of them being space-based missile tracking using large global satellite constellations made up of industry-procured low-cost satellites and with it some elements of the original ambitions set by SDI reemerged. Among others, the SDA works closely with the MDA [14] towards the deployment of associated assets. In October 2022, the SDA was transferred to the United States Space Force (USSF) [15], which had been founded on December 20, 2019 as the sixth branch of the armed services within the Department of Defense (DoD) to function at an equal level as the U.S. Air Force (USAF). The USSF is responsible for space launch, satellite operations, surveillance of the space environment, satellite defense, and missile defense functions. The DoD envisions the

(a) (b) (c)

Figure 4: The Golden Dome Missile Defense Shield (a) Fact Sheet (b) TV announcement (c) Congressional Budget Office (CBO) cost estimates [19]

consolidation of space missions, forces, and authorities within the purview of the USSF so that the USSF will provide this space support to other branches of the armed forces. Figure 3 shows the organizational chart of the USSF and a first level of subdvision in the middle including the Space Development Agency (SDA), the Space Rapid Capabilities Office (Space RCO), the Space Systems Command (SSC), the Space Operations Command (SpOC), and the Space Training and Readiness Command (STARCOM). To the right, the Figure shows an overview of the SDA satellite architecture. To ensure that the Pentagon's national defense system in space operates as seamlessly as possible, three agencies work closely together: the MDA, the SSC, and the SDA. The warfighter's geostationary (GEO) and mid-Earth orbit (MEO) missile-tracking assets are operated primarily by the MDA and the SSC. The SDA is in essence in charge of what is called the Proliferated Warfighter Space Architecture (PWSA) [16], a proliferated constellation of hundeds of satellites in Low Earth Orbit (LEO) delivering capability at speed. LEO satellites orbit at altitudes below 2,000 km. It proliferates new technology every two years, this period is called a tranche, to continually increase capability, currently from tranche 1 to tranche 5+. This architecture is made up of several layers, each of them providing unique and essential capabilities. The space transport layer is a global mesh network providing 24/7 data and communications. The tracking layer provides tracking, targeting and advanced warning of missile threats. The custody layer provides all-weather custody of all identified time-critical targets. The deterrence layer provides space situational awareness, i.e., detecting and tracking objects in space to help satellites avoid collisions. The navigation layer provides alternative positioning, navigation and timing services in case GPS is blocked or unavailable. The battle management layer is a command, control and communications network augmented by artificial intelligence that provides self-tasking, self-prioritization, on-board processing and dissemination. The support layer is composed of ground command and control facilities and user terminals, as well as rapid-response launch services.

On January 27, 2025 President Donald J. Trump signed the executive order about the at that point in time so called Iron Dome for America [17], which was then announced from the White House on May 20, 2025 as the Golden Dome Missile Defense Shield [18] as the officially selected architecture to protect the homeland from advanced missile threats including cruise, ballistic, and hypersonic missiles even launched from space, which should be fully operational before the end of his term in January 2029 with a success rate of very close to 100% and a cost of about $175 billion dollars completed, as stated during the announcement, cf. Figure 4, which also shows an excerpt of the Congressional Budget Office report [19] stating that alone the total estimated cost of deploying and operating the space-based interceptor (SBI) constellation for 20 years would be $161 billion and $542 billion for the lowest- and highest-cost alternatives respectively. The experiences drawn from the U.S. SDI and Israel's Iron Dome influenced the decision to develop the U.S. Golden Dome. In certain ways, the Golden Dome is the continuation with now available superior technology of SDI and also takes as incentive the positive experiences from a deployed system, the Iron Dome, and in a broader sense, from Israel's four-layered active defense network [20]: Iron Dome (short range),

(a) (b) (c) (d)

Figure 5: Israel's Iron Dome Missile Defense System [RAF]: (a) Principle of operation (b) Countering threats (c) Radar sytem (top) and launcher (bottom) in action (d) Intercepting rockets at night

(a) (b)

Figure 6: United States – Israel (a) Israel's multi-layer air defense (b) Country area size comparison

David's Sling (low to mid-range), Arrow II (upper-atmospheric), and Arrow III (exo-atmospheric), even when Israel's defense network operates at a much lower scale, geographically and of required capabilities. The U.S. had signed a memorandum of understanding (MoU) with Israel on May 6, 1986, to jointly develop an indigenous Israeli capability to defend against ballistic missiles shortly after the start of SDI in 1985. Under that agreement Israel was allowed to participate in SDI, and the U.S. and Israel co-developed different versions of the Arrow anti-ballistic missile.

Israel is protected against various airborne threats by a multi-layered defense array, which includes the Arrow-2, Arrow-3, David's Sling, and Iron Dome active defense systems. In particular, Israel's missile defense system, called the Iron Dome [21, 22], is a mobile, short-range, all-weather defense system which protects that small country by launching guided missiles to intercept incoming rockets and other short-range threats in mid-air with a claimed success rate of 90% and first deployed in March 2011. Its purpose is threefold: detection of incoming airborne threats, assessment of their likely point of impact, and interception. The fire control radar system detects and tracks targets at ranges of 4–70 km. Incoming missiles are disregarded conserving the interceptor, if the battle management computer system determines that it will land in an inhabited area posing no threat to life or infrastructure. Typically, an Iron Dome battery is equipped with 3–4 interceptor launchers, each of which contains up to 20 Tamir missiles. Each of those missiles has an approximate cost of $50,000 U.S. dollars. Figure 5 shows key elements of the Iron Dome, how it works, and photos of the performance of its components and of the entire system in real life. Figure 6 shows Israel's multi-layer air defense and one of the main differences w.r.t. the proposed U.S. Golden Dome, the large difference in area coverage.

From the time SDI was conceived, the aerial threats have only continued to escalate and new threats now include hypersonic missiles flying at multiples times of Mach 5 – the speed of sound is 1,234.80 km/h, hypersonic means moving at least five times the speed of sound or 6,174 km/h –, cruise missiles dodging radar systems, and swarms of drones launching surprise attacks from nearly any direction. Among the hypersonic weapons there are primarily two categories [23]. Hypersonic cruise missiles (HCMs) are powered by high-speed, air-breathing engines, or scramjets, after

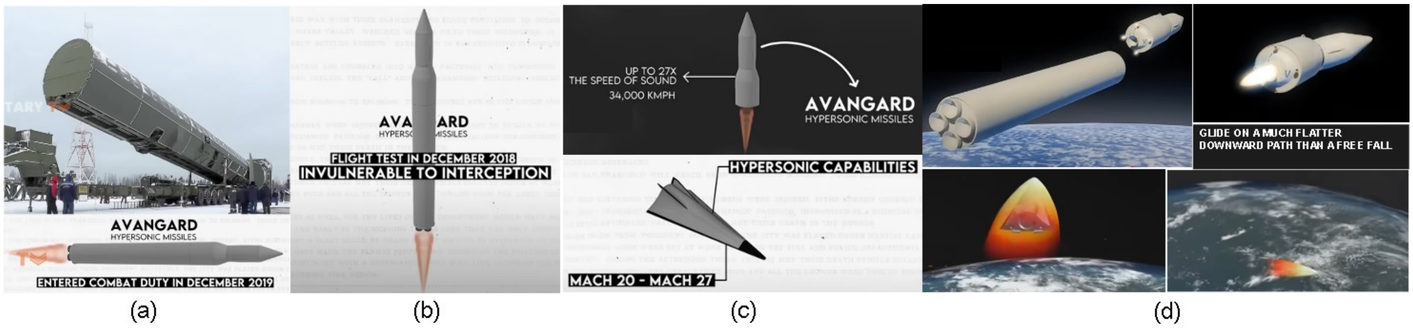


Figure 7: Avangard Hypersonic Glide Vehicle (a) Deployment of Avangard equipped ICBM into a launch silo (b) Flight test in December 2018 (c) Speed up to Mach 20–27 (d) Unpredictable trajectory after reentry gliding down to its target

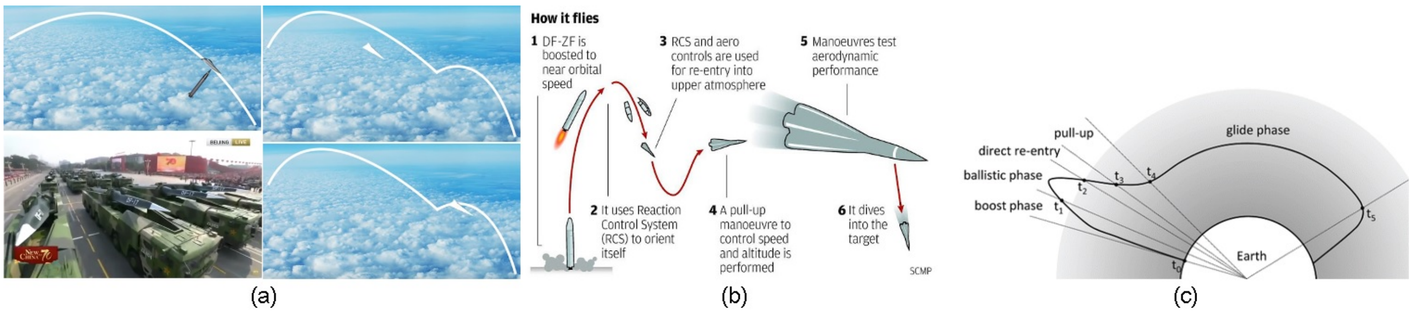


Figure 8: DF-17 / DF-ZF Medium-Range Ballistic Missile (MRBM) with Hypersonic Glide Vehicle (HGV) (a) trajectory of ballistic missile (top left) versus HGV (right) (b) How they fly (c) HGV flight phases

acquiring their target. Hypersonic glide vehicles (HGVs) are launched from a rocket before gliding to its target. In particular, Russia [24] and China [25] have added those weapons to their arsenals. As an example, the Avangard is a Russian Hypersonic Glide Vehicle (HGV) that can carry nuclear and conventional payloads with a speed up to Mach 20–27 and a range larger than 6,000 km. The Avangard can be carried as a multiple independently targetable reentry vehicle (MIRV) payload of heavy intercontinental ballistic missiles (ICBMs) like the SS-19 Stiletto, SS-9 Scarp, and SS-X-29/30 Sarmat (NATO reporting names). Figure 7 shows relevant information about launching an Avangard HGV on an ICBM and its unpredictable gliding trajectory after reentry. On the other hand, again, as one example, the Dong Feng-17 (DF-17, NATO reporting name: CH-SS-22) is a Chinese medium-range ballistic missile (MRBM) system equipped with the DF-ZF, a hypersonic glide vehicle (HGV) that can transport conventional and nuclear payloads with speed up to Mach 5–10 and a range of 1,800–2,500 km. Figure 8 shows different aspects of the DF-17 MRBM and the DF-ZF HGV, and a sequence of their flight phases.

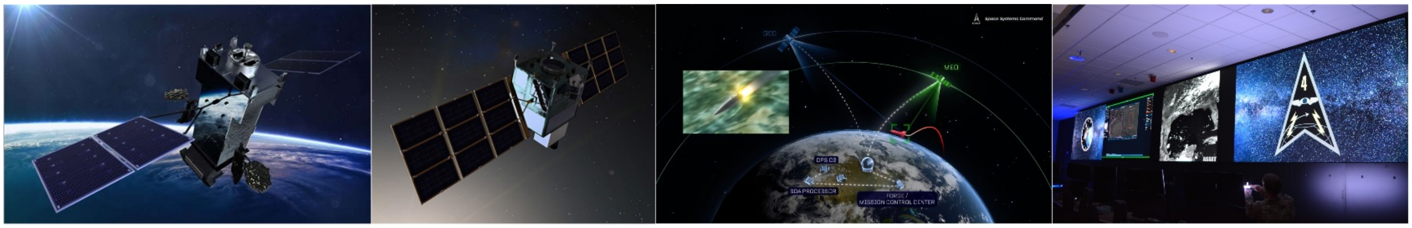
On the U.S. side, three current systems in use could serve as basis to understand current available capabilities: the Patriot, Aegis and Thaad systems. The PATRIOT Air and Missile Defense System [27] is the U.S. Army's most advanced air defense system. Capable of defeating both high performance aircraft and tactical ballistic missiles, the only U.S. operational air defense system that can shoot down attacking missiles. A PATRIOT battery, i.e., the basic firing unit, consists of about 90 soldiers, but only 3 of them in the engagement control station are the personnel required to operate the battery in combat. The prime contractor Raytheon Technologies manufactures the PATRIOT radar and ground systems, and Lockheed Martin manufactures the interceptor missiles. The AEGIS Weapon System [28, 29] is a centralized, automated, command-and-control (C2) and weapons control system. It is designed as a total weapon system, from detection to kill. The AEGIS Ballistic Missile Defense (BMD) is made up of three basic components: sensors, interceptors, and command and control. The BMD is the sea-based component of the Ballistic Missile Defense System (BMDS). The Terminal High Altitude Area Defense (THAAD) Weapon System [30, 31] with its endo/exoatmospheric

(a) (b) (c) (d)

Figure 9: Missile Defense – current and future elements (a) Phased Array Tracking Radar to Intercept on Target (PATRIOT) (b) Aegis Combat System (c) Terminal High Altitude Area Defense (THAAD) (d) Golden Dome for America [DIA] [26]

intercept (E2I) capability is a key element of the Ballistic Missile Defense System (BMDS). The system's threat set includes short-range, medium-range, and limited intermediate-range ballistic missile threats. Each THAAD battery includes five major components: interceptors, launchers, a radar, a fire control unit and support equipment. THAAD intercepts ballistic missiles at higher altitudes and greater ranges than the PATRIOT. While the THAAD is capable of engaging targets at ranges of 150–200 kilometers (km), the PATRIOT's phase-arrayed radar system has a range in excess of 150 kilometers (km) and the capacity to track up to 100 targets, providing missile guidance data for up to nine missiles, the flight ceiling for PATRIOT interceptors is about 20 km and PATRIOT can provide area coverage and defense for about 15–20 km for incoming ballistic missiles. In the case of the Aegis system, its SPY radar can track 100 targets simultaneously at 190 km and can also guide missiles to engage those targets. Currently, all these U.S. systems possess very narow protection footprint, i.e., they do not provide broad areas of protection and therefore cannot be considered area defense weapons.

To illustrate the author's personal involvement in some of the most criticial parts of the Golden Dome factual development areas without disclosing sensitive information, let us first dive deeper into the organization of the United States Space Force (USSF). The USSF org chart in the middle of Figure 3 shows only the first level of subdivision, e.g., of the Space Systems Command (SSC). Underneath that level, we have the Program Executive Offices and some of the so called Space Delta offices including Assured Access to Space, ..., Space Domain Awareness & Combat Power. Under Space Operations Command (SpOC) we have multiple Space Delta offices including, e.g., Space Delta 4, Mission Warning. Its mission is to provide strategic and theater missile warning to the U.S. and international partners through the operation of Overhead Persistent Infrared (OPIR) satellite constellations and globally positioned ground-based radars with its HQ at the Buckley Space Force Base, Colorado. The Next-Gen OPIR is an ongoing development to replace the current missile early warning satellite constellation, the Space-Based Infrared System (SBIRS) making it among others more resilient to counter-space capabilities. In the mid 1990s, DOD selected SBIRS to replace the Defense Support Program (DSP), which is now nearly 5 decades old. The SBIRS constellation consists of satellites in geosynchronous earth orbits (GEO) and highly elliptical orbits (HEO). Equipped with advanced infrared sensors, the purpose of Next-Gen OPIR is to detect and track ballistic missile launches by identifying their heat signatures and securely transmitting this vital data to ground stations. The SSC's Next-Gen OPIR program is developing advanced Geosynchronous Earth Orbit (GEO) and Polar orbit capabilities with prime contractors including Lockheed Martin Space (LMS) and Northrop Grumman Space Systems (NGSS), respectively as well as government contractors for the mission payloads including Raytheon and Ball Aerospace. Next-Gen OPIR provides persistent battlespace awareness and time-critical boost phase missile warning, in partnership with the Space Development Agency (SDA) and the Missile Defense Agency (MDA) to ensure mission effectiveness against advanced threats. Some of the initial technical and managerial challenges were compiled in [32]. The SSC's FORGE EOS is the Future Operationally Resilient Ground Evolution (FORGE) Enterprise Overhead Persistent Infrared (OPIR) Solution (EOS), whose government contract was



(a) (b) (c) (d)

Figure 10: United States Space Force (USSF) Space Systems Command (SSC) - Next-Gen Overhead Persistent Infrared (OPIR), Future Operationally Resilient Ground Evolution (FORGE) (a) Next-Gen OPIR GEO (NGG) space vehicle (b) Next-Gen OPIR Polar (NGP) space vehicle (c) FORGE notional architecture (d) OPIR Battlespace Awareness Center (OBAC), Buckley Space Force Base

just awarded this month and builds upon the existing FORGE framework that provides foundational hardware and software infrastructure, on which OPIR mission applications are built upon. FORGE provides a resilient OPIR ground architecture supporting legacy Space-Based Infrared System (SBIRS) and Next-Gen OPIR satellite payloads (NGG and NGP), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO) constellations, integrates capabilities from both FORGE and non-FORGE efforts, ensuring interoperability and mission flexibility across the missile warning and tracking enterprise. Some main components of SSC's Next-Gen OPIR and FORGE are shown in Figure 10. Some specifics of the work so far performed for this program are included in [11]. In this report, multiple critical elements of next generation missile defense systems are discussed and solutions designed and validated. Specific topics included belong to broad areas like science and technology (S&T), research and development (R&D), prototyping, studies, demonstrations, testing of prototypes, disruptive technologies, experimentation, architecture development, modeling, simulation, and analysis, systems engineering, weapon design and development, integration and assembly, production and fielding, test and evaluation (T&E), operation and sustainment, modernization, hardware and software modifications, data mining, collection, and analysis, research, development, test, and evaluation (RDT&E), mission-related IT as well as cybersecurity. Solutions are presented in detail, for most of them special access is required.

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