HYPERSONIC DEFENCE

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INTRODUCTION

The Russian use of Kinzhal air-launched ballistic missiles (ALBM) as part of its war against Ukraine marks the combat debut of a hypersonic strike system, albeit in this case, an aero-ballistic missile rather than a hypersonic glide vehicle (HGV) or hypersonic cruise missile (HCM). It is nonetheless significant and points to the emerging hypersonic weapons capabilities under development or in some cases, already being deployed, particularly by Russia and China. Hypersonic weapons constitute a significant area of interest for a number of countries, including Australia, France, India, Japan, North Korea, South Korea, Turkey, and the UK as well as the US. The development and deployment of hypersonic strike systems holds significant implications, including with regard to defending against such threats. The attributes of hypersonic weapons, in particular, their speed, manoeuvrability, and flight profile, pose a variety of challenges from a defensive perspective, but as this report will discuss, a range of countermeasures, including technological, tactical and operational approaches, can be developed to mitigate the hypersonic strike threat.

This report will first provide an introduction to hypersonic weapons, encompassing the types, characteristics and attributes, and what differentiates them from other high-speed threats, namely ballistic missiles. Proceeding from this, the report will provide an overview of international hypersonic weapons programmes, trends and drivers, including the rationale for pursuing a hypersonic weapons capability. This will be followed by a detailed analysis of the requirements for hypersonic defence. This will include options for both left-of-launch and counterforce targeting of an adversary's strike capabilities, the interception of hypersonic threats (including near-term and longer-term options), and operational approaches to mitigate the threat posed by hypersonic weapons. The implications for command and control, early warning, and the role of space-based systems, will also be discussed. The report will conclude with a discussion of the role of hypersonic defence as part of a wider integrated air and missile (IAMD) capability, potential opportunities for industry, and the implications for armed forces going forward.

HYPERSONIC WEAPONS:
OVERVIEW, TYPES AND ATTRIBUTES

Hypersonic weapons travel at speeds exceeding Mach 5, that is, five times the speed of sound. There are two principal types of hypersonic missile: an HGV, where a glide vehicle is carried atop a rocket booster to the upper atmosphere, is released, and glides to its target; in contrast, an HCM is powered throughout flight using a scramjet. However, as Tom Karako and Masao Dahlgren explain:

> The common HGV/HCM bifurcation oversimplifies the spectrum of hypersonic missile design possibilities. Focusing on these two types alone impedes anticipating future threats. Future hypersonic systems may, for instance, employ a combination of these propulsion methods or another altogether. A scramjet or other device could be integrated into a glider to increase range or maneuverability.[1]

Ballistic missiles also travel at hypersonic speeds, and as Kolja Brockmann and Dmitry Stefanovich explain, HGVs and HCMs are 'typically slower than ballistic missiles' and 'it is not speed itself but rather the combination of speed with endoatmospheric [that is, within the atmosphere] manoeuvrability that distinguishes HGVs and HCMs from other missile systems'.[2] Manoeuvrable re-entry vehicles (MaRVs), which equip some ballistic missiles (for example, the Chinese DF-15, DF-16, DF-21 and DF-26), can also perform in-flight manoeuvres, although as Karako and Dalhgren note 'MaRVs may also pull high-G turns at hypersonic speeds even though they do not sustain hypersonic flight or possess the same aerodynamic lift characteristics as HGVs'.[3]

It also warrants mention that some ballistic missiles, such as the Russian Iskander-M, can manoeuvre in-flight and follow quasi-ballistic trajectories. This is possible through the use of lifting surfaces, control surfaces or thrust vectoring.[4] The Kinzhal, a derivative of the Iskander-M, reflects a lower-risk and more accessible approach to the development of a hypersonic weapon, as Eugene Saad and Adam Mount note with regard to ALBMs: 'The velocity of a ballistic missile provides a relatively simple means of creating a hypersonic strike option that can provide a prompt means of holding mobile or transient targets at risk…'[5] China has also deployed at least one ALBM (capable of delivering a nuclear payload), designated the CH-AS-X-13,[6] and potentially an air-launched HGV, both of which would be carried by the H-6N long-range bomber.[7]

The combination of speed, endoatmospheric manoeuvrability, and with it, unpredictability of trajectory, and lower flight altitude compared to ballistic missiles, pose significant defensive challenges and implications for strategic stability. This is explained by Brockmann and Stefanovich:

> Both hypersonic boost-glide systems and HCMs could undermine strategic stability. The combination of their speed and manoeuvrability and their limited detectability by ground-based radars can—under certain circumstances—result in target ambiguity, reduced warning times and ineffective defences.[8]

In particular, the lower flight altitude of both HGVs and HCMs significantly reduces their detectability by ground-based radar systems, and thus 'compresses the timeline for decisionmakers assessing their response options and for a defensive system to intercept the attacking weapon—potentially permitting only a single intercept attempt'.[9] In this context, space-based systems for detection and tracking are seen as providing a critical enabling element for a hypersonic defence capability, as Karako and Dahlgren highlight:

> Constrained by the horizon, current BMDS [Ballistic Missile Defense System] sensors can only support counter-hypersonic engagements in the final phases of flight. The speed of hypersonic weapons leaves little time for computing a fire control solution, communicating with command authorities, and completing an engagement… Space-based sensors would enable a "birth-to-death" tracking capability: the ability to follow a hypersonic weapon through the entirety of its trajectory…[10]

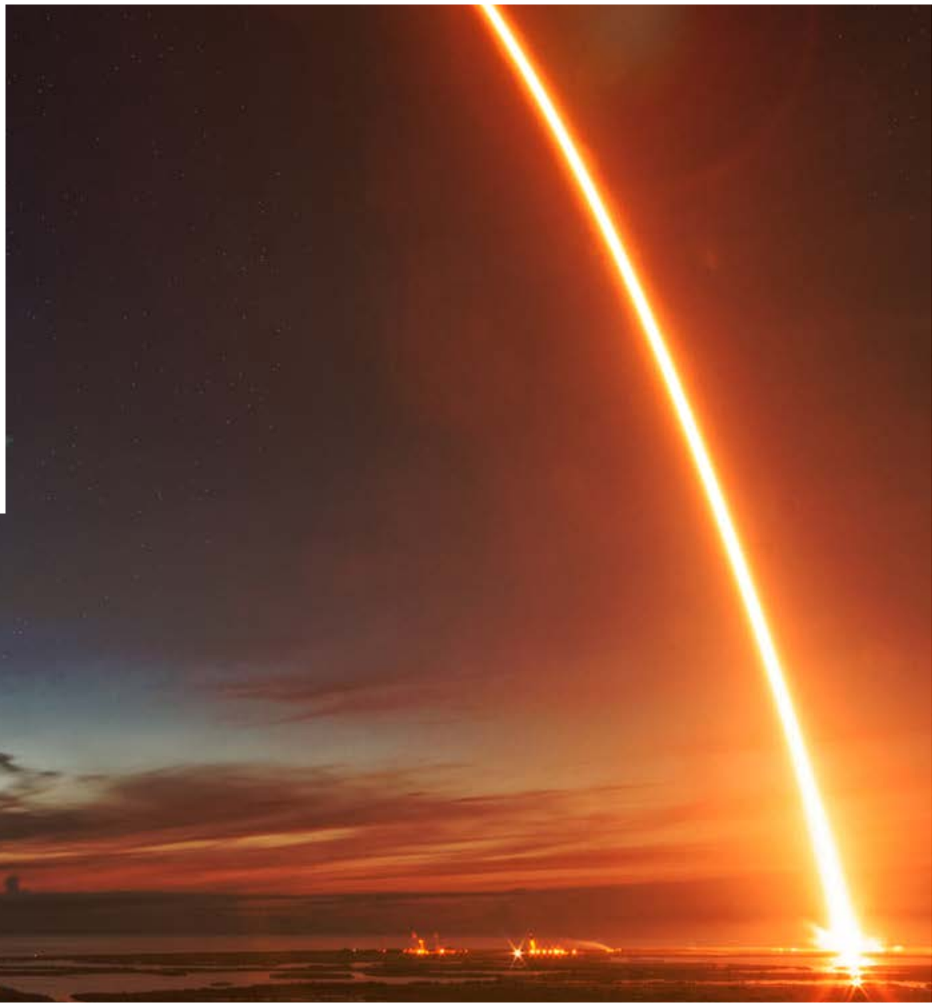
Moreover, tracking a hypersonic weapon through the entirety of its trajectory would enable multiple interception attempts, in particular in the missile's glide phase, and even if unsuccessful, attempted intercepts that force the incoming missile to manoeuvre, would potentially compromise the weapon's effectiveness and increase its vulnerability to interception in its terminal phase.
The attributes of hypersonic weapons that underpin their appeal and potential operational utility also constitute possible weaknesses that can be exploited in defence. The nature of hypersonic flight itself poses significant technical challenges, including with regard to materials, thermal management, and physics with air 'no longer assumed to be air'.[11] This creates 'vulnerabilities that different kill mechanisms can exploit. Hypersonic weapons may be disrupted by smaller impacts or perturbations to their structure or surrounding airflow... Extended flight through the atmosphere may expose them to new failure modes. Their ability to maneuver comes at the cost of expending energy and

range'.[12] However, the ability to detect, track and attempt multiple interceptions will itself be a complex and demanding challenge, as will be discussed below.

What are the drivers for developing a hypersonic weapons capability? States are pursuing hypersonic weapons for two principal reasons: 1) to counter a potential adversary's missile defences (a key motivation, for example, for Russia, China, and North Korea); and or 2) as part of wider efforts to develop robust precision strike capabilities. Hypersonic weapons through their speed and manoeuvrability offer a number of advantages, in particular, with regard to the prosecution of time critical targets (for example, mobile ballistic missile launchers), where the additional speed of a hypersonic weapon is valuable, or vis-à-vis heavily defended targets (such as an aircraft carrier). In 2019 testimony to the US Senate Committee on Armed Services, then-Commander US Strategic Command, General John Hyten, stated with regard to the prosecution of time-sensitive and high-value targets that: 'Conventional hypersonic strike weapons could meet this requirement and provide responsive, long-range, strike options against distant, defended, and/or time-critical threats when other forces are unavailable, denied access, or not preferred'.[13]

Hypersonic weapons reduce the time required to prosecute a target (especially compared to current subsonic cruise missiles), the warning time available to an adversary, and the time available for defensive systems to engage the incoming threat. In the conventional precision strike role, hypersonic systems will require a robust supporting intelligence, surveillance, target acquisition and reconnaissance (ISTAR) capability. This also constitutes a potential vulnerability. Mike White, principal director for hypersonics in the US Office of the Undersecretary of Defense for Research and Engineering, highlighted the difference in time required to prosecute a target between a current subsonic cruise missile and a hypersonic weapon:

You know, we've got JASSM, JASSM-ER. We got Tomahawk [sic] LRASM is coming online for anti-ship missile. Those are Mach 0.6, Mach 0.7 kind of systems. So if you want to fly 500 miles, it's going to take you an hour to get there, from the time you launch the weapon to the time you get there. So the high-speed systems that we're developing, the high-speed strike systems do that 500 miles in only – on the order of 10 minutes.[14]



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INTERNATIONAL HYPERSONIC WEAPONS PROGRAMMES

Before proceeding to discuss the potential options and approaches to provide defence against hypersonic strike systems, a brief overview of international hypersonic weapons programmes is necessary. The following is not exhaustive and intended to highlight key trends and the implications for defence and industry. In this regard, around 12 countries are either pursuing a hypersonic weapons capability or undertaking research relevant to the development of hypersonic aerospace vehicles, with the international market for hypersonic technology, according to a 2021 projection, expected to grow at a compound annual rate of more than 7 percent through to 2025.[70] In the US, the Department of Defense in its fiscal year (FY) 2023 budget has requested $4.7 billion in research, develop, test and evaluation funding for hypersonic projects, this is in contrast to the FY 2022 request of $3.8 billion: it warrants highlighting that the majority of planned spending is on offensive capabilities.[71] In FY 2022, the US Missile Defense Agency requested $247.9 million for hypersonic defence, this was 'up from its $206.8 million FY2021 request and down from the $272.6 million FY2021 appropriation'.[72]

Hypersonic weapons are being developed across the spectrum of potential roles and missions, from a tactical surface-to-surface missile (the Russian Klevok-D2),[73] medium and intermediate-range missiles, through to intercontinental, nuclear-armed HGVs such as the Russian Avangard, and potentially, a Chinese HGV with a fractional orbital bombardment capability. The latter was described by Admiral Charles A. Richard, Commander US Strategic Command, in testimony to the US House Armed Services Committee on Strategic Forces on 1 March 2022, in the following terms:

The PRC's pursuit of an ICBM delivered HGV with FOB capability is a technological achievement with serious implications for strategic stability. On 27 July 2021, the PRC's first HGV FOB test resulted in 40,000 kilometers distance flown and over 100 minutes of flight time—the greatest distance and longest flight time of any land attack weapon system of any nation to date.[74]

Russia was the first country to declare an operational hypersonic strike capability with the Kinzhal, which President Putin announced had entered service in December 2017 in his 1 March 2018 address to the Russian Federal Assembly, followed by the deployment of the Avangard in December 2019,[75] and the first to use hypersonic weapons operationally. Although only the US and China are likely to develop a broad-based hypersonic capability, a number of countries will operate tactical and potentially strategic systems. The following provides a brief overview of publicly disclosed hypersonic weapons developments:

AUSTRALIA

Australia is pursuing in conjunction with the US, the development of a scramjet-powered air-launched HCM to equip tactical aircraft such as the F/A-18E/F Super Hornet and F-35A, under the Southern Cross Integrated Flight Research Experiment (SCIFiRE).[29] Moreover, on 5 April 2022, a new AUKUS (Australia, UK, US) Joint Leaders' Statement was issued, announcing that the trilateral security pact would expand its cooperation to include 'hypersonics and counter-hypersonics'.[30] It is likely that Australia will seek to equip its future SSNs being under the auspices of AUKUS with a land-attack capability, such as that provided by the Tomahawk, or potential future hypersonic weapons. In this context, the US Navy intends to equip its Virginia Payload Module (VPM)-equipped Virginia-class SSNs with the Conventional Prompt Strike (CPS) missile, incorporating the Common Hypersonic Glide Body (C-HGB) payload, providing a long-range hypersonic precision strike capability from the late 2020s onwards.[31] The expanded remit for AUKUS may also enable trilateral cooperation on programmes such as the Glide Phase Interceptor (see below),[32] or the SM-6 Block 1B.[33]

CHINA

China has only publicly disclosed thus far one operational hypersonic weapon, the DF-17 medium-range ballistic missile (MRBM) armed with an HGV, with a range of 1,800-2,500 km. When it debuted at China's National Day Parade on Oct. 1, it was announced as being intended for 'precision strikes against medium- and close-range targets'. The DF-17 utilises the booster from the DF-16 short-range ballistic missile.[34] However, additional weapons providing a hypersonic strike capability may also be either already in service or close to operational deployment. An HGV-equipped ALBM may be operational with the People's Liberation Army Air Force H-6N bomber,[35] and in April 2022, video footage emerged showing the launch of a potential hypersonic missile, possibly designated the YJ-21, from a People's Liberation Army Navy Type 055 cruiser.[36] Admiral Richard in his March 2022 testimony referred to China 'investing heavily in HGVs', highlighted by the 2021 test of an 'ICBM delivered HGV with FOB capability', and this follows prior statements, for example, by then-head of US Northern Command, General Terrence O'Shaughnessy, in February 2020, in which testing of a nuclear-armed intercontinental HGV was reported.[37]

China is developing the technologies required for HCMs. For example, in May 2018, a scramjet test vehicle, the Lingyun-1, was publicly exhibited for the first time in Beijing, while in August 2018 China successfully tested a hypersonic waverider test vehicle, the XingKong-2 ('Starry Sky-2'), which attained a speed of Mach 6. Notably, in April 2019, Xiamen University successfully flew the Jiageng-1 test vehicle, which employed a 'double waverider' configuration.[38] Interest in developing an air-launched hypersonic strike capability has also been noted.[39]

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FRANCE

France is developing its fourth-generation air-launched nuclear missile, the ASN4G ('Air-Sol Nucléaire de 4eme Génération'), which will be a scramjet-powered HCM and is due to enter service in the mid-2030s, replacing the current ASMP-A.[40] It is also developing the 'Vehicule Manoeuvrant Experimental' ('Experimental Manoeuvring Vehicle') or V-MAX HGV.[41]

INDIA

India is pursuing two hypersonic weapon projects, the BrahMos-2, developed by the BrahMos joint venture between India and Russia, and another HCM project. The BrahMos-2 is intended to be an HCM capable of speeds of Mach 7; HCM development is supported by the scramjet-powered Hypersonic Technology Demonstrator Vehicle (HSTDV).[42]

JAPAN

Japan has outlined plans for two hypersonic weapon systems: the Hyper-Velocity Gliding Projectile (HVGP) and a Hypersonic Cruising Missile. Japan outlined in its Midterm Defense Program (FY 2019-2023) plans to strengthen the defence of 'remote islands in the southwest region', including through the establishment of HVGP units.[43] The HVGP is intended to be a tactical HGV, capable of delivering a penetrating warhead for targeting, for example, aircraft carriers, or a 'high-density EFP' (explosively formed penetrator) warhead for 'area suppression'. The HCM will be a scramjet-powered missile, armed with the same warheads as the HVGP, and was intended to provide a standoff capability to counter "ships and landing forces attempting to invade Japan'.[44] It has been subsequently reported that the HCM may only serve as a technology demonstrator and may not enter service, with the HVGP expected to enter service in 2026.[45]

It was also announced in January 2022 that the US and Japan will collaborate on emerging defence technologies, including hypersonic defence.[46] This builds on existing cooperation in areas such as missile defence, highlighted by the co-development between the US and Japan of the SM-3 Block IIA interceptor,[47] with Japanese interest in co-development of hypersonic technologies also being mentioned by the US Department of Defense Chief Technology Officer in October 2021.[48] Japan has expressed interest in contributing to a US-led space-based detection and tracking system for hypersonic threats,[49] and is also considering the use of unmanned air systems, potentially equipped with advanced infra-red sensors, to 'enable the early detection of hypersonic missiles'.[50] Further, it was announced in January 2022 that Japan is developing electromagnetic railgun technology to provide a counter-hypersonic capability, alongside interceptors and long-range strike systems to 'create a three-tiered deterrent', with a potential railgun system entering service in the latter half of the 2020s.[51]

NORTH KOREA

North Korea is developing HGVs as part of continued efforts to modernise and enhance its armed forces.[52] In September 2021 and again in January 2022, North Korea tested an HGV-armed ballistic missile, the Hwasong-8.[53] North Korea's pursuit of HGVs will likely be motivated by the requirement to penetrate particularly US and Japanese missile defences in order to prosecute targets in South Korea and Japan in the event of renewed war on the Korean peninsula.

RUSSIA

In addition to the aforementioned Kinzhal, Avangard, and Klevok-D2, Russia is developing multiple hypersonic weapons, including air, ground and sea-launched systems. Boris Obnosov, director general of the Tactical Missiles Corporation, has stated that 'dozens of hypersonic weapons projects' are underway.[54] The 3K22 Tsirkon HCM has been successfully tested from the Yasen-class submarine Severodvinsk and the Admiral Gorshkov (lead ship of the eponymous class), has a speed of Mach 9 and a range of around 1,000 km. It will equip the Russian Navy's Yasen/Yasen-M and modernised Oscar II-class nuclear-powered submarines and UKSK vertical launch system (VLS)-equipped warships (that is, all ships capable of launching the Kalibr cruise missile). In his 1 March 2022 statement, Admiral Richard stated that the Tsirkon is 'operationally fielded now'.[55] A ground-launched variant of the Tsirkon may be deployed following remarks by President Putin that a ground-launched hypersonic missile with intermediate range is also under development.[56]

An air-launched long-range hypersonic missile, designated Kh-95, has been reported:[57] this may be related to the 'Gremlin', also known as the GZUR (from the Russian for 'hypersonic guided missile'), a scramjet-powered HCM with a range of 1,500 km, capable of Mach 6, and sized to fit within the bomb bay of a Tupolev Tu-95MS Bear.[58] Another air-launched HCM, 'Ostrota', is intended to equip Russian tactical aircraft, such as the Sukhoi Su-34, as well as bombers, and provide a more affordable weapon than, for example, the 'Gremlin'; in this regard, in contrast to the 'Gremlin', the 'Ostrota' may have a range of 400-500 km.[59] Hypersonic weapons are seen as central to Russia's long-term military development, for example, the Chief of the Russian General Staff, Valery Gerasimov stated in March 2018 that: 'In the long term, an increase of capacities of high-precisions [sic] weapons, including hypersonic ones, will allow moving the main part of strategic deterrence to the non-nuclear sector from the nuclear one'.[60] However, given the impact of sanctions imposed on Russia following its full-scale invasion of Ukraine, Moscow's ability to develop and produce highly sophisticated hypersonic weapon systems, as well as its wider military ambitions, will likely be constrained.

SOUTH KOREA

In part in response to North Korean missile developments, South Korea has begun development of an HCM, Hycore. Janes reported in February 2022 that the development of Hycore began in 2018, with testing planned to commence in 2022; the missile will be ground-launched, and capable of speeds in excess of Mach 6, with air and sea-based systems to follow subsequently.[61].

UNITED KINGDOM

In July 2019, Air Vice Marshal Simon Rochelle, then Chief of Staff Capability, announced at the Chief of the Air Staff's Air and Space Power Conference, that the UK sought to deploy a hypersonic weapon by 2023.[62] Whilst in April 2020, a joint US-UK study, Thresher (deriving from the acronym Tactical High-Speed, Responsive and Highly Efficient Round), between the US Air Force Research Laboratory and Defence Science and Technology Laboratory, and due to complete in 2022 or 2023, was disclosed.[63] Whilst in February 2020, Admiral Sir Ben Key, the First Sea Lord and Chief of the Naval Staff, announced in a speech to industry, his vision of 'a future where we are setting ourselves a challenge to become a global leader in hypersonic weapons'.[64] The April 2022 announcement that the development of hypersonic and counter-hypersonic technologies under the auspices of AUKUS will likely be a significant contributor to the First Sea Lord's vision and the wider British development and acquisition of hypersonic weapon systems.

UNITED STATES

The US is undertaking multiple programmes relating to the development of offensive and defensive hypersonic weapon systems, for tactical, theatre and conventional strategic use, although interest in an intercontinental HGV capability has also been reported.[65] Both HGVs and HCMs are under development, with the US Army seeking to deploy on an experimental basis, the ground-launched Long-Range Hypersonic Weapon, which utilises the C-HGB HGV and will also be deployed by the US Navy, in 2023 (the naval variant is due to follow, initially onboard the Zumwalt-class destroyers from 2025).[66] Both the US Air Force and Navy are also looking to introduce air-launched HCMs into service, the Hypersonic Attack Cruise Missile (HACM) and Hypersonic Air-Launched Anti-Surface Warfare missile (HALO) by 2027 and 2028, respectively.[67]

The importance of hypersonic weapons to the US Department of Defense was articulated by Mike White, and cited by Janes: 'The department has developed a hypersonics modernization strategy that accelerates the development and delivery of transformational warfighting capabilities', which includes 'developing air-, land-, and sea-launched, conventionally armed hypersonic strike weapons for highly survivable, long-range, time-critical defeat of maritime, coastal and inland targets of critical importance on the tactical battlefield'.[68] The US also possesses a nascent counter-hypersonic capability with the naval SM-6,[69] and is developing a system-of-systems approach to hypersonic defence, including a space-based detection and tracking architecture, and interceptors.

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HYPERSONIC DEFENCE

From the preceding discussion, the diversity of hypersonic weapons capabilities being pursued will be evident. In light of the Russian invasion of Ukraine and its neo-imperial ambitions, the threat posed by Russian hypersonic weapons will be of particular concern and provide a benchmark for developing a defensive capability. Moreover, as Russian military weaknesses are highlighted by their operational performance in Ukraine, Moscow may seek to rely on asymmetric capabilities, such as hypersonic weapons, to mitigate those areas of weakness. Russia is, as discussed above, developing a layered, hypersonic strike capability centred on HCMs, alongside its already deployed Kinzhal ALBM and the Avangard ICBM-launched HGV; the possibility that Russia develops an HGV for the sub-strategic role cannot be dismissed (for example, to equip the RS-26 ballistic missile). In the Asia-Pacific, China is developing an expansive hypersonic strike capability which would enable it to prosecute strikes against both regional targets and beyond, whilst North Korea's development of hypersonic weapons will likely be primarily intended to counter US, South Korean and Japanese missile defence capabilities and enable strikes against regional targets.

Hypersonic weapons should be seen as part of a wider strike capability alongside ballistic and cruise missiles and other air threats, and as Karako and Dahlgren suggest, 'Hypersonic weapons combine the speed and range of ballistic missiles with the low-altitude and maneuverable flight profile of cruise missiles… Instead of thinking about hypersonic defense as an adjunct to the legacy ballistic missile defense problem, it might be better understood as a form of complex air defense'.[76] Whilst some aspects of defending against hypersonic threats will be specific to that mission, much will also be applicable to wider air and missile defence. This is especially with regard to left-of-launch, counterforce and passive defence approaches. In addition, as Karako and Dahlgren highlight: 'Developing hypersonic defenses need not and should not happen in a vacuum or as a new standalone stovepipe. Hypersonic defense can leverage ongoing investments in both ballistic and cruise missile defenses and hypersonic strike, all of which draw upon a similar industrial base and leverage similar sensors and networks'.[77] Moreover, Karako and Dahlgren emphasise the evolving nature of the wider missile and aerospace threat:

New ballistic missiles are being flown with lower and more heavily shaped trajectories. New cruise missiles sustain higher speeds and are becoming more difficult to detect. Future threats will include missile-drone combinations, spaceplanes, aeroballistic missiles, and other hybrids that strain simple categorization. Hypersonic missiles thus do not represent a boutique problem. They exemplify a broader evolution in the missile threat—one which demands changes to the broader missile defense paradigm.[78]

Although hypersonic weapons, due to their combination of speed, manoeuvrability, altitude and flight profile, constitute a significant defensive challenge, it is not insurmountable. The interception of threats in flight is but one component of air and missile defence, alongside counter/anti-proliferation efforts, deterrence, conventional counterforce, and passive defence, forming the 'five pillars of ballistic missile defence'.[79] It is outside the scope of this report to consider counter and anti-proliferation efforts, beyond stating that denying access to operational hypersonic strike capabilities to a potential adversary would greatly ease the defensive challenge. In this context, conventional counterforce operations against an adversary's hypersonic strike (and wider air and missile) capabilities, 'left-of-launch', will be a valuable component of a defensive approach. The role and importance of counterforce operations as part of wider missile defence efforts was articulated in the US 2019 Missile Defense Review: 'U.S. attack operations supporting missile defense will degrade, disrupt, or destroy an adversary's missiles before they are launched. Such operations are part of a comprehensive missile defense strategy and increase the effectiveness of active missile defenses by reducing the number of adversary missiles to be intercepted'.[80]

Counterforce operations against long-range threats, such as the 2,000 km-range Kinzhal, may be particularly challenging but the development of advanced low-observable crewed and uncrewed air systems, together with stand-off weapons, could provide a means of undertaking counterforce strikes in contested airspace. In this regard, innovative concepts such as the LongShot, air-launched air-to-air missile-armed uncrewed air system,[81] could also contribute to the counterforce mission by intercepting stand-off missile-armed aircraft at range (thus countering a variety of missile threats). Similarly, a 2018 US Center for Strategic and Budgetary Assessments report on Air and Missile Defense at a Crossroads, noted the potential utility of extended-range air-launched interceptors for both ballistic missile defence and countering HGVs and other hypersonic threats: 'Extended-range air-launched interceptors could greatly increase the lethal radius of U.S. combat aircraft and allow them to attack some high-value airborne targets while remaining out of range of many enemy defenses', and with 'appropriate sensors and kinematics could also be effective against HGVs—and possibly other hypersonic weapons'.[82] The development of 'loyal wingmen' such as the MQ-28A Ghost Bat,[83] providing advanced, modular capabilities and extended range (especially compared to current tactical combat aircraft), will also provide a significant counterforce capability, through offering the range, persistence and precision strike capabilities required to detect, track and prosecute mobile missile launchers. Aside from the benefits of attacking threats at source, counterforce targeting will force an adversary to rely on longer-range systems, which are more costly and even at hypersonic speeds, will provide more warning time.

A challenge common to both the finding, fixing, tracking and engagement of hypersonic strike systems for counterforce purposes and for the adversary seeking to prosecute long-range strikes is the dependence on a robust intelligence, surveillance, target acquisition and reconnaissance (ISTAR) capability (or 'kill chain'). An adversary's supporting ISTAR system provides a potential vulnerability which can be targeted both kinetically and non-kinetically (for example via cyber or electronic warfare), in order to degrade and disrupt the ability to provide the precision targeting support necessary. Conversely, developing resilient, distributed sensor networks both to improve battlespace awareness and survivability, would enhance one's own defence against hypersonic threats and contribute to wider military effectiveness.

It also warrants highlighting that defending against hypersonic threats is inherently multi-domain. In this respect, the US Summary of the Joint All-Domain Command and Control (JADC2) Strategy sets out '"Sense and integrate"' as 'the ability to discover, collect, correlate, aggregate, process, and exploit data from all domains and sources (friendly, adversary, and neutral), and share the information as the basis for understanding and decision-making'.[84] Such an approach would be critical to the effectiveness of hypersonic defence, and would also potentially be an application for artificial intelligence, as explained by Michael O'Gara:

…correctly designing systems for the use of AI can also provide improved capabilities for integrated defensive fires. Consider the speed at which…a hypersonic weapon can transit an engagement window. Opportunities to counter can simply be lost when dependent on the speed of human reasoning and interaction…AI holds promise in handling resource priorities across domains more seamlessly while being capable of initiating responses based on more accurate and timely threat assessments.[85]

Central to an effective defence against hypersonic threats will be an ability to detect and track missiles, as close to launch as possible, in order that they can be tracked and engaged. The US is seeking to achieve this through the development of the Hypersonic and Ballistic Tracking Space Sensor (HBTSS), a constellation of Low Earth Orbit satellites, which will detect 'maneuvering hypersonic missiles flying below the range of today's ballistic missile detection satellites and above the radar of terminal-phase targeting systems'.[86] HBTSS will be cued by Defense Support and Space-Based Infrared System (SBIRS), and subsequently, the Next-Generation Overhead Persistent Infrared System, satellites that detect the launch of ballistic missiles, track the hypersonic missile during its glide phase, and then pass targeting data to interceptors.[87] Moreover, as Karako and Dahlgren note, 'With its higher sensitivity and medium field of view, HBTSS would provide the detailed, low-latency data—"fire-control-quality data"—needed to support glide-phase intercepts'.[88] That is, rather than relying on terminal defence, hypersonic threats could be intercepted in their mid-course, glide phase. The significance of this is explained by Karako and Dahlgren:

Hypersonic weapons in their glide phase maneuver significantly less to conserve energy… A long-range interceptor, remotely cued by space sensors to permit earlier launch, offers a larger battlespace, more warning time, and the ability to employ shoot-look-shoot shot doctrines. Besides the primary effect of alleviating the terminal intercept challenge, longer-range intercept capability may have the secondary benefit of encouraging the threat to employ circuitous routes and earlier maneuvers that diminish endgame performance.[89]

As Steve Trimble highlights, even a failed interception attempt is beneficial:

Even if an improved THAAD or SM-3 is unable to directly intercept a missile, the attempt can force the HGV to maneuver and bleed off energy. By making several intercept attempts along the flight path, the HGV loses speed and becomes more vulnerable to traditional interceptors in the terminal phase.[90]

Whilst the development of a large-scale space-based detection and tracking architecture would most likely be cost-prohibitive for most states, the development of lower-cost space access and satellite capabilities, may enable credible contributions to a US-led system, or potentially a collaborative European effort. In this regard, under the auspices of the European Union's Permanent Structured Cooperation (PESCO) initiative, five European countries (France, Italy, the Netherlands, Spain and Finland) are collaborating on 'Timely Warning and

Interception with Space-based Theater surveillance', or Twister, which will include an endoatmospheric interceptor to counter hypersonic and other advanced threats.[91]

The US is pursuing multiple approaches and options for a hypersonic defence architecture:

> MDA's recommended setup for countering hypersonics would include: elevated infrared sensors; integrated command, control, battle management and communications; and layered defenses with "effectors" that can engage enemy systems in both the glide and terminal phases of flight… Effectors could include kinetic "hit-to-kill" interceptors, directed energy weapons such as lasers and high-powered microwaves, or other tools like blast fragmentation warheads that could detonate in the vicinity of the target and disrupt it.[92]

In terms of effectors, the US Defense Advanced Research Projects Agency (DARPA) is developing counter-hypersonic technology under the Glide Breaker programme (underway since 2018) and 'some other things',[93] with the Missile Defense Agency developing the Glide Phase Interceptor (supplanting the previous Regional Glide Phase Weapon System).[94] The Glide Phase Interceptor (GPI) is intended to be launched from the MK-41 VLS which equips US Navy Ticonderoga-class cruisers, Arleigh Burke-class destroyers and the forthcoming Constellation-class frigates, as well as the Aegis Ashore system, and multiple allied ship classes. In this context, the GPI would be a valuable area for cooperation under AUKUS. Development of the GPI is currently facing budgetary uncertainty.[95] A key element of the Glide Breaker programme and central to efforts to develop a counter-hypersonic interceptor is an enhanced divert and attitude control system (DACS) with both Aerojet Rocketdyne and Northrop Grumman competing to develop a suitable solution.[96] Lockheed Martin and Raytheon had also proposed enhanced versions of the THAAD (Dart) and SM-3 (Hawk) respectively to fulfil the Regional Glide Phase Weapon System requirement.[97]

In contrast to ballistic missile defence, hit-to-kill interceptions may not be required, as Karako and Dahlgren explain: 'Weapons that damage or disrupt hypersonic weapons earlier in flight might lower the challenge facing terminal defenses. In the harsh environment of sustained hypersonic flight, explosive shockwaves or even small heat shield punctures could destabilize or destroy a vehicle'.[98] John Markow noted with regard to HCMs that they have 'minimal maneuverability…[and] tight design tolerances for optimum performance', whilst proposing an interceptor armed with sub-interceptors to target an air volume.[99] The development of effective and affordable hypersonic defences will be a challenge and as with the wider air and missile environment, point to the use of innovative technologies to supplement current interceptors such as THAAD, the SM-3 and SM-6, which have high unit costs.[100] Directed energy weapons, namely high-power microwave systems, which 'generate very short-duration high-power pulses of electromagnetic energy using waveforms that are designed to damage sensitive electronic components such as PGM seekers, guidance systems, and control systems',[101] and lasers may be suitable. Although as Malcolm Claus highlights, a space-based laser 'would have to compensate for the effects of atmospheric interference on the beam, including atmospheric absorption and diffraction', with the plasma effects associated with hypersonic flight also affecting power requirements and the type of laser needed.[102] Karako and Dahlgren also draw attention to the potential contribution of additive manufacturing to the wider hypersonic enterprise, which 'may ease the production of complex structural and propulsion system components',[103] and lower production costs. Electromagnetic railguns also offer a means of countering a variety of air and missile, including hypersonic, threats and similarly, hyper-velocity projectiles (HVPs) that can be fired by conventional artillery may also provide a low-cost air and missile defence capability.[104]

Finally, passive defence measures, including dispersal, hardening of vulnerable or high-value facilities, camouflage, concealment and deception, possessing reconstitution capabilities, and innovative operational concepts, will be a valuable component of defending against hypersonic and wider air and missile threats.[105]

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CONCLUSION

The development and deployment of hypersonic weapons will provide their operators with a significantly enhanced strike capability and pose a major defensive challenge. The combination of speed, endoatmospheric manoeuvrability, flight altitude and the unpredictable trajectory provide major challenges to the detection, tracking and interception of hypersonic weapons, by compressing the timelines for detecting an incoming threat, the engagement window and time available to attempt additional interceptions. Moreover, at present, only the US is believed to possess a nascent defensive capability against hypersonic threats, centred on the SM-6 and only in the terminal phase. However, the attributes of hypersonic weapons, whilst making them potent threats, also constitute sources of weakness that may aid in developing defensive solutions. In particular, the physics of hypersonic flight mean that the performance and design margins for a hypersonic missile are highly sensitive and thus susceptible to disruption, meaning that, for example, a blast fragmentation warhead detonating in proximity, or dispensing particulate matter, to an incoming threat may be sufficient to destroy it. Similarly, the manoeuvrability of an HGV comes at the expense of speed and range, thus even failed interceptions will degrade its performance.

This would require the ability to target the HGV in its glide phase, which is contingent on possessing the means to detect, track and engage hypersonic threats throughout their flight, from launch. Such a capability will most likely depend on a space-based sensor system operating in conjunction with land, air and sea-based assets, as well as in the cyber domain, a point recognised by Japan, European states, and the US which is developing the HBTSS as a key component of its wider missile defence efforts. The development of low-cost, operationally responsive space launch technologies will be an important contributor in this regard, as well as providing the ability to replace systems lost to an adversary's counter-space capabilities. This also highlights the inherently multi- and cross-domain nature of hypersonic defence with its associated implications for command and control and decision-making processes.

The interception of an incoming hypersonic threat would involve, for example, space and ground-based systems detecting and tracking the missile, possibly together with UAVs, and ship and ground-launched interceptors, with potentially supporting electronic warfare systems being employed, and the adversary's supporting ISTAR network being subject to cyber and kinetic attacks. Given the speeds at which hypersonic engagements will take place, AI may be employed to support the overall engagement process. It also warrants highlighting that counterforce operations against any adversary's hypersonic, and wider air and missile strike capabilities, would be a critical component of defending against such threats. The targeting both kinetically and non-kinetically, of an adversary's wider ISTAR capabilities in order to disrupt and degrade its battlespace awareness and ability to prosecute precision strikes, will also be of critical importance.

This again highlights the multi-faceted and multi-domain nature of hypersonic defence and how developing a credible capability in this area also enhances wider air and missile defence and overall military effectiveness. Whilst defending against hypersonic threats will necessarily involve the development of advanced and specific technological solutions, it will also involve activities that have a wider utility, including passive defence measures such as concepts that emphasise distributed and dispersed operations, or introducing new command and control processes that breakdown stovepipes, or the adoption of multi-domain frameworks. The development of innovative approaches to hypersonic defence will also be an aspect of industry's contribution. The development of technologies that lower the cost of interception, enhance the ability to detect and track hypersonic, and other advanced aerospace threats, and enable multi-role systems, will be of particular importance. In this regard, the SM-6 is a valuable example, initially developed to provide ship-based air defence, the missile has subsequently also taken on a missile defence role, acquired an anti-ship capability, and with the Block 1B configuration, will acquire a hypersonic capability.

The development of effective hypersonic defences will require a multi-faceted approach, harnessing new technologies, operational concepts and investment. Hypersonic weapons, whilst highly potent and challenging, are not an insurmountable threat. As Russia's extensive use of long-range missiles, including the Kinzhal, in Ukraine vividly demonstrates, air and missile defence is of fundamental importance. The possession of credible air and missile defences, as part of a wider military posture, will be critical to deterrence, and should war breakout, to the defeat of an adversary.

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