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Key Points

America's strategic competitors are developing capabilities to conduct maneuver warfare in space. This threatens the security of U.S. satellites that have predictable orbits and limited ability to maneuver using chemical propellants.

China's space maneuver warfare forces will include vehicles with nuclear thermal and electric propulsion capable of rapidly transferring between orbits to conduct offensive and defensive missions.

DOD must adopt a new force design that includes satellites and other vehicles with nuclear thermal and electric propulsion capable of decisive maneuver warfare from, to, and in space.

The safety, maneuverability, high thrust-to-weight ratio, and fuel efficiency of nuclear thermal and electric propulsion is the key to developing a space force that can actively deter, protect, and defend America's national interests in Earth orbit and beyond.

DOD should deploy ASAT weapons systems capable of holding Chinese and Russian targets at risk. It should also hedge against risk by deploying existing capabilites that enable satellites to conduct limited defensive maneuvers. This is especially needed now to bridge until maneuvering space nuclear thermal propulsion forces can be fielded.

Maneuver Warfare in Space: The Strategic Mandate for Nuclear Propulsion

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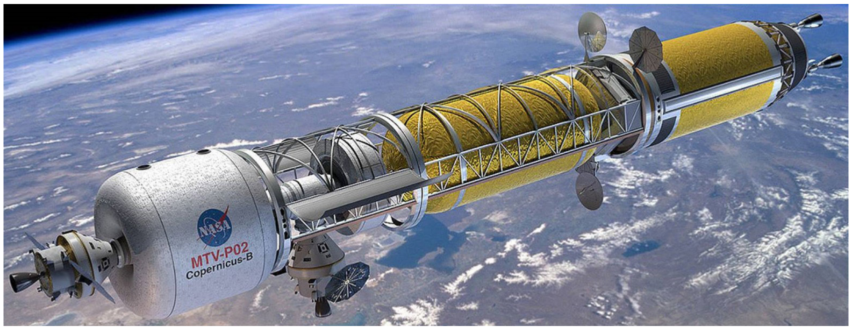
Abstract

America's national security space enterprise is at an inflection point. Current U.S. Space Force (USSF) designs are based on constellation architectures with limited maneuverability and armed with few countermeasures. These constellations are increasingly vulnerable to attack, as China and Russia are both deploying new anti-satellite (ASAT) weapons. Furthermore, they plan to propel their own new, multi-layered counterspace architectures with fuel-efficient, space nuclear propulsion (SNP) technologies. These weapon systems highlight they are shifting to a warfighting strategy based on rapidly maneuvering in space to conduct offensive and defensive operations.

Current U.S. space systems powered by chemical rockets can be thought of like the airships of a century ago, while adversary space nuclear thermal propulsion (SNTP) systems are like modern fighter aircraft, given their increased thrust and extended endurance. SNTP can provide China and Russia with the means to leapfrog current U.S. space architectures and operational concepts and devastate U.S. space forces. However, this does not have to be our future. DOD has an opportunity to leverage decades of SNTP technology development to create a more maneuverable and defendable space architecture to protect U.S. interests. Creating this new, maneuver-based force design will be a major step toward ensuring the USSF has the resources it needs to gain and maintain our nation's space superiority in peace and in war.

Credit: NASA



Introduction

The unfettered use of space is critical to modern life in the United States, as well as its ability to defend its global interests from an unprecedented array of threats. Whereas the space domain was once considered a sanctuary, today it is increasingly contested. China and Russia have both developed ground-based and space-based anti-satellite (ASAT) weapons that can degrade, damage, and even destroy America's vital spacepower capabilities. Although the Department of Defense (DOD) has released a Defense Space Strategy to address some of these threats through necessary resilience initiatives, this strategy has a major shortcoming: it is better suited to counter limited, terrestrial-based space attacks than the dynamic threats that come from new maneuverable and fast-moving weapons in, from, and to space.[1] While maneuvering space weapons sound like they belong in the realm of science fiction, they are a near-term reality. The U.S. national security space enterprise must take steps to ensure it continues to deliver strategic effects from, to, and in space. Chief among these steps is for the United States to field its own space nuclear thermal propulsion (SNTP) technologies to rapidly maneuver satellites and other space vehicles. SNTP will expedite the transition of DOD's space architecture from one dependant on vulnerable satellites locked in predictable orbits to a more dynamic, operationally safe, and survivable force structure that is capable of prevailing against great power aggression.

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U.S. satellite constellations currently in orbit were designed with a key underlying assumption: that space was an uncontested domain. The result is a set of capabilities intended to maximize the mission efficiency, lifespan, and reliability of DOD's operational satellites. Consequently, these satellites are mostly large, monolithic systems that deliver tremendous mission functionality per unit.[2] However, their highly predictable orbital paths, altitudes, and overflight timing make them easy targets for enemy attacks.[3] An airpower analogy is when U.S. B-52 bombers flew multiple days of strikes on Hanoi during the Vietnam War. Although the B-52s were highly capable aircraft, they flew the same altitudes and flight paths, and their easily targetable positioning made them sitting ducks for North Vietnam's Soviet-made surface-to-air missiles. On one particularly bad day of the campaign, six B-52s were shot down.[4]

China and Russia have long recognized and opportunistically sought to exploit these and other vulnerabilities of DOD's space forces. China is developing what it refers to as a multi-layered counterspace architecture. One layer includes capabilities like radio-frequency jammers and illumination lasers that can temporarily debilitate satellites. Another layer includes weapons that can permanently degrade and even destroy satellites, such as ground-launched ASAT missiles that can reach satellites at all orbital altitudes and directed energy weapons like high-power lasers.[5] Russia is developing a similar set of weapons and has demonstrated its ability to kinetically kill satellites in orbit. According to General James Dickinson, Commander of U.S. Space Command, Russia's launch of a direct ascent ASAT missile in November 2021 illustrates it is "deploying capabilities to actively deny access to and use of space by the United States and its allies and partners."[6]

These threats do not negate the advantages the space domain provides to U.S. forces, just their historical uncontested nature. Where space-based communications and situational awareness have played critical roles in U.S. military operations for decades, they will only become more important in the decades to come. In fact, they are essential to the success of DOD's highest priority terrestrial-focused operational concepts and capabilities. The United States cannot remain idle as its adversaries sprint ahead. The technical solutions do exist—DOD must fight back and pursue its own SNTP capabilities.

The U.S. National Security Space Enterprise Is at An Inflection Point

Since the launch of the first military satellites in 1959, the U.S. military has relied on orbital assets to support its air, land, and sea operations. The concept of space assets as "supporting" capabilities is key to understanding the space enterprise inherited by the new U.S. Space Force. Consider seven specific attributes space-based capabilities presented to military commanders for decades: freedom of action in space; overflight of restricted or denied areas; a global perspective; responsiveness; multi-user capacity; and increased speed, reach, and persistence relative to terrestrial alternatives.

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In terms of freedom of action in space, satellites enjoyed the ability to orbit without active threats seeking to destroy them. Meanwhile, orbiting in space means satellites could overfly sovereign national territory without interruption because international law does not extend a nation's territorial boundaries past the Earth's atmosphere. Even without direct overflight, a single satellite in a Low Earth Orbit (LEO) can view hundreds of miles at a time, while a satellite in a more distant Geosynchronous Earth Orbit (GEO) can view 42 percent of the Earth's surface area. Space assets afforded commanders with a global perspective, the ultimate "high ground" view for gaining situational awareness and facilitating command and control of their terrestrial forces. In this way, satellite constellations provide commanders capabilities such as persistent communications and intelligence, surveillance, and reconnaissance (ISR) in faster timeframes than ground or air-based platforms, and operators could rapidly re-task some constellations to meet ISR and other warfighter needs as their priorities shifted.

Importantly, space assets could provide concurrent support to multiple mission partners worldwide. As one example, millions of people constantly harness Global Positioning System (GPS) data to provide positioning, navigation, and timing (PNT) services for various purposes. Satellites in space additionally enjoy the advantage of greater speed, reach, and persistence compared to vehicles operating in the air, on land, and at sea. Furthermore, due to the orbital parameters of a constellation's design, each satellite can operate as part of a system-of-systems that is capable of continuous operations and create effects at distance with persistent coverage that does not require long logistics chains and overseas basing agreements.

Over time, the military services designed and improved individual satellites, and later constellations of satellites, to support other mission requirements. Current joint space doctrine still addresses this more limited view of spacepower, pointing to historical advantages like the all-encompassing global perspective of satellites, their lack of overflight restrictions, and the persistence of satellites in geosynchronous orbits.

It is important to understand that while there will always be a need for space missions that provide support to warfighters, the way they are conducted, protected, and defended must change given China and Russia's rapid development of counterspace weapons. While mostly out of sight of the public, military and commercial space operators are already experiencing a contested space environment. Purposeful interference, like the jamming of space-based assets and their communication links to their terrestrial control facilities, occurs on a routine basis. In addition, allied space-faring nations like France have had adversary spacecraft rendezvous, with their national security satellites—meaning they approached them closely, to within visual range or closer—without warning or prior coordination.[7] While it is possible to interpret these incidents as reconnaissance activities, it is more likely they are preparatory efforts for more aggressive actions in space by China and Russia. And, though not exactly the same, these actions could be compared to aggressive posturing of naval craft at sea or airspace infringements in the air in that they are likely meant to intimidate or incite a defensive response. The implications of these threats cannot be overstated. They will alter numerous U.S. military operating assumptions and demand new capabilities, like the ability to maneuver rapidly between orbits to provide offensive, defensive, and warfighting support capabilities from space wherever needed.

It also cannot be overstated that modern terrestrial military operations cannot be executed without space-based systems. Consider the U.S. Space Force's GPS satellite constellation. GPS provides positioning, navigation, and timing information globally and is inextricably integrated with much of the free world's critical infrastructure. If an attack significantly degraded this one constellation, it would disrupt national and international air travel, banking networks, data collection, and other operations and networks upon which our society depends. The GPS constellation also provides navigation and timing signals the U.S. military needs to conduct many of its operations, including precision air drops in support of disaster relief missions and precision strikes in time of war. This is just one example of why the increasing adversary threats to space assets need to be addressed seriously.

The stark vision of a contested space domain is articulated in DOD's 2020 Defense Space Strategy, which describes China as the "most immediate and serious threat" to U.S. national security objectives in space.[8] This strategy argues that a more resilient national security space architecture is needed to counter emerging threats. Resiliency measures include the development of satellite constellations that can absorb limited kinetic and non-kinetic attacks and continue to provide critical services to U.S. air, land, and sea forces worldwide—in other words, constellations with enough nodes that there is no single point of failure. This is currently not the case with most current GEO constellations that rely on a handful of large, monolithic satellites that can be easily targeted. Enemy attacks that eliminate a relatively small number of satellites in these constellations could greatly disrupt the overhead surveillance, global communications, and other capabilities they provide.

One operating concept to facilitate this strategy is to launch what is known as proliferated LEO satellite constellations. The proliferated LEO satellite concept entails deploying hundreds, even thousands of small satellites in constellations to form a "mesh" network that does not have a single point of failure whose destruction would have an outsized effect. Denying enemies the ability to inflict a quick knockout blow is exactly what force designs like this are intended to achieve. However, proliferating satellites in LEO alone will not be enough to address the full range of space weapons that China and Russia are pursuing.[9]

Types of Space Nuclear Propulsion

Nuclear Thermal Propulsion (NTP) is a high thrust system that heats hydrogen as a propellant. It is the nuclear equivalent of a chemical rocket but has much better propellant efficiency (Isp) enabling the spacecraft to remain in space and carry out multiple missions. NTP is well suited for meeting operational requirements such as quick response and fuel efficiency.

Nuclear Electric Propulsion (NEP) consists of a nuclear reactor system that generates electricity that in turn powers thrusts such as Hall thrusters or ion thrusters. These are low thrust systems that work great for missions where speed is not a requirement, as they are slower but have very good propellant efficiency. Nuclear electric power systems would also be needed for space weapons that are powered by electricity such as lasers.

To this point, U.S. satellites—whether they are in legacy monolithic constellations or proliferated constructs—operate in orbits that are predictable and can be tracked by adversaries that have even a basic space tracking network. China believes that both types of constellations are "easy to attack and difficult to defend." Plus, not every satellite mission system can operate in a proliferated LEO constellation.[10] In addition to creating constellations that eliminate critical points of failure, DOD should begin to deploy satellites that can move, or maneuver, to avoid attacks and change orbits as needed. Without this flexibility and maneuverability, DOD's push to field larger numbers of satellites per constellation may simply provide more targets for an adversary to destroy.[11] While this does present a dilemma to the adversary, it becomes a more surmountable one as their space offensive capabilities improve.

The ability for satellites to accomplish small maneuvers in space is not new. Current satellite constellations are controlled by either chemical or electric propulsion. Electric propulsion, while very efficient, is very slow. Chemical propellant, while very powerful with thrust, is not fuel-efficient and as such only provides limited options in a dynamic, warfighting domain such as space. Most satellites can use chemical propellant-powered thrusters to maintain their desired orbit, execute limited maneuvers like adjusting their position to perform a specific tasking, or deorbit after mission completion. Given the cost and other challenges associated with launching mass into space, satellites typically carry small amounts of chemical propellant. Expending this limited store of propellant to avoid rapidly moving threats would reduce a satellite's operational lifespan, which would prematurely end its mission life and require an early replacement.

A better way to harness the advantages of maneuver in space is to develop a more powerful and fuel-efficient means of doing so, which is why space nuclear thermal and electric propulsion technologies must be part of DOD's future space force design. This technology will allow DOD to adopt a space strategy that includes fielding a maneuverable force that is more survivable and has other operational defensive and offensive benefits. In short, SNTP will empower an entirely new era of maneuver warfare in space.

SNTP technology has existed for several decades. From the 1960s to the 1980s, the United States matured SNTP technologies but never operationalized them simply because the threat environment at the time did not require the ability to rapidly maneuver on orbit. The situation is now radically different—China has already shifted to a strategy of maneuver warfare in space that leverages space-based and ground-based weapons systems, and by 2040 they plan for their architecture to include space vehicles with nuclear thermal and electric propulsion.[12] The era of change we are seeing on orbit is akin to the time when mechanized armor first showed up on the battlefield in World War I. Numerous modes of military operations that had previously been critical to warfare, including horse cavalry, were rendered obsolete by tanks, aircraft, and machine guns. Those who failed to recognize and adapt to this new reality were massively overcome.

The U.S. Space Force and other players in the national security space enterprise now face a similar inflection point and must respond appropriately or find their most critical assets at risk of obliteration. It is time to move beyond a traditional, predictable satellite constellation model to a space force design that harnesses the attributes of speed, agility, fuel efficiency, and enhanced maneuver. This will require DOD to progress from treating SNTP as a research and development project to creating a force of space vehicles with nuclear thermal propulsion capable of superior space maneuver warfare. To reiterate, the United States, once the leader in SNTP, could have deployed an SNTP-based force design decades ago. The threat environment in space has changed from a sanctuary to a warfighting domain, and our nation's strategy and capabilities for operating in this contested environment must change as well.

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Understanding How Today's Satellite Constellation Force Design Developed

DOD developed its current satellite constellation force design over the last seven decades. Space operations concepts explored by the RAND Corporation and published in its 1946 report Preliminary Design of an Experimental World-Circling Spaceship predicted a wide range of uses for satellites such as reconnaissance, weather observation, communications relay, missile guidance, bomb impact spotting, and bombardment from space.[13] Visionaries of the era viewed satellites as individual entities with specific missions and did not anticipate the multi-satellite constellation force design that later emerged.

With the dawn of the Space Age in 1957, individual satellites launched into orbits had limited mission durations. Due to the immature state of space technologies, these missions typically relied on physically deorbiting a spacecraft component to retrieve data, such as a capsule containing exposed reconnaissance film so it could be processed on Earth. Technological advances in the 1960s led to satellites that were fully able to conduct ISR and other missions like providing real-time warning of missile launches while remaining on orbit. The growth in the number of missions that satellites could perform, combined with the extension of their operational lives to years rather than days and weeks, led to a steady increase in the total number of satellites in orbit. In the 1970s, requirements to provide global navigation and communication services saw the development of constellations of satellites that could deliver information with a degree of persistence that far exceeded what individual satellites could provide.

Early thinking about conflict in space

During the 1950s and 1960s, Air Force General Thomas White, General Curtis LeMay, General Thomas Power, and other Air Force leaders believed conflict in and from space would someday become a reality. They were primarily concerned for Soviet attacks on American systems on orbit and nuclear strikes from space against the U.S. homeland. These leaders advocated a concept called "Aerospace Vision" which portended the need for a maneuverable, survivable warfighting orbital force to address adversary advances in offensive space weapons. Senior policy leaders in the Kennedy and Johnson administrations were apprehensive about potentially spurring another level of the arms race with the Soviet Union, so pursued an alternate concept branded "Space for Peace" that sought to keep space free of overtly hostile military activities. Facing technological and internal bureaucratic hurdles, the Soviet Union wanted more time to catch up to the U.S. lead in space and temporarily acceded to such limitations on weapons development under the Outer Space Treaty and United Nations resolutions. This is another reason why the U.S. military continued to see its space forces as sufficient to provide supporting services to terrestrial military functions.

In time, U.S. military requirements demanded an ever-increasing number of services from assets in space. These growing requirements drove the development of a satellite constellation structure that became and remains a critical means for seamlessly commanding and controlling U.S. and allied forces worldwide. By the end of the Cold War, U.S. space missions were mostly batched into the major categories of missile warning, satellite communications, weather, PNT, and ISR. High-demand space systems for each of these categories are now organized into a multi-segment, multi-satellite operational design and mission execution model.

The Three-segment current satellite constellation force design model

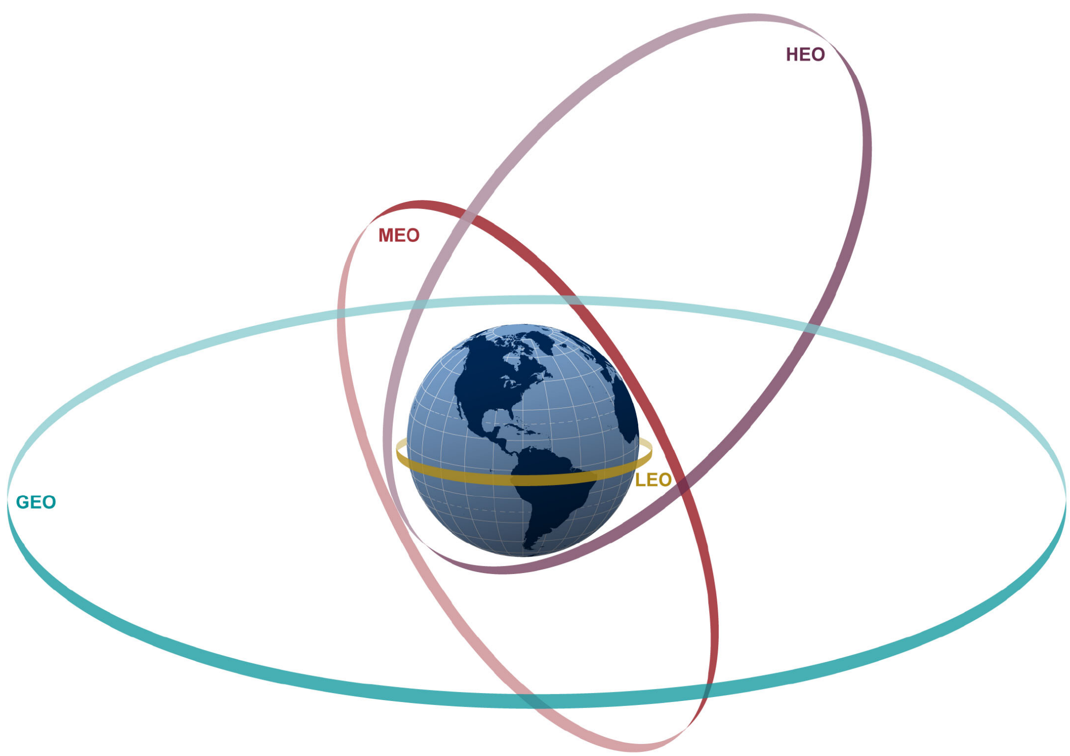
The architectural design for most legacy space warfighting support systems generally follows a three-segment model that consists of an orbital segment with satellites equipped with powerful sensors and processing power; a terrestrial segment that receives the data and transmits it to human and machine recipients; and a network of communication nodes known as the "link segment" that connects all three segments.

- **Orbital segment.** Spacecraft can be designed to operate as unitary assets or as part of a multi-satellite constellation. Mission effects and services that space capabilities are required to provide shape their force designs. As an example, the orbital segment for the GPS constellation consists of at least 24 operational satellites and several spare satellites on orbit to ensure continuous coverage in case of technical glitches or emergencies. The GPS constellation is arranged into six equally spaced "orbital planes" surrounding the Earth to maximize coverage and ensure any part of the GPS terrestrial segment can view four satellites from any point on the planet and receive signals needed for precision navigation. An orbital plane is a defining parameter of an orbit used for reference of a satellite as compared to the equator. These planes are typically fixed for the duration of a constellation's operational lifespan, since it takes a very large amount of chemical propellant to change them.
- **Terrestrial segment.** The terrestrial segment of a space system includes all satellite constellation ground control stations, antennas, tracking stations, launch sites, and user equipment for monitoring and controlling missions. Mission control centers process, analyze, and distribute spacecraft telemetry and issue commands, upload data, and update software to maintain the health of orbiting constellations. Continuing with the GPS example, its terrestrial segment consists of a master control station,

an alternate master control station, 11 command and control antennas, and 16 monitoring sites. Control stations may also be responsible for configuration management and archiving data from satellite missions.

- **Link segment.** Data links are crucial to the exchange of information across a satellite constellation's orbital segment and its terrestrial segment. In addition to transmitting information from space to Earth, data links facilitate command and control of satellites in space. In recent years, crosslinks have been added to constellation orbital segments to facilitate continuous data transfers between satellites orbiting on one side of the Earth and their ground stations located on the other side of the Earth. This is important since mission requirements can require satellites to respond to ground users without waiting for the satellites to overfly traditional downlink points.

It is also important to understand that each satellite in a constellation occupies a different position in relation to the Earth to achieve desired mission effects. This is called an "orbital regime." In the Earth orbital regime, most satellites operate in one of three main orbit types: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Earth Orbit (GEO). LEO is at an altitude between 90 miles and 160 miles above the Earth. Missions typically assigned to this orbital type include ISR, weather,



Orbit types	Altitude (miles)	Uses
Low Earth Orbit (LEO)	Up to approximately 1,200	• Communications • Human spaceflight • Intelligence, Surveillance, and Reconnaissance
Medium Earth Orbit (MEO)	Approximately 1,200 to 22,000	• Communications • Position, navigation, and timing
Highly Elliptical Orbit (HEO)	Approximately 25,000 at apogee	• Communications • Missile warning • Intelligence, Surveillance, and Reconnaissance
Geosynchronous Earth Orbit (GEO)	Approximately 22,000	• Communications • Missile warning • Intelligence, Surveillance, and Reconnaissance

Figure 1: Types of Orbits

Image source: DOD | GAO

and soon some proliferated constellations for missile warning. MEO is generally between 1,243 miles and 22,236 miles above the Earth. This orbit is the standard operational zone for the U.S. GPS system and foreign PNT satellite systems. GEO begins at MEO's maximum altitude and ends at 22,237 miles above the Earth's equator. This orbit is used mostly for communications, weather, and ISR satellites. The common denominator for satellites in GEO is the need for them to persistently "stare" at a given area on the planet perform their mission, which they achieve by remaining on orbit in a fixed location relative to the ground.

Current ability to maneuver

Today's space capabilities are designed to maximize their mission efficiency and effectiveness and minimize their production and launch costs. This is another reason why DOD's satellites are now incapable of making major maneuvers in space to avoid threats and perform other functions. This does not mean that current satellites are completely incapable of maneuvering. Once a rocket launches a satellite into its assigned orbital slot, satellites can use their onboard chemical propulsion system to achieve its final mission orbit and then its small thrusters to make small orbital adjustments over its operational life. Chemical propellant loads needed for more aggressive, repeated maneuvers would greatly increase satellite mass and the cost of launching them. The desire to maximize efficiency in an era when threats in space were low and launch costs were high is also why DOD typically designed its satellites to have long lifespans and perform multiple missions. These are no longer valid assumptions. Space has become a contested warfighting domain, and technological innovations such as composite materials and reusable launch vehicles are beginning to lower launch costs and other barriers to access space.

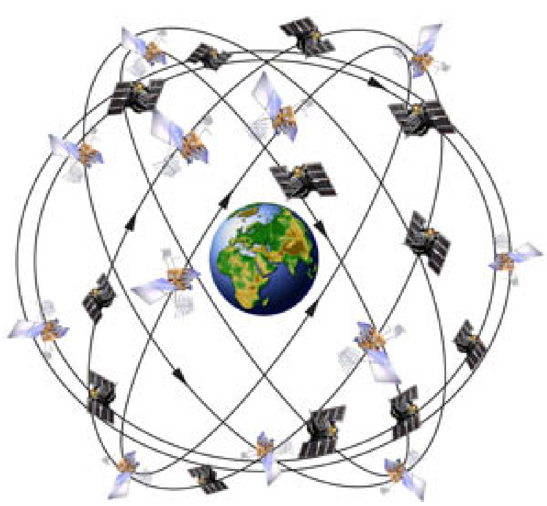


Figure 2: The GPS Constellation Image source: U.S. Space Force

Vulnerabilities and Other Disadvantages of Current U.S. Satellite Constellations

Since the launch of the first American satellite into orbit in 1958, satellite constellations have become indispensable to modern life. Because they are critical to today's highly interconnected world, the degradation or destruction of space assets and the networks they enable could result in massive economic losses and cost many lives. As alluded to in the previous example, GPS is now vital to nearly all forms of air, land, and sea transportation. The human and economic consequences of even a temporary loss of GPS signals to these sectors could be severe. GPS and other satellite constellations have become a "center of gravity" for the military and economic power of the U.S. This reality has not gone unnoticed by China and Russia.

During Operation Desert Storm—called the "first space war" by some—China's military leaders noted that space systems provided U.S.-led coalition forces with precision navigation and enhanced command and control across challenging terrain. These nascent advantages became more and more critical to U.S. forces during Operations Allied Force in Kosovo and later in Operation Enduring Freedom and

Operation Iraqi Freedom with the advent of operational GPS-guided weapons in the late 1990s. Today, DOD's reliance on space is central to its new warfighting concepts including Joint All Domain Command and Control (JADC2). It is no surprise, then, that China, in particular, has rapidly fielded multiple space and counterspace systems with the intent to surpass and eventually gain military superiority over the United States, as well as hold U.S. systems in space at risk.

China's view of space warfare

China seeks to exploit U.S. vulnerabilities in space through its unique view of deterrence and warfighting. America's greatest strategic competitor does not share the U.S. perspective of basing deterrence solely on threatening the use of force—China intends to use force to coerce and prevent an enemy from intervening against its operations in the first place. This "attack to deter" concept relies on rapidly maneuvering to exploit an adversary's weak points and achieve psychological and physical effects.[14] Toward this end, the PLA is preparing to conduct operations that will disrupt, preempt, and dislocate its enemies:

- **Disruption.** China could conduct disruption operations in a "period of tension" or combine them with "rapid and destructive" space attacks to create reversible and irreversible effects on U.S. and allied space systems.[15] This could include pre-conflict operations such as jamming and blinding an adversary's intelligence satellites with lasers. In a more advanced state of crisis, these lesser actions could be combined with simultaneous kinetic strikes.
- **Preemption.** Preemptive operations are intended to defeat an enemy before fighting has begun. China believes it is important to "create psychological fear… and have an influence on… national decision makers" to achieve its strategic objectives before a war has officially been declared.[16] This course of action is vital to China's attack to deter form of deterrence.
- **Dislocation.** If an attack to deter fails to create the desired impact and coerce U.S. leadership to take a strategic pause, China would be prepared to conduct prompt operations to dislocate U.S. and allied spacepower advantages by delivering "destructive strikes to the enemy [in space]…in order to fight rapidly, conclude the operation rapidly, and to withdraw from the confrontation."[17]

According to publicly available sources, China continues to expand its operational counterspace weaponry, including its arsenal of ground-launched missiles carrying ASAT kinetic kill vehicles and space electronic warfare capabilities.[18] The PLA has demonstrated kinetic ASAT weapons that can threaten U.S. space systems in LEO, MEO, and GEO. It also has operational units that use radio-frequency jamming to disrupt SATCOM, GPS, missile warning, and other vital space systems. The PLA is developing and testing weapons that can rendezvous with orbiting U.S. satellites and observe or attack them kinetically using robotic arms or non-kinetically with electronic warfare, as described earlier. All these capabilities are part of China's preparations to conduct its "rapid and destructive" space warfare.[19]

Looking Forward

Today, satellites with limited chemical propellants can take weeks to months to maneuver across orbital regimes and take other actions to avoid attack and defend themselves against these burgeoning threats. As Chinese and Russian military space and counter-space operations continue to mature, the ability to rapidly maneuver across orbits and even out to the moon—referred to as

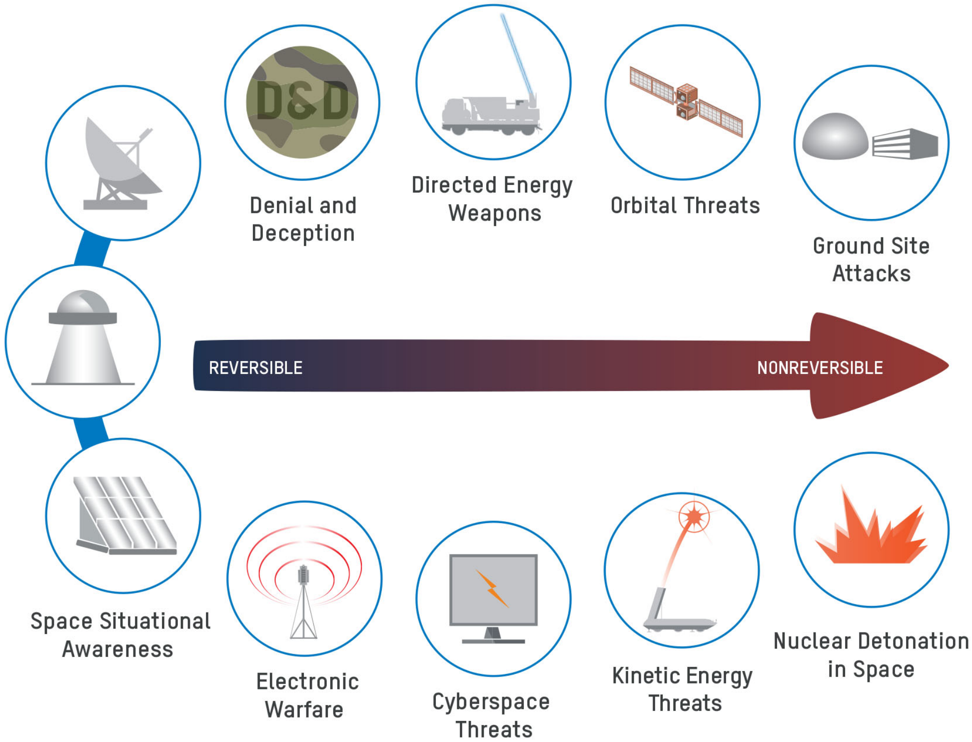


Figure 3: Counterspace Threat Continuum

Image Source: Defense Intelligence Agency

cis-lunar space—will become increasingly critical to U.S. security interests. The USSF must address its maneuver disadvantages, change its forces, and alter the way they operate to get ahead of emerging threats, rather than wait for adversaries to fully mature them. This will require the USSF to field new space vehicles with SNP technologies. Otherwise, the United States and its allies and friends will be at greater risk due to China and Russia's pursuit of nuclear thermal and electric propulsion vehicles and other weapons systems that will give them a major advantage in space maneuver warfare.

Transitioning U.S. Military Space Strategy from Limited to Enhanced Space Maneuver Warfare

Given that space is an increasingly contested operational environment, it is imperative for the United States to shift its space force design and warfighting strategy to conduct maneuver operations in orbit and beyond. This would greatly increase the U.S. military's options to take deliberate measures to deter, avoid, and defeat threats—field an active defense—instead of simply allowing its passive constellations to absorb attacks to the point of failure.

At present, U.S. satellite constellations supporting civilian and national security missions rely on chemical-based propulsion to maintain their orbits and make limited maneuvers to steer out of the way of incoming objects. While chemical-based propulsion gives satellites some ability to maneuver, their limited onboard fuel supply means they can quickly run out of propellant. This is comparable to aircraft that have ranges that are fundamentally limited by their fuel capacity and speed. Military forces exploit these limitations by moving their high-value targets to locations deep in their country's interiors, out of range of an enemy's aircraft. Adversaries also know how limited fuel affects spacecraft operations and have designed strategies to gradually reduce satellite mission lifespans by forcing their operators to command defensive maneuvers that deplete satellite chemical propellant stores. Consider a plausible scenario where the U.S. Space Command maneuvers an ISR satellite to avoid a tracking laser fired by an adversary attempting to blind the satellite's sensors. Over time, these maneuvers would deplete the satellite's propellant stores, preventing it from maintaining its required mission orbital parameters. Even though the satellite may still have functioning sensors and other payloads, it would become operationally useless.

Given that space is an increasingly contested operational environment, it is imperative for the United States to shift its space force design and warfighting strategy to conduct maneuver operations in orbit and beyond.

Any country seeking to degrade an adversary's space capabilities must consider how it can most efficiently achieve the greatest successes. In the context of offensive space operations, this means determining space targets that would create the most debilitating effects on an enemy's psychological condition and ability to conduct military operations. Finding and attacking these critical elements, or centers of gravity, are also a commonsense approach to terrestrial warfare. Consider strategic bombing theory as an example. A goal of major strategic bombing campaigns of the past was to deplete an enemy's warfighting capability by using bombers and other aircraft to strike industrial targets. In space, targeting an enemy's space infrastructure is a means of degrading or limiting their warfighting effectiveness. This is where maneuver enters the equation from a defensive perspective. Targeted space assets that can rapidly maneuver are more difficult for an enemy to attack. Plus, the ability to maneuver increases options to degrade an enemy's ability to project power in space and other operating domains. In short, maneuver warfare is about maneuvering around an enemy's strengths and degrading its ability to continue to fight by exploiting its critical vulnerabilities. This maneuver-based space warfighting concept is grounded in three principles: 1) Identify an enemy's centers of gravity; 2) Exploit an adversary's systemic centers of gravity; and 3) Maintain your own space and terrestrial force advantages.

- **Identify and target centers of gravity.** In maneuver warfare, the center of gravity is an adversary's greatest weakness, not its greatest strength. For the United States and its allies, satellite constellations and other space forces are critical to their economies in addition to their ability to conduct decisive military operations. They are therefore also one of their greatest vulnerabilities—which make them a center of gravity for enemy attacks.
- **Exploit enemy centers of gravity.** A successful space campaign must hit an enemy's vulnerabilities hard, fast, and continuously. This requires treating attacks from, to, and in space as valid warfighting options rather than treating space missions as warfighting support functions. More simply put, it all comes down to proactively deterring an attack while simultaneously seizing the initiative and being in position to deny or degrade an enemy's space warfighting options.
- **Maintain advantages in space and other operating domains.** Setting the terms for deterrence and warfighting operations—which requires determining the best times, places, pace, intensity, and types of engagements—is essential to maintaining the initiative over adversaries. This applies to space warfare as well as other forms of combat operations. The main challenge of

> maneuver is to establish and sustain the strengths of friendly forces while exploiting enemy weaknesses.

The U.S. national security space enterprise is at a crossroads—it can create a future force capable of maneuver warfare in space, or it can persist with legacy force design concepts that make it vulnerable to China's and Russia's ASAT capabilities. Deterrence and the ability to prevail in war requires agile U.S. space forces. This is similar to capabilities that operate in the air domain. The U.S. non-maneuvering "passive" space architecture is analogous to aircraft that maintain constant speeds, altitudes, and headings inflight. While this is desirable and economical in the commercial sector as a way to transport passengers over long distances in peacetime conditions, it makes military aircraft that do this in contested airspace much easier to target. The ability to maneuver changes this markedly, which is why rapid and sustainable maneuvering must be a design requirement for U.S. forces in space. As General (ret.) and former astronaut Kevin Chilton says, "Delta v [the ability to change velocity as needed] is the coin of the realm." The sooner the United States acknowledges this reality and develops superior space maneuver capabilities of its own, the better.

This new space calculus also ties to deterrence theory. Shaping a competitor's actions is a key objective in peace as well as in war. Securing desired effects while avoiding outright conflict is an incredibly smart, efficient form of engagement, which is why some countries seek to develop nuclear weapons. Countries facing a nuclear-armed opponent may be far less willing to pursue certain activities because the potential benefits of doing so are outweighed by the risk of nuclear conflict. In a space context, U.S. leaders should never allow themselves to be "self-deterred" by failing to develop countermeasures to an adversary's space forces. As an example, the United States must not shy away from developing countermeasures to the orbital weapon carrying a hypersonic glide vehicle recently tested by China simply because of how serious of a threat it poses; that only cedes China the advantage in space by default.[20]

It is also important to understand that maneuver in space is not the sole means of protecting orbiting assets. Maneuvering space forces should be part of a multi-tiered force design approach that includes proliferated constellations and hardened systems. Proliferated constellations involve launching a highly distributed number of satellites into constellations so an enemy would have to degrade or destroy a large number of satellites to compromise a constellation's operational effectiveness. Although there is no single point of failure in this amorphous approach, there is a tipping point where a certain number of satellites must be destroyed. Hardening satellites is not like adding armor to a tank, but it is one measure that provides them with limited protection against things like radiation from space and the limited use of nuclear weapons in the upper atmosphere and in space.

As with any layered defense approach, it is important to understand where each layer affords value. A shift to maneuvering capabilities should focus on adapting satellite constellations that are critical national resources and can increase defensive and offensive options against threats. Two examples include GPS and ISR satellite constellations. Whether guiding precision munitions or keeping power plants operating, GPS provides navigation and timing data that is vital to our national and economic security. ISR satellites operating in LEO and GEO are similarly vital, whether providing information for military operations or empowering farmers to better understand how to care for their crops. All these resources will be at increased risk if the United States fails to take a new look at an old technology—nuclear thermal propulsion—to create a space force capable of defensive and offensive maneuver warfare.

Nuclear Thermal Propulsion: Advanced Propulsion for Enhanced Maneuver Advantage

Nuclear thermal propulsion is the key technology that is necessary to underpin a USSF and warfighting strategy design to counter China's and Russia's ASATs. Engines that chemically burn fuels with an oxidizer to create thrust are now the most common form of propulsion for rockets and other space vehicles. While chemical rockets have higher thrust than SNTP, the advantage of SNTP is that less propellant is required to achieve a given thrust.[21] To compensate for lower thrust, SNTP can conduct longer, more propellant-efficient engine run times or "burns" and at lower mass so that it can achieve higher velocities, hence shorter flight times. SNTP can perform much longer missions as well as multiple missions from a single vehicle. It can also be resupplied with hydrogen (NTP) propellants. Nonetheless, the nuclear reactor systems can operate for years in space without the need to be refueled.

SNTP engines are far more propellant efficient than chemical propulsion

SNTP engines can also deliver the velocity and maneuverability needed to conduct maneuver operations in space with great efficiency—bottom line, they can operate with less "propellant" than their chemical counterparts and therefore can operate for longer mission times. SNTP engines are designed with a small nuclear reactor that uses fission to generate heat. Propellant, typically liquid hydrogen, is superheated and thermodynamically expanded as it flows through the fission reactor. The higher the engine's temperature, the greater the thrust and propellant efficiency (or specific impulse). Moderating materials, control rods, and reflectors made of temperature-tolerating materials, such as graphite and ceramics, control thermal power created by the fission reaction. These materials can sustain high temperature and are the "secret sauce" that allow SNTP engines to generate higher specific impulse than chemical engines. New materials such as ceramic composites are now being explored and may be able achieve even greater SNTP engine specific impulse and thrust-to-weight ratios.

Increased energy density of SNTP engines

To put into context the SNTP energy advantages—the ability to generate thrust with less propellant and other materials—the uranium used in NTP reactors, typically Uranium 235, has an energy density 4 million times greater than hydrazine, a chemical propellant in many satellite propulsion engines (thrusters). While the mass of the hydrogen propellant is comparable to the mass of a chemical rocket's propellant, the sum of the hydrogen and nuclear reactor's mass is much less than the sum of the chemical propellant and combustion chamber's mass in a chemical engine system.

When all factors are considered, nuclear thermal propulsion systems are more than twice as fuel-efficient as chemical propulsion systems. This means they generate a given amount of thrust with less than half the amount of propellant mass. They are also able to deliver more than 100,000 Newtons of thrust—that's enough power to accelerate a typical automobile from 0 to 60 miles per hour in 0.3 seconds. Such efficiency, power, and speed are essential to achieving the responsiveness needed for maneuvering operations in Earth orbit, between orbits, and in cis-lunar space.

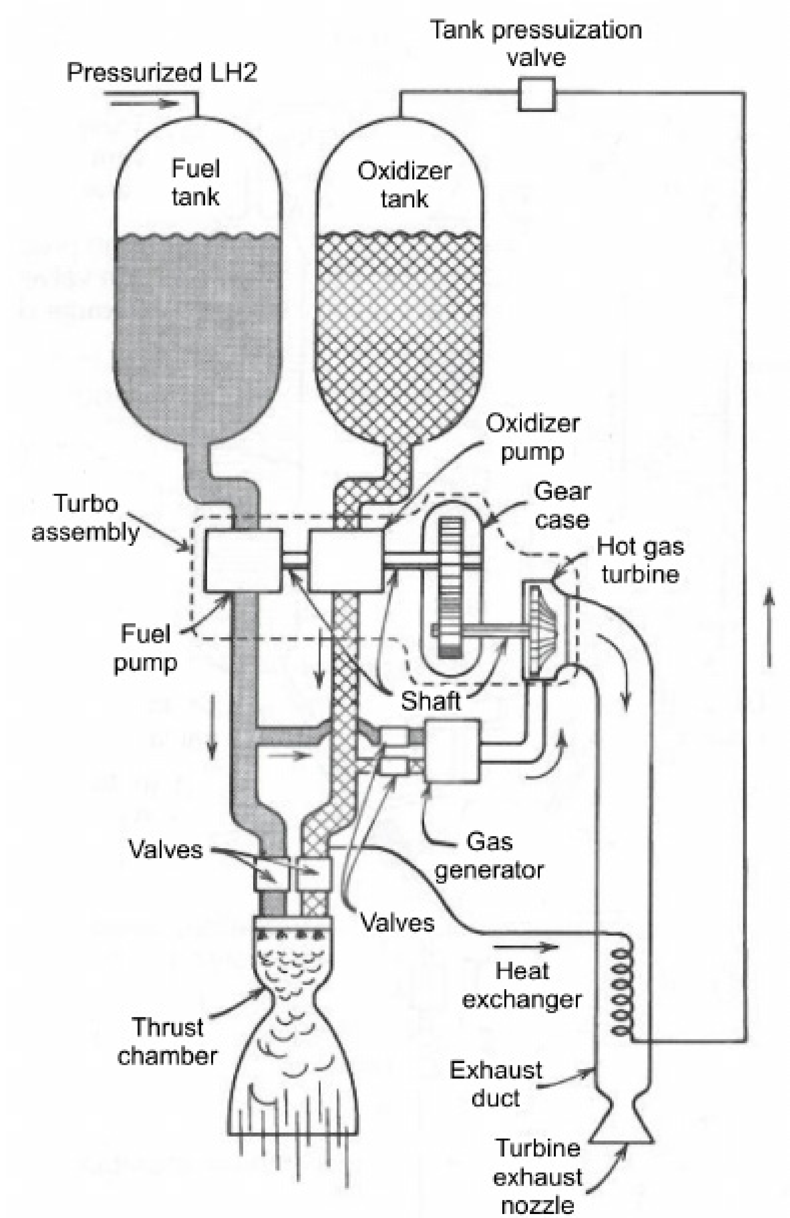


Figure 4: Chemical Propulsion Engine

Credit: Available via Research Gate

Nuclear thermal propulsion in space is a safe capability

Nuclear thermal propulsion is not only efficient, but it is also very safe to operate. Engineers have improved reactor designs and procedures over the past 70 years with human safety as the number one priority. These engine systems should not be considered in the same vein as nuclear weapons or legacy nuclear power reactors. Instead, the reactor is essentially a "heater" that heats its propellant by using fission energy—it has no explosive or overheating capacity when stored and launched. This is because SNTP reactors are kept in a "cold, subcritical state" when stored prior to and during launches. This means the materials are not a radioactive hazard until the reactor is turned on for a prolonged period, which occurs in space and not during launch or within the Earth's atmosphere. Plus, the most common nuclear fission material used in nuclear propulsion projects to date, prior to fissioning—Uranium 235—has relatively low radioactive levels that match the types of background radiation we are exposed to from natural sources on Earth.[22] Once deployed in a "nuclear safe orbit" (broadly anything above 750 km), the reactor only needs to run during the actual thrust operation of the engine or to provide electrical power to its thrusters and instruments. For nuclear thermal propulsion, this translates to short thrust times of several minutes. SNTP engines do not generate radioactivity when not running, but they do generate from some radioactive fission products they contain. However, if any fission products escape from the reactor, they are harmlessly dispersed into the vast expanse of space.

A different scenario where safety would be demonstrated is in the unlikely event of the SNTP reactor plunging back into the earth upon launch. Of course, the physical impact of any object falling from great heights is also a factor with non-nuclear launch objects, such as conventional rockets and satellites. These are mitigated by launching the nuclear space vehicle on board a standard chemically propelled launch vehicle over water and securing a launch path that minimizes or avoids such an impact altogether. Therefore, an additional consideration for a shutdown nuclear reactor is what happens if it is plunged into water. Any potential for the reactor to lead to a criticality event, or nuclear fission

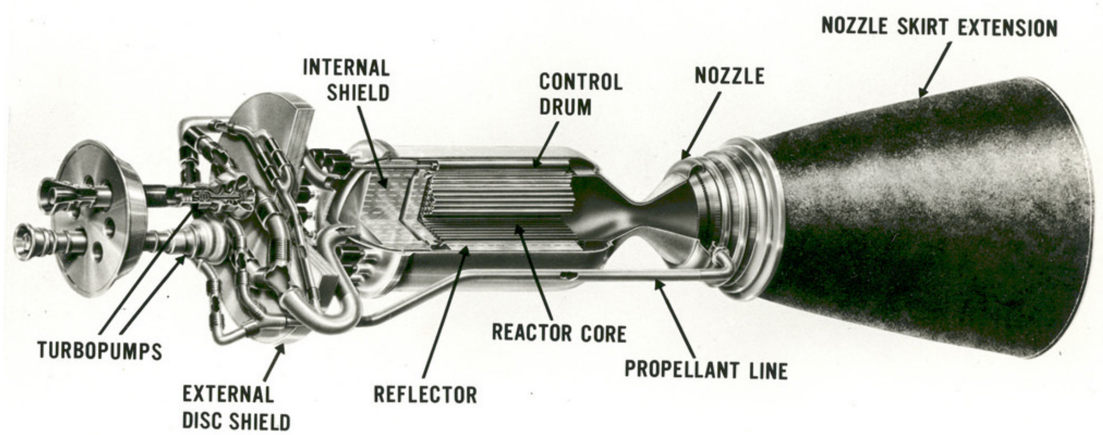


Figure 5: Nuclear Thermal Propulsion Engine

Credit: NASA

chain reaction, is prevented by the design of the space reactor in the first place—recall that the reactor works by generating heat, not an explosion. This ensures that inadvertent criticality events cannot occur, even in the event of a launch failure resulting in a crash into the ocean. It is also important to note the safety risk that exists from the current liquid chemical propellant engines. These propellants are incredibly toxic and present a far greater threat to human safety if they fall back to earth as part of a failed launch attempt.

The view that spacecraft powered and propelled by nuclear systems will lead to disasters continues to persist in some communities and has repeatedly prompted policymakers to decide against pursuing these technologies. Previous experience over nearly seven decades shows that accidents are rare and the technology is safe, easy to control, and operationally viable. The Defense Advanced Projects Research Agency's (DARPA) demonstration rocket for agile cislunar operations (DRACO) project is taking an even more innovative approach to nuclear safety by testing the propulsion efficiencies of low enriched uranium-based core reactor-engines in orbit.[23] Presidential authorization is not required for low enriched uranium (LEU) reactor engines. Should a high enriched uranium(HEU)-based core be used, as a final check to ensure safety, presidential approval is required for launching HEU nuclear materials and reactor-based systems into space.[24] In either case, the impact on our national security from not operationalizing this technology is far greater than the safety and environmental concerns that have been solved thanks to decades of research and testing.

Past and present requirements for space nuclear thermal propulsion

The United States has studied, tested, and regulated nuclear propulsion systems since the 1960s but never flew them in space due to self-induced policy and budget constraints. In the early years of the Cold War, nuclear rocket engines were thought of as a near-term solution for the upper stages of intercontinental ballistic missiles (ICBMs) and as power sources for large spy satellites. In the late 1950s and early 1960s, nuclear thermal engines were looked at as options for propelling hardware and personnel located at military lunar bases and the Strategic Air Command's concept for manned Earth-orbiting C2 outposts. However, nuclear thermal propulsion research projects such as the nuclear engine for rocket vehicle application (NERVA) program never transitioned to operational engines that flew in space. Engines were also developed for flight before being transferred to NASA to support its post-Apollo Mars exploration efforts. As national priorities shifted from deep space exploration and toward the Space Transportation System, commonly known as the Space Shuttle, and other Earth-orbiting assets, these SNTP programs never became operational and were finally canceled in the early 1970s.

The Strategic Defense Initiative (SDI) of the 1980s temporarily resurrected interest in SNTP. SDI sought to use space-based weapons to protect the United States from incoming Soviet ICBMs and other threats. U.S. leaders also explored SNP for space vehicles that could conduct rapid orbital transfers, high-speed missile intercepts, and anti-satellite missions as well as observe, inspect, and potentially strike spacecraft if required. The U.S. Government curtailed these efforts at the end of the Cold War, as it did a number of other defense programs that were designed to maintain DOD's comparative advantages over the USSR.

It is now time to revisit nuclear propulsion as a technology that will transform U.S. national security space operations from a limited maneuver, limited resilience model to a force design capable of maneuver warfare. This is a must-do for the U.S. space enterprise given China's shift to space maneuver warfare and the rapid growth in ASAT threats and hypersonic weapons that could carry nuclear warheads. DOD previously deferred transitioning its SNP science and technology (S&T) efforts to acquisition programs because of the lack of a threat to its space architecture. Alternate solutions were considered more than acceptable in the past. This is no longer the case, and the unique capabilities provided by SNP are extremely relevant for operations in a contested space domain. Fortunately, the U.S. space enterprise community has a long history of science and technology investments that has created a technological foundation for the rapid acquisition of space vehicles with nuclear thermal propulsion. This seed can easily grow into capabilities that will maintain America's strategic advantages in space.

Figure 6: DRACO Concept Image

Image source: DARPA

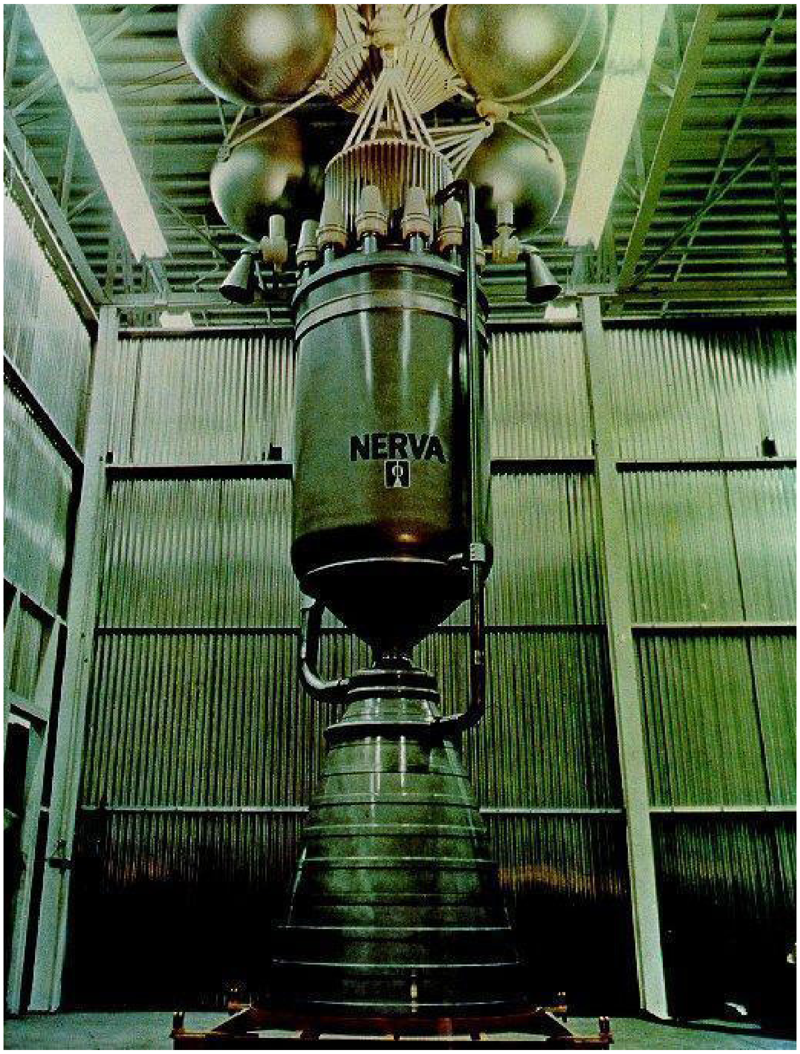


Figure 7: NERVA Rocket Engine

Credit: NASA image available via WIRED

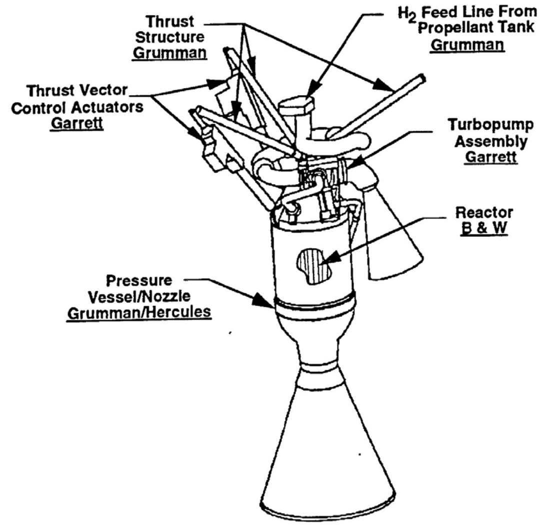


Figure 8: SDI Nuclear Engine

Credit: R.A. Haslett, Space Nuclear Thermal Propulsion Progam Final Report (Bethpage, NY: Grumman Aerospace Corporation, 1995), p. 1–6.

In the meantime, it is important that the Space Force provide a hedge while DRACO continues its testing and transition into a program of record. Maneuver warfare is already a present-day situation. In order to counter Chinese ASATs and secure future SNTP-enhanced maneuver forces, it is imperative that we deploy comparable weapons systems and means to save limited chemical propellants and ensure some measure of maneuver for the defense of critical satellite constellations. Two such hedges are the deployment of the United States' own kinetic ASAT systems leveraging current programs of record, such as the Standard Missile-3 or the Ground Based Mid-Course Defense (GMD) interceptor. In addition, the Mission Extension Vehicle (MEV) has been demonstrated on commercial satellite systems as a means of extending life and conducting orbital transfers. Currently in testing, MEVs are spacecraft designed to reposition or maneuver a satellite to a new mission orbit or orbital slot without using onboard propellant. In 2019, MEV-1 docked with Intelsat 901 and successfully moved it to a new orbit. While designed for GEO operations, it may be feasible to modify MEV-type vehicles for use in other orbital regimes. MEVs are a bridge option, not an enduring solution, since they are still not as fast and responsive as space nuclear thermal propulsion.

Conclusion and Recommendations

Our country is now awake to the threats that China and Russia pose to our national security, including our vital interests in space. Traditional resiliency measures alone are insufficient to protect and defend against enemies like China that believe rapid and destructive space warfare will be part of future great power conflicts.[25]

The U.S. military's vulnerability to kinetic anti-satellite missiles and directed energy weapons are magnified by its chemically propelled satellite constellations. DOD must address these vulnerabilities by fielding forces that can gain and maintain the degree of dominance in space necessary to prevail against great power aggression. Vehicles that can rapidly maneuver to accomplish defensive and offensive operations in, from, and to space will be vital to achieving this objective. This will require the Department of Defense to invest and deploy SNTP technologies that are safe, reliable, and give satellites and other spacecraft the ability to conduct rapid maneuvers that chemical propulsion cannot. Due to technological advances, nuclear propulsion is now far more efficient than technologies developed by the NERVA project in the 1960s and SDI in the 1980s. It is also a safe technology. Thrust is not created by a nuclear explosion, but by transferring heat from a nuclear reactor to a liquid propellant that expands and exits through a nozzle to provide thrust for a spacecraft. Failing to deploy this game-changing technology would increase risk that our nation will not be able to protect and defend its vital interests in space against the increasingly capable space forces of China and Russia.

The following recommendations are intended to inform the development of U.S. forces in space capable of defensive and offensive maneuver operations leveraging currently available cost-effective technology.

- DOD should adopt a new space force design capable of decisive maneuver warfare in space. Without the ability to rapidly maneuver, DOD's disaggregated and proliferated LEO systems will only provide additional targets for Chinese and Russian kinetic and non-kinetic counterspace weapons systems. DOD's 2020 Defense Space Strategy is a good start to address changing threats, but it does not go far enough.
- DOD, in partnership with NASA and the Department of Energy, should develop and field SNTP and other technologies that will increase their ability to deter and defeat threats against the U.S. national security space architecture. After nearly 70 years of development, experimentation, and testing, now is time to operationalize SNTP space systems.
- Beginning in FY 2024, the Biden administration and Congress should allocate the resources necessary to move DARPA's DRACO program from science and technology development to a full acquisition program of record. This will help DOD to operationalize a space maneuver warfare-based force design before America's strategic competitors.
- Until maneuvering SNTP forces can be fielded, DOD should deploy ground-based and space-based kinetic ASAT weapons systems capable of holding Chinese and Russian targets at risk. This will provide U.S. leadership with near-term options to deter and defend against anti-satellite threats. DOD could achieve this objective by repurposing existing initiatives, including its standard missile and ground based mid-course missile defense interceptor programs.
- DOD should hedge against risk by deploying the mission extension vehicle (MEV) to provide GPS and other vital satellite constellations the ability to conduct limited defensive maneuvers while preserving their onboard chemical propellant.
- The U.S. Space Force must educate the public and Congress on the growing

threat to U.S. space systems and the need to create a more robust force design that will enhance deterrence. SNP can help create a much-needed agile maneuvering force capable of generating a wide range of defensive and offensive effects in, from, and to space at a time and place of our choosing.

The U.S. Space Force has a vital mission: to organize, train, and equip for the conduct of decisive military operations to, from, and in space. Gone are the days when space was simply a force multiplier for air, land, and sea forces. At hand is nothing less than the time foreseen by visionaries such as General Bernard Schriever, who prophetically said, "Several decades from now, the important battles may not be sea battles or air battles, but space battles, and we should be spending a certain fraction of our national resources to ensure that we do not lag in obtaining space supremacy."[26] Without the capability to maneuver in space it will be difficult for the United States to prepare for such a future—and that future is now. ✪

Endnotes

1 Department of Defense (DOD), *Defense Space Strategy Summary* (Washington, DC: DOD, June 2020).
2 For more on how and why the U.S. space architecture was developed into its current state, see Kevin P. Chilton and Lukas Autenried, *The Backbone of JADC2: Satellite Communications for Information Age Warfare* (Arlington, VA: The Mitchell Institute for Aerospace Studies Spacepower Advantage Center of Excellence, December 2021).
3 This also includes the small sat-based proliferated constellations under the "resilience" concept. While there may be more satellites in the constellation to provide a tougher targeting calculus, it does not remove the threat from the space vehicles of kinetic or non-kinetic attack, given current Chinese and Russian doctrine.
4 Walter J. Boyne, "Linebacker II," *Air Force Magazine*, November 1, 1997.
5 Office of the Director of National Intelligence (ODNI), *Annual Threat Assessment of the U.S. Intelligence Community* (McLean, VA: ODNI, April 9, 2021), pp. 7–8.
6 "Russian direct-ascent anti-satellite missile test creates significant, long-lasting space debris," press release, U.S. Space Command Public Affairs Office, November 15, 2021.
7 Angelique Chrisafis, "'Act of espionage': France Accuses Russia of trying to spy on satellite data," *The Guardian*, September 7, 2018. In space lexicon, this kind of rendezvous conducted without prior knowledge or approval is referred to as "snuggling up."
8 DOD, Defense Space Strategy Summary, p. 3.
9 For more on LEO constellations and their potential, especially when paired with laser communications and updated ground infrastructure, see Chilton and Autenried, *The Backbone of JADC2*.
10 U.S.-China Economic and Security Review Commission (USCC), *2019 Report to Congress of the U.S.-China Economic and Security Review Commission* (Washington, DC: U.S. Government Printing Office, November 2019), p. 380.
11 While a more resilient force design such as proliferated LEO would help deter attacks, no study has been conducted on how many satellites could be lost before constellations, proliferated or monolithic, reach their tipping points in terms of not being effective.
12 Avery Thompson, "China Wants a Nuclear Space Shuttle by 2040," *Popular Mechanics*, November 16, 2017.
13 *Preliminary Design of an Experimental World-Circling Spaceship* (Santa Monica, CA: RAND Corporation, 1946).
14 Sun Zhaoli, *The Science of Military Strategy* (Beijing: Academy of Military Science Military Strategy Studies Department, Military Science Press, December 2013); and Christopher Stone, "Rethinking the National Security Space Strategy, Chinese vs. American Perceptions of Space Deterrence," *Space Review*, November 4, 2013.
15 Zhaoli, *The Science of Military Strategy*, p. 230.
16 Zhaoli, The Science of Military Strategy, p. 229.
17 Kevin Pollpeter, "The Chinese Vision of Space Military Operations," in, *China's Evolving Military Strategy* (Washington, DC: Brookings Institution, 2016), p. 342.
18 ODNI, Annual Threat Assessment of the U.S. Intelligence Community, pp. 7–8.
19 Zhaoli, The Science of Military Strategy, p. 240
20 Theresa Hitchens, "It's a FOBS, Space Force's Saltzman confirms amid Chinese weapons test confusion," *Breaking Defense*, November 29, 2021.
21 NTP has much higher (2–3 times) specific impulse (Isp) than chemical propellant. Specific impulse or Isp is is a measure of how efficiently a reaction mass engine creates thrust.
22 U.S. Air Force, U.S. Department of Energy, *Final Environmental Impact Statement: Space Nuclear Thermal Propulsion Program, Particle Bed Reactor Propulsion Technology Development and Validation* (Washington, DC: U.S. Air Force, May 1993).
23 Nathan Greiner, "DRACO Program Overview," DARPA Briefing Prepared for The Aerospace Industries Association (AIA) Space Council, May 4, 2021.
24 Reina S. Buenconsejo et al., *Launch Approval Processes for the Space Nuclear Power and Propulsion Enterprise* (Washington, DC: Institute for Defense Analyses, September2019), pp. 46–47.
25 Zhaoli, The Science of Military Strategy, p. 240
26 Maj. Gen Bernard A. Schriever, Address to Astronautics Symposium, Air Force Office of Scientific Research, San Diego, February 19, 1957.

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