Hypersonic weapon systems: High expectations

By Gabriel Elefteriu and William Freer

Interest in hypersonic flight stretches back decades but it has undergone a renaissance since the mid-2010s.[1] The People's Republic of China (PRC) and Russia, in particular, have made quick progress on this frontier of military technology. It is generally accepted that these two nations have already fielded operational hypersonic systems: the world's first actively deployed hypersonic weapon – the DF-ZF, deployed on the DF-17 Medium Range Ballistic Missile (MRBM) – entered service with the People's Liberation Army (PLA) in 2019.[2] Meanwhile, the United States (US) is seen to be lagging behind with its first hypersonic weapon, the Long Range Hypersonic Weapon (LRHW), only expected

[1] The fastest crewed powered flight record was achieved in 1967 by the X-15 at Mach 6.7 (well into hypersonic speed range), flying at 102,000 feet (or 31,000 metres). In 1968, Tony Benn, then Minister for Technology, when queried on reduced investment in hypersonics research, stated: 'Preference should be accorded to...more modest types of aircraft and weapons, our research into hypersonic flight has...been critically reviewed and progressively reduced. From being a main commitment, it is now at a minimum level consistent with our maintaining an interest in the field as a possible springboard for the future.' See: 'Hypersonic Flight Research – Volume 765: debated on Thursday 23 May 1968', Hansard, 23/05/1968, https://bit.ly/3uKBdrX (checked: 04/12/2023).
[2] Geoffrey Chambers, 'An Exploratory Analysis of the Chinese Hypersonics Research Landscape', China Aerospace Studies Institute, 31/05/2022, https://bit.ly/3Nbzwu2 (checked: 04/12/2023). The DF-ZF was previously known as the Wu-14 and the US had been following its development since roughly 2014; the sudden appearance of the DF-17 carrying DF-ZFs in the 2019 National Day Parade was a surprise.

to enter service in 2025, and with several other research programmes underway. The United Kingdom (UK) has also started to take interest, with hypersonics forming one of the key areas for cooperation in AUKUS Pillar 2.[3]

It is essential to understand the real impact these weapons might have on the overall military balance, and how this calculation may change over the coming years. This Explainer offers a grounded overview of hypersonic weapons as a military capability, providing an explanation of their broad technical characteristics, together with a review of their military application and potential drawbacks.

Typology and attributes

Definition

There is no strict and universally-accepted definition of **hypersonic *weapons***. This is because many of the systems which are generally understood to fall within this category have similar characteristics – whether in terms of flight parameters or military effect – with other existing capabilities.

In technical terms, **hypersonic *flight*** refers to an object which travels at least five times the speed of sound (also referred to as Mach 5, approximately 1 mile/second or 3,700 miles per hour (mph).[4] Speeds between Mach 1 and Mach 5 are classified as *supersonic*.

Table 1: comparison of select subsonic, supersonic, and hypersonic missile systems

Name	Type	Top speed	Range
Tomahawk Block IV	US subsonic cruise missile	Mach 0.7	1,000 miles
Storm Shadow	Anglo-French subsonic cruise missile	Mach 0.9	350 miles
AGM-88G HARM	US supersonic anti-radiation missile	Mach 1.9	186 miles
P-800 Oniks	Russian supersonic cruise missile	Mach 2.5	174 miles

[3] 'Aukus Pillar 2: Advanced capabilities programme', House of Commons Library: Research Briefing, (09/11/2023), https://bit.ly/3T4VhiP (checked: 04/12/2023).
[4] Kolja Brockmann and Markus Schiller, 'A matter of speed? Understanding hypersonic missile systems', Stockholm International Peace Research Institute, 04/02/2022, https://bit.ly/47Yh4Ng (checked: 04/12/2023).

Kalibr	Russian supersonic cruise missile	Mach 2.9	2,800 miles
Zircon*	Russian hypersonic cruise missile	Mach 6-8	620 miles
DF-ZF carried by the DF-17*	Chinese hypersonic glide vehicle	Mach 10	1,180 miles
Avangard carried by the Sarmat*	Russian hypersonic glide vehicle	Mach 20	3,730 miles
Common Hypersonic Glide Body (C-HCB) carried by the LRHW	US hypersonic glide vehicle	Mach 17	1,420 miles

*Alleged or estimated top speeds and ranges

Vehicles flying above Mach 5 for sustained periods of time experience new physical challenges. There is no specific threshold where this begins to occur (with various physical challenges emerging between Mach 3-12 depending on vehicle design and flight conditions), but in general most experts take Mach 5 as the 'formal' threshold for supersonic flight.[5] Of notable importance is that at around **Mach 10** the plasma effects *begin* to kick in (see Box 1).[6] It is also worth noting that the speed of sound varies with altitude in particular, meaning that achieving a certain Mach speed at lower flight profiles is a different problem than doing so at higher altitudes.

Box 1: Heating and the plasma effect

Hypersonic weapon system design creates an extremely difficult engineering problem. Perhaps the most important single challenge is the extreme and sustained heating of the vehicle from air pressure and air friction at high speeds. Other fast moving objects (ballistic missiles and spacecraft on atmospheric re-entry, for example) have to contend with extreme heat, but only for short periods, whereas hypersonic vehicles are in this state almost throughout their flight.

From around Mach 10 the air particles around the vehicle will begin to ionise and generate a plasma layer that disrupts incoming or outgoing communications, the faster the vehicle travels the thicker the plasma layer becomes.[7] This would impact targeting – potentially making it impossible to track and hit moving targets – and also reduce precision overall. This 'communications blackout' is also a known problem for ballistic missiles on terminal approach.

[5] These physical challenges being intense air resistance and the increased heat and turbulence that the friction and shockwaves from the air resistance (dependent to an extent on vehicle configuration) causes.
[6] John T. Watts, Christian Totti and Mark J. Massa, 'Primer on Hypersonic Weapons in the Indo-Pacific Region', Atlantic Council, 15/08/2020, https://bit.ly/3Gqb2Jy (checked: 04/12/2023).
[7] Mark J. Lewis, 'Plasma Field Telemetry for Hypersonic Flight', Department of Aerospace Engineering: University of Maryland, 05/03/2007, https://bit.ly/3NdTzbc (checked: 04/12/2023).

One solution, in the case of fixed targets, can be to use extremely capable inertial navigation systems, such as future quantum compass technology.[8] Another approach could be for the hypersonic vehicle/missile to slow down below the plasma limit in order to reacquire the target, and then re-accelerate for the terminal phase.[9]

But hypersonic speed alone is not sufficient to designate a military vehicle, regardless of its warhead, as a hypersonic weapon system. One obvious difficulty in this case would be in distinguishing from **ballistic missiles** – starting with the world's first, the Second World War German V2 – which also achieve terminal velocities well in excess of Mach 5. Another issue to consider is the degree of the vehicle's manoeuvrability during its flight: the Manoeuvrable Re-entry Vehicles (MaRVs) deployed on some ballistic missiles are also able to change trajectory, especially to confuse missile defences, but only in the terminal phase of the weapon's ballistic arc.[10] Then there are more exotic or hybrid weapons like Fractional Orbital Bombardment System (FOBS) which are both capable of hypersonic travel and manoeuvrable during atmospheric flight but whose other characteristics such as prolonged space travel arguably places them in a separate category.[11]

Pulling these considerations together, it is possible to outline a more specific ***minimal*** definition of hypersonic weapon systems as **military vehicles which fly at over Mach 5 inside the atmosphere without rocket propulsion for most of their trajectory**. This definition also helps to separate weapons which can reach hypersonic speeds (which may be using older technologies) from genuine hypersonic weapons (enabled by technological breakthroughs that unlock a new performance spectrum).

It is worth noting that this is only the theoretical baseline. To offer a distinguishing advantage over other weapons for the purposes of military strategy, more advanced hypersonic weapon systems should also have one or more of the following characteristics:

- Speeds significantly in excess of Mach 5;

[8] Hayley Dunning, 'Quantum sensor for a future navigation system tested aboard Royal Navy ship', Imperial College London, 26/05/2023, https://bit.ly/3T8QKfi (checked: 04/12/2023).
[9] It is of course difficult for unpowered glide vehicles to pick up speed once they have slowed down.
[10] David Wright and Cameron L. Tracy, 'Hypersonic Weapons: Vulnerability to Missile Defences and Comparison to MaRVs', *Science and Global Security*, (2023), https://bit.ly/4a6sZKC (checked: 04/12/2023). In some cases, MaRV equipped ballistic missiles can change course by hundreds of kilometres.
[11] A system first trialled by the Soviets in the 1960s and then later abandoned, the PRC is now believed to be testing their own FOB system. See: Chris Cooney, 'Hypersonic Missiles: UK, US, and Australia to boost defence co-operation', *BBC*, 05/04/2022, https://bit.ly/3N8lKbm (checked: 04/12/2023).

- An ability to execute substantial manoeuvres at different points along their flightpath; and,
- An ability to strike fixed and mobile targets at very long ranges.

In practical terms, therefore, the operational requirements for hypersonic weapons as an effective military capability with unique characteristics – i.e. one that is significantly different from other weapons such as high-performance rocket designs like the Russian Kinzhal – are likely to be highly specified, particularly in terms of speed and maximum range.

Types of hypersonic weapons

There are two major technological pathways for 'true' hypersonic weapon systems design, both of which are being pursued by all major players: gliders and powered missiles.[12] Broadly speaking, they lead to the two main classes of strike weapons:

- Hypersonic Glide Vehicles (HGV): A glide vehicle is launched from a booster (most likely a ballistic missile). Once the booster has reached the desired speed and altitude the glide body then separates and flies unpowered (in the upper atmosphere at altitudes of 20-50 miles) towards the target before diving in the terminal phase – the glider can manoeuvre to confuse defences and make its target unclear.[13]

- Hypersonic Cruise Missiles (HCM): Similar to subsonic and supersonic cruise missiles, HCMs fly a non-ballistic trajectory. HCMs need a special engine (a ramjet or a scramjet capable of Mach 6 and Mach 10+ respectively), but these engines require a high speed to operate; HCMs need a booster to get them up to speed.[14]

[12] FOBS and aero-ballistic missiles like Kinzhal that achieve hypersonic speeds using older technologies rather than scramjets or HGV designs may be considered 'hybrid' hypersonic weapons. The Russian R-37 air-to-air missile would also fall into this category if rumours about its supposed hypersonic speed are confirmed.
[13] 'Hypersonic Missiles', UK Parliament Postnote: Number 696, 26/06/2023, https://bit.ly/3R7q8bN (checked: 04/12/2023).
[14] *Ibid.*

Box 2: The scramjet problem

A scramjet (supersonic combustion ramjet) uses oxygen from a stream of supersonic air to burn its fuel, rather than an oxidizer. The air is compressed by the speed of the airflow itself, removing the need for rotating blades such as those used in traditional jet engines.[15] This means that for a scramjet powered HCM to function, the missile must first be launched up to a high speed (somewhere between Mach 3-5) by a rocket booster.[16] At such high speeds the air molecules spend only milliseconds in the engine (making it difficult for fuel and air to mix properly) and if the missile pitches and yaws, the airflow is disrupted, making combustion even more difficult.[17] There is a further drawback: scramjets require a high altitude as well as high speed to generate the necessary air pressure, thus they can only function at heights of 12.5 miles (20km) or above – making them more visible to radar at longer ranges than super- or subsonic cruise missiles.[18]

Costs

Hypersonic flight technology sits at the cutting edge of engineering and therefore the associated research and development (R&D) and subsequent procurement costs for operational hypersonic weapons are very high.

Over the past four years the US has spent US$8 billion (£6.3 billion) on hypersonic weapons programmes – in addition to R&D investments in this area stretching back decades – with another US$13 billion (£10.2 billion) earmarked for 2023-2027 (and no operational system so far).[19] Production line costs will also be high, with the price-tag for a single Army HGV system (the LRHW) estimated at US$41 million (£32 million).[20] By contrast, a Short-Range Ballistic Missile (SRBM)/Intermediate-Range Ballistic Missile (IRBM) costs between US$10-US$20 million (£8-16 million), and a Tomahawk cruise missile – though it is a completely different class of weapon, making comparisons misleading – costs roughly US$2 million (£1.6 million).

[15] John T. Watts, Christian Totti and Mark J. Massa, 'Primer on Hypersonic Weapons in the Indo-Pacific Region', Atlantic Council, 15/08/2020, https://bit.ly/3Gqb2Jy (checked: 04/12/2023).
[16] 'Hypersonic Missiles', UK Parliament Postnote: Number 696, 26/06/2023, https://bit.ly/3R7q8bN (checked: 04/12/2023).
[17] Richard Stone, 'National Pride is at Stake: Russia, China, United States rush to build hypersonic weapons', *Science*, 08/01/2020, https://bit.ly/3Gqplhl (checked: 04/12/2023).
[18] Sidharth Kaushal, 'The Zircon: How much of a threat does Russia's hypersonic missile pose', RUSI, 24/01/23, https://bit.ly/3Gp3Ygm (checked: 04/12/2023).
[19] 'US Hypersonic Weapons and Alternatives', *Congressional Budget Office*, 30/01/2023, https://bit.ly/3GotXod (checked: 04/12/2023).
[20] Kelley M. Sayler, 'The US Army's Long-Range Hypersonic Weapon (LRHW)', *Congressional Research Service*, 15/09/2023, https://bit.ly/3N8mJZ6 (checked: 04/12/2023).

Employment scenarios

In their mission profiles and employment scenarios, hypersonic weapons are best viewed as an *extension* or *evolution* of existing high-performance cruise and ballistic missiles, especially when combined – in terms of reach – with the advantages of stealth aviation which allows weapon launches from closer distances to the enemy.

But is this simply a question of striking *faster* and *deeper*? There is no simple answer, because hypersonic weapons perform differently in different scenarios, particularly when used as part of joint strike packages. One way to frame our understanding of this capability is to break down their potential combat employment into three general categories.

1. **Rapid strike (tactical/operational):** While hypersonic weapons are widely known as *long-range* capabilities, employing some of them, especially HCMs, at *short range* (under 125 miles) can change the tactical game in many scenarios, including at sea and in the air, and particularly when sequenced with different weapons such as SRBMs or one-way drones. They can radically compress the 'kill chain', allowing prompt strikes on high-value targets of opportunity; and due to their flight characteristics they are more likely to penetrate any defences. In a variety of scenarios, the combination of short range fire and extreme speed would give the enemy only seconds to react once the incoming HCM (or even HGV) is detected, and therefore increasing the probability of a kill. In the naval domain for example, a warship's radar will only detect an incoming low-flying missile once it has crossed the horizon: in a hypothetical scenario (as no current hypersonic can fly this low) where such a missile flies at Mach 6, this means approximately 15 seconds to impact.

   This mode of employment appears most suited to HCM designs rather than HGVs, given that the latter require a longer time and range for the initial ballistic phase of their flight. Short-range HCMs will also likely have a smaller form-factor, making them deployable in greater numbers from a greater variety of platforms. However, HCMs spend most of their flight time at high altitudes, which theoretically makes them more observable to radar.

2. **Long-range strike (operational):** Undoubtedly, the key military advantage of hypersonic weapon systems is the ability to conduct long-range strike missions against well-defended, strategically-significant targets at the

theatre/operational level. Here, it is important to distinguish between the two slightly different 'ends' of the challenge:

- Engaging *forward-deployed* enemy assets from a great distance (to keep the launch platform safe), such as Anti-Access/Area Denial (A2/AD) capabilities or heavily defended coastal infrastructure; and,
- Engaging major targets located *deep behind* the front lines, like air bases, strategic headquarters or key infrastructure, from closer proximity to the active battlefield.

Long-range conventional strike is not a new task, but current capabilities designed to achieve it – such as cruise missiles like the Tomahawk or stealth bombers like the B2 or B21, or ballistic missiles like the Russian Iskander – are facing increasingly effective air and missile defences on both sides. Hypersonic missiles – particularly HGVs – offer, in theory, the killer combination of both speed and range that can penetrate even the most advanced Integrated Air and Missile Defence (IAMD) systems.

The threat cuts both ways, in theory. American and allied hypersonic weapons – especially submarine-deployed HGVs in the future – can play a major role in destroying A2/AD 'bubbles', particularly if launched from submarines or stealth bombers. Conversely, Russian and Chinese hypersonic strikes could target the aircraft carriers of allies and partners or major bases such as those in Germany, Japan or Guam.

As hypersonic arsenals grow, the risk of a crippling large-scale surprise conventional strike on critical theatre- and strategic-level assets will likewise escalate and potentially alter strategic calculations for conventional deterrence.

3. **Nuclear deterrence (strategic):** Arguably the most controversial aspect of hypersonic weapons as dual-use systems is their potential impact on nuclear deterrence and strategic stability.[21] This is a two-fold problem:

   a. In a conventional (non-nuclear) configuration, long-range hypersonic weapons can theoretically be used to cripple ballistic missile defences and/or target the leadership and core command and control nodes. As a *conventional* 'first strike' option that arguably shifts the strategic balance without the use of nuclear attack, this

[21] Paige P. Cone, 'Future Warfare Series No. 59: Assessing the Influence of Hypersonic Weapons on Deterrence', United States Air Force Centre for Strategic Deterrence Studies, 24/09/2019, https://bit.ly/4a1FnM7 (checked: 04/12/2023).

could present the defender with a difficult dilemma about how to respond.

b. Nuclear-armed hypersonic weapons are inherently destabilising at the strategic level, chiefly because of the difficulty of even detecting and recognising a *nuclear* hypersonic first strike before the defender's military system has time to fully react; but also because these weapons – especially in a nuclear configuration aimed at fixed targets – are so much more difficult to intercept. In addition, the fact that high-end hypersonic weapons are both dual-use (conventional/nuclear) *and* can operate at strategic distances, would make it virtually impossible, theoretically, to distinguish between a nuclear and a non-nuclear hypersonic salvo to begin with.

Effectiveness: Key questions

Much of the promised performance of hypersonic weapons remains theoretical at this stage. There have been no clear instances of battlefield use of genuine hypersonic missile technology for long-range strike.[22] Nonetheless, there is some consensus on the main questions over their effectiveness.

Precision

While specific data on the accuracy of existing hypersonic weapon systems is a closely guarded secret, it can be expected that the increased difficulties of manoeuvring at such high speeds make them less accurate than a subsonic cruise missile (unless they slow down during the terminal phase). This also means, however, that hypersonic weapons are likely to be more accurate than standard ballistic missiles (which generally cannot correct their flight path in the terminal phase – unless the re-entry vehicles are MaRVs).[23]

The plasma effect means that a hypersonic missile has to slow down close to the target area in order to correct its course for precision impact on mobile targets. The relevance of this speed/precision trade-off will vary with the specific combat scenario: even if the main advantage of extreme velocity is lost on final

[22] The Kinzhal has been used in Ukraine. Russia classes this as a hypersonic weapon but it is essentially an aero-ballistic missile which flies on a depressed trajectory. See: John T. Watts, Christian Totti and Mark J. Massa, 'Primer on Hypersonic Weapons in the Indo-Pacific Region', Atlantic Council, 15/08/2020, https://bit.ly/3Gqb2Jy (checked: 04/12/2023).

[23] David Wright and Cameron L. Tracy, 'Hypersonic Weapons: Vulnerability to Missile Defences and Comparison to MaRVs', *Science and Global Security*, (2023), https://bit.ly/4a6sZKC (checked: 04/12/2023).

approach, arriving in the area very quickly in the first place – before the defender can react properly – can still provide a winning solution.

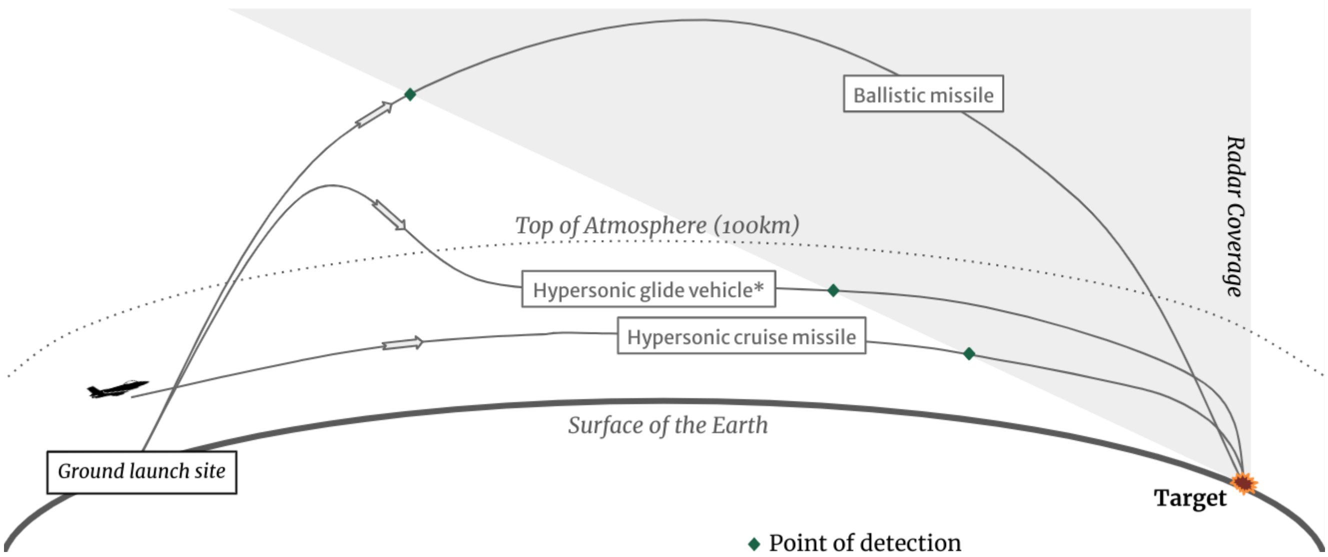
Detection

Due to the curvature of the Earth, ground based radars will detect hypersonic missiles later in their journey than ballistic missiles, but earlier than terrain-hugging cruise missiles.[24] Diagram 1 below shows missile trajectories and example radar coverage. The problem with hypersonics, however, is that once they start to generate the plasma effect at very high speeds this can make them easier to detect and then track (two different but related problems) – the plume of plasma generated is actually more visible to radar than the hypersonic missile itself.[25]

Furthermore, the variables around the use of the weapon – especially launch location – matters greatly. Launched from the same location, surface radar warning time for a ballistic missile with a range of approximately 1,860 miles compared to a HGV with the same range would be reduced from about 12 minutes to about six minutes before impact. But this difference would be reduced if there were effective space-based sensors in use.[26]

[24] 'Today's Missile Threat: China', *Missile Defense Advocacy Alliance*, 01/2023, https://bit.ly/46IuyM9 (checked: 04/12/2023).
[25] Richard Stone, 'National Pride is at Stake: Russia, China, United States rush to build hypersonic weapons', *Science*, 08/01/2020, https://bit.ly/3Gqplhl (checked: 04/12/2023). This is a very complex problem and highly dependent on a range of variables, such as flight condition, chemistry of the air, ablation, and radar frequency.
[26] Paige P. Cone, 'Future Warfare Series No. 59: Assessing the Influence of Hypersonic Weapons on Deterrence', United States Air Force Centre for Strategic Deterrence Studies, 24/09/2019, https://bit.ly/4a1FnM7 (checked: 04/12/2023).

Diagram 1: Example missile trajectories and radar coverage



*Note the apogee (the highest point it reaches) of a HGV can come within the atmosphere

Interception

Some existing air defence and Ballistic Missile Defence (BMD) systems such as PAC-3, the Aegis or THAAD already possess nascent hypersonic interception capabilities.[27] Moreover, missile defence is a 'team sport', with many variables which can decrease or increase the chances of both the attacker and defender. Improving integration between different sensor and defence systems across land, sea, air and space will certainly improve the possibility of detecting, tracking and intercepting hypersonic weapons.[28] It is also feasible to develop new ways of destroying hypersonic missiles such as directed energy weapons, or clouds of shrapnel.[29]

As with every military technology, the development, fielding and defence against hypersonic weapon systems will develop into a cycle of measure-countermeasure. At present it appears that the weapon performance and mission profiles enabled by hypersonic missiles are still limited in terms of their overall effectiveness. But there is vast scope for improvement and the problem will not go away.

[27] Alexander H. Montgomery and Amy J. Nelson, 'Ukraine and the Kinzhal: Don't Believe the Hypersonic Hype', Brookings Institute, 23/05/2023, https://bit.ly/3QZs9H2 (checked: 04/12/2023).
[28] See the space-based sensor layers developed as part of America's Proliferated Warfighter Space Architecture.
[29] 'Hypersonic Missiles', UK Parliament Postnote: Number 696, 26/06/2023, https://bit.ly/3R7q8bN (checked: 04/12/2023).

Conclusion

There is no doubt that hypersonic weapons represent a growing threat in the hands of adversaries, particularly as technological progress improves their capabilities. But there is less clarity on the specific strategic and operational characteristics of this threat, and its overall importance – for now. At the same time, hypersonic weapons clearly open up new options and possibilities for British and allied strategy as well. This is particularly the case as, unlike adversaries, Britain (and almost all allied countries) does not operate conventionally armed ballistic missiles.[30] Equipping the armed forces of the UK with hypersonic weapons could generate strategic advantage, acting as an *extender* to Britain's strategic reach. But this would involve great expense.

As with the airpower offence versus defence questions which came up during the 1949-1989 Cold War – a similar time of acute systemic competition when policymakers had to decide the balance between building bombers and fighters versus anti-aircraft systems – today's leaders will also be called to choose between different pathways and options in developing their countries' (counter-)hypersonic weapons arsenals. Decisions will be linked to other strategies and wider considerations, but it is worth keeping in mind that however 'hypersonic policy-making' will look going forward, it will involve trade-offs.

[30] Even the US only operates one type of conventional ballistic missile, the short range ATACM SRBM. See: 'Missiles of the World: Missiles of the United States', Missile Threat: CSIS Missile Defense Project, 03/03/2021, https://bit.ly/3T4f55S (checked: 04/12/2023).

About the authors

Gabriel Elefteriu FRAeS is Deputy Director (Defence and Space) at the Council on Geostrategy.

William Freer is Research Fellow in National Security at the Council on Geostrategy.

“ Dedicated to making Britain, as well as other free and open nations, more united, stronger and greener.

ISBN: 978-1-914441-49-3

Address: 14 Old Queen Street, Westminster, London, SW1H 9HP
Phone: 020 3915 5625
Email: info@geostrategy.org.uk

Geostrategy Ltd., trading as Council on Geostrategy, is a company limited by guarantee in England and Wales. Registration no. 13132479. Registered address: Geostrategy Ltd., Lower Ground Floor Office, 231 Shoreditch High Street, London, E1 6PJ.