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High-Altitude Nuclear Explosions

Myths and Reality

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THE ISSUE

Thankfully, no party has used nuclear weapons in war since 1945. Treaties limiting nuclear tests and weapon inventories during the Cold War highlighted the pragmatism of world leaders. As memories fade, and nascent nuclear states mature, the potential for their use (or misuse) rises. In a strategic environment with multiple nuclear-armed states of various sizes and incentives, it is important to understand the science underlying the use of nuclear weapons in novel and unexpected ways. As opposed to the ground bursts of World War II, their use in the sky has potential to achieve certain objectives without catastrophic loss of life. Due partly to the lack of testing and partly to a somber reluctance to consider this potentiality, many misunderstandings persist. There is a need to address prevailing myths about the use of high-altitude nuclear explosions and provide realities rooted in the existing research on the subject.

Waging war against an enemy with dominant digital communications systems is a recipe for defeat. Modern digital communications structures enable lethal kill-chain targeting cycles, seamless command and control, and precision guidance that dominate the enemy. This reality makes the space and cyber domains a primary target in future warfare. All tacticians seek to degrade their adversaries' communications in war, but few consider the literal "nuclear option" that could fundamentally upend the current communications ecosystem. High-altitude nuclear explosions (HANEs) allow an actor to degrade modern communications, either on the ground or in the sky. Closer to the ground, HANEs create a high-altitude electromagnetic pulse (HEMP) that could shut down power plants, cellular towers, and electronic devices. Higher in the sky, HANEs produce radiation that can damage or destroy satellites. If a state actor (or rogue element) decides that access to digital systems or the space domain is giving its adversary an unfair edge, it might decide to use a HANE to negate this advantage without directly killing a single human.

The norm against using nuclear weapons endured for decades, but recent saber-rattling and proliferation trends suggest this restraint is fragile. Would adversaries consider launching a HANE attack that destroys and degrades electronics without direct loss of human life? Would such an attack be perceived as a breach of the international taboo on nuclear weapons use? This paper examines existing research on HANE effects to dispel misconceptions and clarify the potential consequences of such a scenario.

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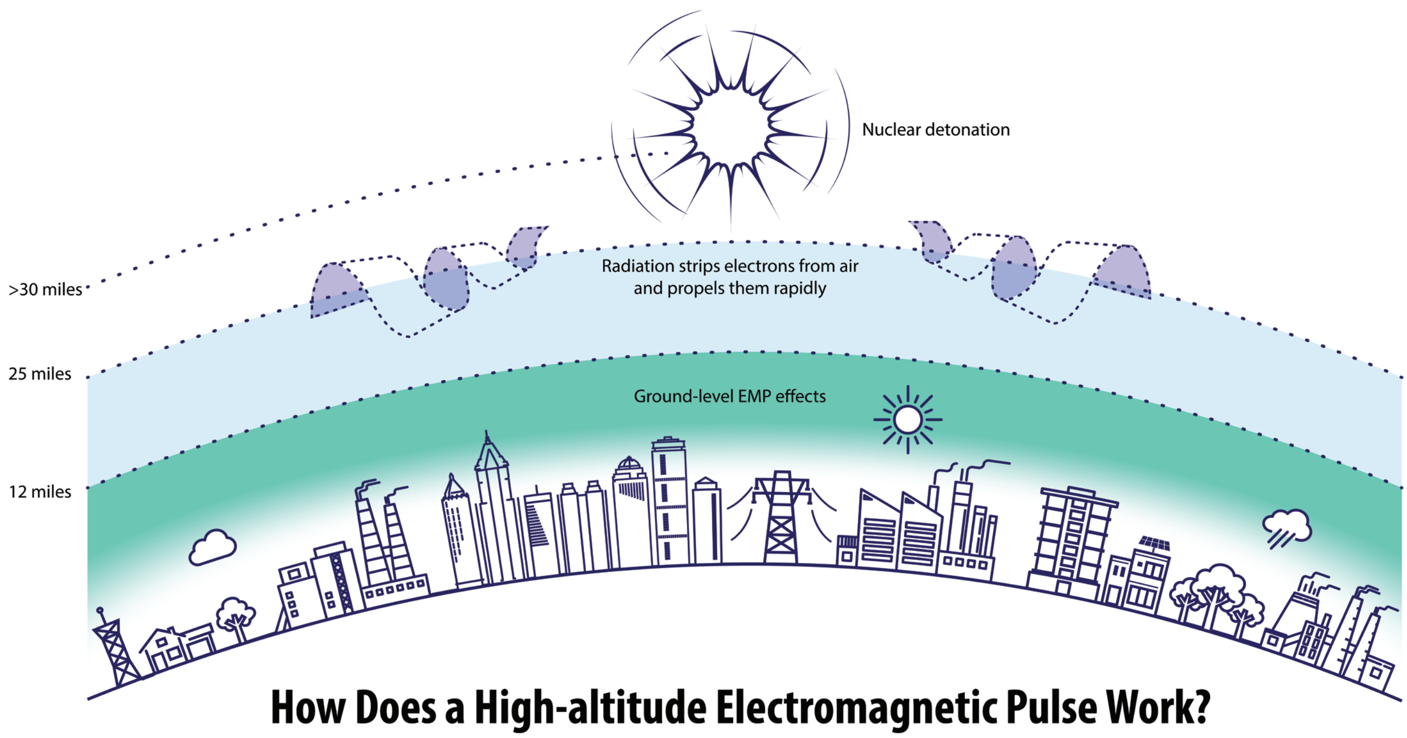
HANE EFFECTS 101

A HANE is a nuclear detonation above 30 kilometers (19 miles), where the density of air is low enough that energy from the nuclear weapon interacts with its surroundings in a markedly different manner than a "mushroom cloud" of a detonation nearer to the ground.[1] These detonations create damage to electronics within the Earth's atmosphere through their production of HEMPs. E1, the most damaging HEMP mechanism created by HANEs, results because the air density is extremely low around the explosion, unlike at lower altitudes.[2] Therefore, electromagnetic radiation can travel great distances in a downward direction before interacting with air molecules (Figure 1). Many of these interactions result in ionization, or the freeing of electrons, which cause a burst of electromagnetic energy as they are deflected by the Earth's magnetic field.[3] This burst of energy, or EMP, occurs over a large area, where it causes damage and disruption to electronics.

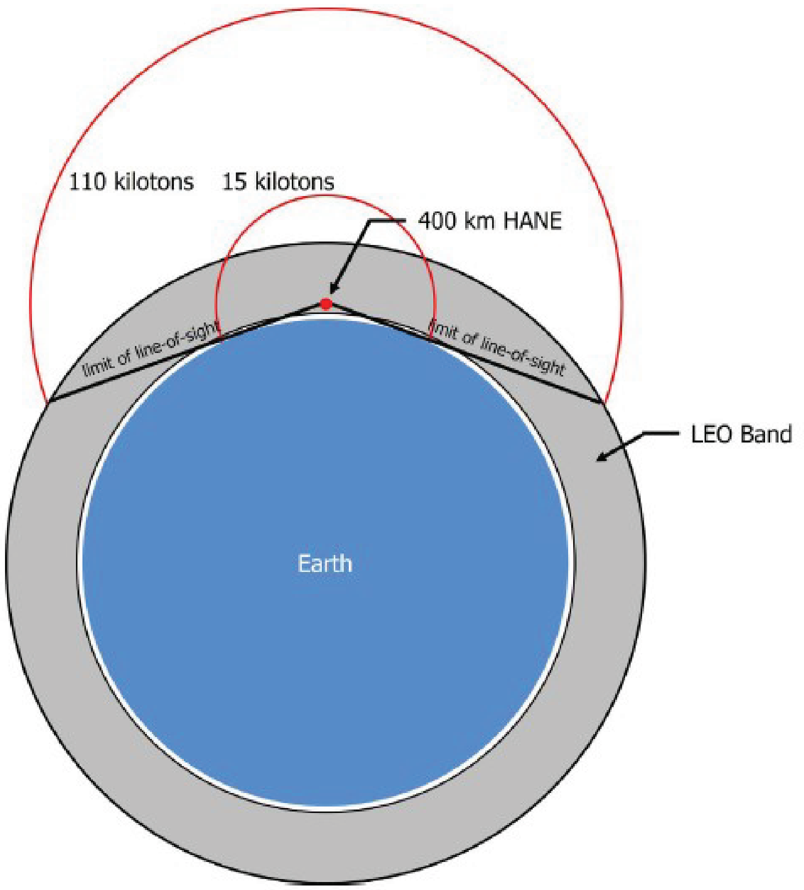
HANEs can damage or destroy satellites through two primary mechanisms. First, high levels of prompt radiation from gamma rays, X-rays, and neutrons can travel relatively unimpeded directly to satellites due to the low density of the atmosphere (Figure 2). This is limited to satellites within line of sight (LOS) of the HANE, with the Earth shielding many others. The amount of prompt radiation, or dose, that a satellite receives increases with increasing yield and decreases proportional to the square of the distance from the explosion. Second, free electrons resulting from an explosion can become trapped in artificial radiation belts due to the Earth's magnetic field, creating a hostile environment for satellites passing through. These electrons can be trapped for years and may drastically decrease the lifespans of satellites orbiting through them, even if they were initially outside of the

Figure 1: Creation of the E1 Field of a HEMP



Source: DaHan Liao, Larry Markel, and Yilu Liu, "Study Probes Risks to Power Plants from Electromagnetic Pulse," Oak Ridge National Laboratory, November 9, 2023, U.S. Department of Energy, https://www.ornl.gov/news/study-probes-risks-power-plants-electromagnetic-pulse. Graphic created by Andy Sproles/ORNL.

Figure 2: Prompt Radiation Field of View from a 400-km (LEO) HANE



Note: Red circles represent where satellites are at risk for damage for two different yields. For large weapons, all LEO satellites that are not shielded by the Earth are at risk.

Source: Don Snyder et al., *The Effects of High Altitude Nuclear Explosions on Non-Military Satellites* (n.p.: RAND Homeland Security Operational Analysis Center, 2025), 9, https://www.rand.org/pubs/research_reports/RRA3028-3.html. Graphic used with permission from RAND.

HANE's LOS.[4] Additionally, this radiation belt presents challenges in reconstituting space with new satellites due to the lasting effects. For example, a new satellite designed to last two years may only last a couple of months due to the new trapped radiation. Shielding and radiation hardening can significantly increase the amount of radiation dose required for damage from both of these mechanisms; however, it is not practical to completely shield from the prompt effects of a HANE of sufficient yield and proximity.[5] Additionally, shielding to the level required to protect against HANE effects is generally only seen in military satellites because it is currently cost-prohibitive for commercial applications.[6]

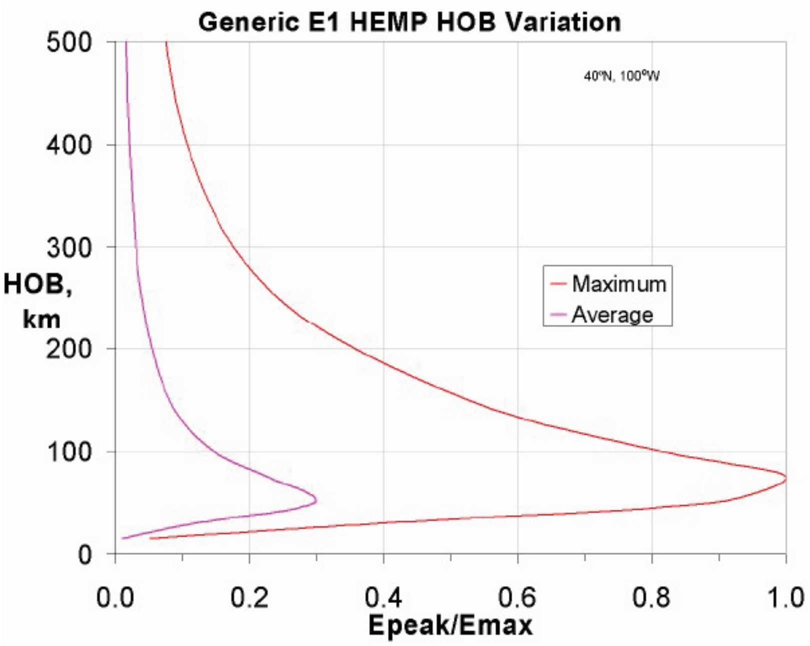
SPACE, GROUND, OR BOTH

Altitude is the key factor determining whether the most significant effects of a HANE are experienced on the ground or on satellites. An explosion at a height of 30 kilometers (19 miles) would create an appreciable, though not maximal, EMP and have minimal effects on satellites.[7] Satellites in this scenario are largely unscathed due to the attenuation of prompt radiation in the Earth's atmosphere and further distance from low Earth orbit (LEO) satellites. Peak HEMP E1 occurs close to 75 kilometers (47 miles) above the surface and starts to drop off considerably after 100 kilometers (62 miles), as shown in Figure 3.[8] While the strength of the HEMP decreases considerably above this height, the ground area affected increases (Figure 4). Higher altitude HANEs, such as the previous U.S. test Starfish Prime at 300 kilometers (186 miles), affect a larger area but have a much weaker associated HEMP.[9] These higher explosions will also have significantly greater impacts on satellites due to a lack of attenuation in the atmosphere, their closer proximity to many satellites in orbit, and the increasing field of view of satellites at risk with increasing altitude (Figure 1).

MYTH #1: NO ONE WOULD USE A NUCLEAR WEAPON (EVEN AT HIGH ALTITUDE)

The constraint against nuclear explosions held true for over 70 years and made sense when the costs of international repercussions outweighed the benefits from use. For decades, the structuralism of the global order constrained adversaries. Post-World War II geopolitics rarely degenerated into great power combat because it was not in any nation's interest to do so. Structures such as the United Nations and the World Trade Organization provided forums where countries could achieve political objectives without resorting to violence. In 1963, the United States, Soviet Union, and United Kingdom signed the Limited Test Ban Treaty (LTBT), which prohibits nuclear weapons tests in the atmosphere, outer space, and underwater.[10] After the Cold War, globalism guaranteed collective gains for states willing to abide by international norms. Thomas Friedman described a "Golden Straitjacket" that offers nations wealth and progress if they abide by the rules and norms of the international order.[11] Multiple indicators—from the Russian invasion of sovereign European territory and threats of tactical

Figure 3: HEMP E1 Field vs. Height of Burst (HOB) of a Typical Weapon



Source: Edward Savage, James Gilbert, and William Radasky, *The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid* (Oak Ridge, TN: Metatech Corporation, 2010), 2.13, http://large.stanford.edu/courses/2019/ph241/rogers1/docs/meta-r-320.pdf.

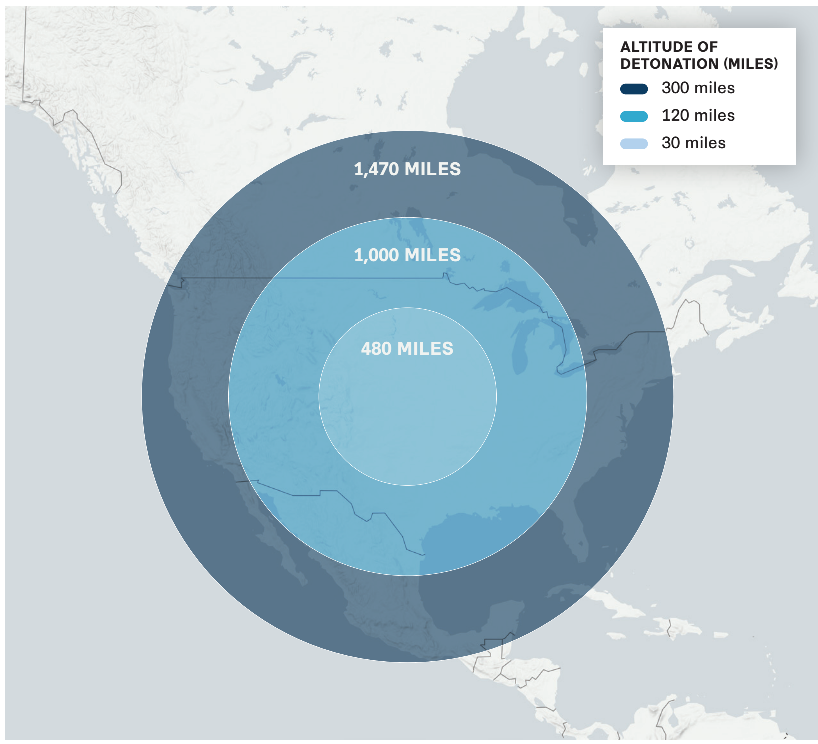
while the leaders of each of these nations have thus far restrained themselves, there is the possibility that a coup or uprising could result in more unpredictable leadership that would use available tools in unpredictable ways.

In the ongoing Russia-Ukraine War, the space domain remains accessible to all sides, allowing advanced communications, weapons guidance, drone operations, and data integration. This semi-permissive access is not guaranteed in future warfare. Russia and its precursor, the Soviet Union, have a history of surprising scientific breakthroughs that upend geopolitics. In 1957, the Soviet Union shocked the world with the launch of Sputnik, the first artificial Earth satellite. In 2021, Russia destroyed one of its own satellites with an antisatellite missile, foreshadowing a future threat to the United States' vast orbital communication infrastructure. In 2024, after withdrawing from nuclear weapons in Ukraine to the United States stepping back from international bodies—suggest this era is nearing its end, and nations should prepare for the dynamics of a post-globalism era. It is impossible to predict when a pariah state will finally decide that its national interests are better served by destroying the tools the rest of the world depends upon. However, the reasons for their restraint appear to be decreasing.

For decades, the structuralism of the global order constrained adversaries.

The use could be precise or haphazard. A rational state actor would wait until the optimum time to use latent capabilities to uproot the world order. While one state could use a bevy of tools, such as cyberattacks and anti-satellite weapons, to temporarily disrupt satellite and internet access without permanent destruction, another state actor may consider the large, destructive effects a single HANE offers. And

Figure 4: Increasing Altitude of HANEs Results in a Larger Area Affected



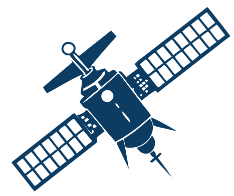
Note: HEMP strength does, however, drop off significantly after its maximum value at around 75 kilometers (see Figure 2).

Source: Edward Savage, James Gilbert, and William Radasky, *The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid* (Oak Ridge, TN: Metatech Corporation, 2010), 2.15, http://large.stanford.edu/courses/2019/ph241/rogers1/docs/meta-r-320.pdf.

multiple arms control agreements, Russia launched a satellite in orbit that could employ a nuclear weapon. U.S. Acting Assistant Secretary of Defense for Space Policy Vipin Narang stated that the prospect of this space weapon poses "a threat to satellites operated by countries and companies around the globe, as well as to the vital communications, scientific, meteorological, agricultural, commercial, and national security services upon which we all depend."[12]

China is also actively studying the effects of space-based nuclear weapons. The Northwest Institute of Nuclear Technology (NINT), a People's Liberation Army (PLA) research and development institute, published a paper detailing the effects of a space-based nuclear weapon on LEO satellites like the Starlink network.[13] Another NINT paper noted, "A combination of soft and hard kill methods should be adopted to make some Starlink satellites lose their functions and destroy the constellation's operating system."[14] From the figures in that paper, one can identify optimal altitudes for various military effects.

Figure 5: Optimal Altitudes for Desired Effects

Altitude	EMP/Satellite Effect	Primary Use Case	Example Images
100 km+	Increasing effects on satellites and decreasing HEMP with increasing altitude	Indiscriminately destroy satellite infrastructure	
50–100 km	Maximized HEMP on ground with minor effects on LEO satellites	Maximize HEMP effects on the ground	
30–50 km	Significant disruption to electronics on ground	HEMP while preserving satellite infrastructure	
0–20 km	Highly localized (source-region EMP) disruption to electronics	Traditional blast, prompt radiation, thermal, residual radiation effects	

Source: Author's analysis.

MYTH #2: HEMPS WILL DISABLE EVERYTHING ELECTRONIC

The *Call of Duty* franchise offers HEMPs as an option during battle. When a player uses one, it disables all the opponent's command and control capabilities, such as their map, unmanned aerial vehicle (UAV) assets, and even their electronic weapon sights for a fixed period. While *Call of Duty* brings attention to the topic of HEMPs to a wider audience, it misrepresents them in many ways. First, the in-game EMP consistently shuts down everything electronic. In reality, HEMPs create stochastic effects—which have a probability pattern that can be analyzed statistically, not predicted precisely. For example, one device could be destroyed, while an identical one meters away is spared due to having a slightly different orientation.[15] Additionally, the HEMP effects from *Call of Duty* are transient, lasting under a minute, but would actually be varied over time. Many electrical components would be instantaneously and permanently damaged and never come back online, while others would be only temporarily disrupted.[16] The misrepresentation of EMP effects seen in *Call of Duty* is not unique. Similar themes are seen in movies such as *The Matrix*, *GoldenEye*, and *Ocean's Eleven*. The general public often overestimates the effects of a

HEMP since these examples are often their only exposure to this subject.

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The effects of a HEMP on devices depend on the intensity of the EMP field, the orientation of the device with respect to that field, the inherent shielding of the device, and the sensitivity of the device's microelectronics.[17] The amount of energy collected depends on several factors, including its size and orientation to the pulse. Long cables, antennas, and railroad tracks would be able to collect a significant amount of energy that could damage large systems, such as large power transformers.[18] While devices such as cellphones are small collectors, some components, such as semiconductor diodes and transistors, may be more sensitive to pulses from a HEMP.[19] Three people standing next to each other with three different phones could have three different outcomes. One's circuits may be relatively undamaged, with the owner noticing no internal disruption, while a second has issues that resolve after a restart, and a third person's phone loses functionality critical to operation.

While two of the phones in this example are not destroyed, much of their functionality may be unavailable due to the modern, interconnected network of systems required. Gamma rays and X-rays can ionize atoms in the atmosphere, which can disrupt radiofrequency waves passing through them for anywhere from seconds to hours, depending on the frequency.[20] Communications infrastructure, such as cell towers, may be inoperable due to damage from a HEMP, which could also disrupt the electrical power generation required to operate communications infrastructure.[21] Finally, communications satellites at low Earth orbit—less than 2,000 kilometers (1,243 miles)[22]—may also be disrupted or destroyed depending on the altitude of the HANE creating the HEMP.[23] This is the orbital region most affected by HANEs and is advantageous for many communications satellites.[24]

It is difficult to pinpoint the exact damage that could come from a HEMP due to the complex mechanisms and limited test data. It is important for decisionmakers to understand that there will be significant disruption and damage to electrical devices, but that it will not be ubiquitous.

MYTH #3: A HANE HARMS THE USER AS MUCH AS THE TARGET

HANEs have the capability to harm their user through both effects on their satellites and HEMP effects within the Earth's atmosphere. Regarding the former, a common supposition exists that it would not make sense for a state to use a HANE in space because it would damage or destroy its own satellites as well. First, this assumes that all states are as reliant on satellites as the United States. Many nuclear-armed states are not. The United States is currently dominant in the satellite sector and has made multiple decisions and investments to maintain its strategic advantages in this domain.[25]

Second, states can employ HANEs in ways that limit the amount of damage to their own satellites. For example, an actor could choose to detonate a HANE that optimizes damaging enemy satellites while minimizing collateral damage to its own based on satellite locations at the planned time and location of the detonation. However, given that there are thousands of satellites deployed in LEO—and that the prompt radiation field of view (as shown in Figure 2) means a HANE could affect up to 20 percent of LEO satellites[26]—it is impossible for most states to avoid destroying a portion of their own satellites and causing significant damage to those of their allies and commercial entities. Additionally, trapped electrons could still affect many satellites that had been shielded from the HANE by the Earth.

To minimize space effects, a state could pursue a lower-altitude HANE, such as at around 30 kilometers (19 miles), to primarily target HEMP effects within the Earth's atmosphere.[27] If employed over the battlefield, HEMP attacks would likely disrupt both friendly and enemy units. In certain cases, this could benefit the user if it is less reliant on susceptible electronics. However, it may be more suitable for attacking a target nation that is physically separated from the battlefield. For example, Russia could employ a lower-altitude HANE over the United States to disrupt its geographically distant battlefield efforts in Eastern Europe. Attacks like these could significantly impact an enemy while costing little in terms of technological fratricide or direct loss of human life and could potentially have less chance of large-scale escalation than the use of a surface nuclear weapon.

REALITY #1: HANES OFFER A LESS PROVOCATIVE OPTION THAN GROUND-BASED NUCLEAR DETONATIONS

HANEs do not have the same direct effects on human lives. As they are detonated at an altitude where the atmosphere is very thin or nonexistent, this means no significant air blast will arrive on the ground and harm civilians or infrastructure. Additionally, very little prompt or delayed radiation will make it to the Earth's surface due to attenuation or absorption by the atmosphere.[28] The airblast, thermal, and radiation effects from traditional surface or near-surface detonations could lead to the direct deaths of millions of people and could prompt an equal or greater retaliatory strike on the state that originally employed such a weapon.

HANEs offer a favorable option by avoiding these direct lethal effects on civilians. They can be targeted to primarily affect electronics on the ground, satellites, or a combination of both. Those detonated between the sweet spot of 30–50 kilometers (19–31 miles) above sea level create HEMPs that impact electronics on the ground but have less effect on satellites. This could be a desirable option for a state that wants to limit damage to its own satellites and minimize escalatory concerns associated with damaging nuclear command, control, and communications (NC3) satellites. HANEs detonated above that altitude also have the potential to destroy LEO satellites, causing catastrophic global economic effects and potentially affecting NC3 systems in orbit.

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REALITY #2: HANES WILL STILL CAUSE HUMAN SUFFERING

While the detonation would not directly kill humans, the indirect effects likely would. The long-term loss of power plants, cellular towers, and access to satellites would have profound effects on the affected population. In 2008, the U.S. congressional commission released a study on HEMP effects on U.S. territory. It noted, even 17 years ago, that the "pervasive use of electronics of all forms represents the greatest source of vulnerability to attack by EMP." The report offered a somber acknowledgement of the long-term consequences of a HEMP attack on the United States:

> A single EMP attack may seriously degrade or shut down a large part of the electric power grid. . . . Electrical power is necessary to support other critical infrastructures. . . . Many people may ultimately die for lack of the basic elements necessary to sustain life in dense urban and suburban communities.[29]

In response, Congress implemented several recommendations for U.S. power grids. These mitigate the risk but are unlikely to completely defend against loss of life. Additionally, less-developed nations remain vulnerable.

REALITY # 3: THE EFFECTS OF HANES CAN BE ANTICIPATED AND MITIGATED

There are multiple steps policymakers can take to mitigate the effects of HANEs in future conflicts. Satellite effects can be reduced by focusing on radiation hardening to include shielding, physical changes of circuitry, and redundancy. Radiation-hardening components designed to withstand extreme post-HANE environments are currently a niche market for critical military satellites.[30] The emphasis on hardening could be expanded to a broader set of devices, especially as many commercial satellites are starting to be used on the battlefield. HEMP effects within the Earth's atmosphere can also be mitigated. Increased emphasis on HEMP testing could identify the most vulnerable systems early in the acquisition process so that these systems are designed with increased HEMP survivability from the beginning.

Finally, the impact of HANEs can be mitigated through decreasing dependency on electronic systems and training. Military leaders should be wary of single capabilities that may be susceptible to an enemy HANE. Leaders should incorporate training scenarios for their soldiers that recreate degraded environments where some key capabilities are taken away, such as radios and GPS.[31] Additionally, soldiers can be trained on how to minimize the effects of an EMP, for example, by ensuring there is redundancy in their communications pathways. They can also be trained in how to troubleshoot, identify, and (if necessary) repair damaged components of a system.

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While HANEs' exact impact and long-term destruction will vary, this paper seeks to highlight what is known and dispel popular misunderstandings about them. In the past, global agreements formed a bulwark against the use of nuclear devices, but states are now relooking at their nuclear inventories and considering using these powerful devices in unconventional ways to achieve their goals. Leaders can no longer ignore this threat and the relevant effects posed by HANEs. Military leaders need to be cognizant of their effects on warfighters and capabilities, and local leaders need to understand their effects on power plants and civilian life. While the impacts of HANEs are difficult to grasp, there are tangible ways for U.S. policymakers and military leaders to mitigate them. ■

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Cover Photo: James/Adobe Stock

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