HYPERSONIC BOOST-GLIDE SYSTEMS AND HYPERSONIC CRUISE MISSILES

Challenges for the Missile Technology Control Regime

KOLJA BROCKMANN AND DMITRY STEFANOVICH

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Summary

The Missile Technology Control Regime (MTCR) is the main multilateral export control regime through which states seek to prevent the proliferation of missiles and uncrewed aerial vehicles (UAVs). In recent years, hypersonic missiles have gained increased attention in the MTCR and in arms control discussions. Hypersonic missiles generally combine the abilities to perform prolonged flight at speeds of Mach 5—that is, five times the speed of sound—and beyond, and to manoeuvre in a way that enables a variable flight profile. There are two main types of hypersonic missile systems: hypersonic boost-glide systems and hypersonic cruise missiles (HCMs). Hypersonic boost-glide systems usually consist of a ballistic rocket booster and a hypersonic glide vehicle (HGV). HCMs are cruise missiles that usually use an air-breathing scramjet engine. Although these two types cover most hypersonic missile systems currently in development, there is a spectrum of possible hypersonic missile designs that combine different propulsion systems, trajectories and glide capabilities. Hypersonic missiles have been envisioned both as nuclear weapon delivery systems that would enable an assured second-strike capability and as conventional precision-strike or rapid response weapons.

Several of the systems under development are capable of carrying both nuclear weapons and conventional payloads. As with many other missiles systems, this may result in ambiguity over the payload that an incoming missile carries and hence how the targeted state assesses and reacts to such a launch. The ambiguity may be particularly significant if paired with the characteristics of HGVs and HCMs, and may have a destabilizing effect on strategic stability and international peace and security. For this reason, hypersonic missiles have increasingly been the subject of arms control, non-proliferation and export control discussions. Export controls have traditionally focused on nuclear delivery systems. However, the MTCR controls on delivery systems 'capable of' carrying payloads of at least 500 kilograms weight to at least 300 kilometres range mean that it also controls dual-capable HGVs and HCMs beyond the payload–range threshold.

The export controls prescribed by the MTCR already create extensive controls on the key missile technologies that hypersonic boost-glide systems and HCMs require. In most cases, the parameters of these controls mean that the types of subsystems, items and technologies required for HGVs and HCMs are already covered. However, there is some ambiguity over when HGVs would fall under controls within category I or within category II of the MTCR Equipment, Software and Technology Annex—thus determining how restrictive states' controls on their transfers would be. This is particularly significant as the restrictiveness and extent of some of the controls on related dual-use goods and technologies are linked to whether the complete system is covered by category I. There is an ongoing discussion among the MTCR partners about clarifying the coverage of HGVs and whether any amendments or additional controls on relevant dual-use technologies may be required. This discussion—which could include dialogue with the Wassenaar Arrangement—should also address possible future controls on spaceplanes and other reusable spacecraft.

The hype around hypersonic missiles and technological and status-related drivers have increasingly resulted in an arms race dynamic and the spread of hypersonic missile programmes, as well as increased investments in the development of missile defence capabilities against hypersonic missiles. In this context, it is ever more important to strengthen efforts towards the non-proliferation of hypersonic missile technology, to slow the spread of complete hypersonic missile systems and the required technology. The MTCR should resolve remaining ambiguities over its coverage of hypersonic glide vehicles and continue to monitor and consider possible expansion of its controls on dual-use items to maintain a system of export controls that adequately targets HGVs and HCMs. To maximize the reach and effectiveness of the controls it prescribes, the MTCR should specifically promote them to its adherents and non-partners, including China. Particularly building on its unique role as a technical policy forum, the MTCR should engage with related missile non-proliferation instruments, including the Wassenaar Arrangement and the Hague Code of Conduct, to help strengthen complementary export controls, transparency and confidence-building measures, and arms control instruments. Finally, to address destabilizing effects of missile proliferation the MTCR can be a forum for strengthening the implementation of United Nations Security Council resolutions that target relevant missile programmes.

Abbreviations

AI	Artificial intelligence
ASN4G	Air–sol nucléaire de 4e génération (French missile)
CBN	Chemical, biological or nuclear (weapons)
FOBS	Fractional orbital bombardment system
HCM	Hypersonic cruise missile
HCOC	Hague Code of Conduct against Ballistic Missile Proliferation
HGV	Hypersonic glide vehicle
HIFiRE	Hypersonic International Flight Research Experimentation Program
HSTDV	Hypersonic technology demonstrator vehicle
HVGP	Hyper velocity gliding projectile
ICBM	Intercontinental-range ballistic missile
IRBM	Intermediate-range ballistic missile
MaRV	Manoeuvrable re-entry vehicle
MTCR	Missile Technology Control Regime
SCIFiRE	Southern Cross Integrated Flight Research Experiment
SLBM	Submarine-launched ballistic missile
SLV	Space launch vehicle
TCBM	Transparency and confidence-building measure
UAV	Uncrewed (or ‘unmanned’) aerial vehicle
UN	United Nations
V-MAX	Véhicule manoeuvrant experimental (programme of France)

1. Introduction

In recent years, hypersonic missiles have quickly become one of the most sought-after types of missile systems, particularly due to their purported ability to defeat air and missile defences. Hypersonic missiles generally combine the abilities to perform prolonged flight at speeds of Mach 5—that is, five times the speed of sound—and beyond, and to manoeuvre in a way that enables a variable flight profile.[1] There are two main types of hypersonic missile systems: hypersonic boost-glide systems and hypersonic cruise missiles (HCMs). Hypersonic boost-glide systems usually consist of a ballistic rocket booster and a hypersonic glide vehicle (HGV). Although these two types cover most hypersonic missile systems currently in development, there is a spectrum of possible hypersonic missile designs that combine different propulsion systems, trajectories and glide capabilities.[2] The speed, manoeuvrability, possible trajectories and ability to defeat missile defences vary significantly between different hypersonic missile designs. These characteristics, however, are also shared with other missiles, in particular ballistic missiles with manoeuvrable re-entry vehicles, although the actual capabilities significantly overlap and are not exclusive to either type of missile system. Hypersonic missiles have been envisioned both as nuclear weapon delivery systems that would enable an assured second-strike capability and as conventional precision-strike or rapid response weapons.

The last several years have seen significant hype around hypersonic missiles and their reported and advertised capabilities. However, hypersonic missile technology is not new. It has evolved from various concepts, studies and demonstrators of hypersonic air vehicles that have been developed since at least the 1940s.[3] Russian and Chinese programmes in particular have advanced to a stage where their armed forces are already deploying their first hypersonic weapon systems.[4] The United States also has long-running programmes for developing a variety of hypersonic weapon systems for the different branches of its armed forces.[5] While the Chinese, Russian and US programmes are characterized by long-term development efforts and significant costs, the Democratic People's Republic of Korea (DPRK, North Korea) too has recently performed a test flight of what it claims to be an HGV, which comes only a few years after declaring its ambition to possess hypersonic missiles.[6] A growing number of states—including France, India, Japan, the Republic of Korea (South Korea), Australia and others—are also undertaking hypersonic missile development programmes or engaging in international scientific cooperation in key technology areas required for hypersonic aerospace vehicles.[7]

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,

[1] See e.g. Brockmann, K. and Schiller, M., 'A matter of speed? Understanding hypersonic missile systems', SIPRI Topical Backgrounder, 4 Feb. 2022.

[2] Karako, T. and Dahlgren, M., *Complex Air Defense: Countering the Hypersonic Missile Threat*, Center for Strategic and International Studies Missile Defense Project report (Rowman & Littlefield: Lanham, MD, Feb. 2022), pp. 8–9.

[3] Hallion, R. P., 'From Max Valier to Project PRIME (1924–1967)', in Hallion (ed.), *The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology*, vol. 1 (Air Force History Museums Programme: Bolling Air Force Base, DC, 1998).

[4] Sayler, K. M., 'Hypersonic weapons: Background and issues for Congress', Congressional Research Service, Updated 17 Mar. 2022, pp. 12–17.

[5] Sayler (note 4), pp. 4–9.

[6] Masterson, J., 'North Korea claims to test hypersonic missile', *Arms Control Today*, vol. 51 (Nov. 2021).

[7] Speier, R. H. et al., *Hypersonic Missile Nonproliferation: Hindering the Spread of a New Class of Weapon* (RAND Corporation: Santa Monica, CA, 2017), pp. 21–31 and Appendix B.

Box 1.1. The Missile Technology Control Regime

The Missile Technology Control Regime (MTCR) is an informal political understanding among a group of 35 supplier states that aims to limit the proliferation of missiles and other uncrewed delivery systems capable of delivering chemical, biological or nuclear (CBN) weapons—referred to by the MTCR as weapons of mass destruction. It was established by the Group of Seven (G7) largest industrialized states in 1987, originally as an instrument to help prevent the proliferation of nuclear weapons by controlling missiles capable of delivering them. The scope of the MTCR has since expanded to include ballistic and cruise missiles capable of delivering CBN weapons. Through the MTCR, the participating states (MTCR partners) harmonize their export controls, following the MTCR Guidelines for Sensitive Missile-Relevant Transfers (MTCR guidelines) and by maintaining a control list (MTCR Equipment, Software, and Technology Annex) that covers missiles and certain uncrewed aerial vehicles (UAVs) and relevant dual-use goods and technologies. The annex divides the items it covers into two categories:

Category I includes any complete missile or UAV 'capable of delivering a payload of at least 500 kg to a range of at least 300 km' (e.g. ballistic missiles, space launch vehicles, cruise missiles and reconnaissance drones); complete major subsystems (e.g. rocket stages and engines, guidance systems and re-entry vehicles); related software and technology; and specially designed production facilities. For all Category I items, the partners commit to exercising an 'unconditional strong presumption of denial', meaning that no licences for exports of such items should be issued under all but the most exceptional circumstances. The export of Category I production facilities is prohibited without exception.

Category II includes dual-use missile- and UAV-related components, and complete missile and UAV systems with a range of at least 300 km, regardless of their payload capability. Exports of such systems destined for any CBN weapons delivery end-use are also subject to a strong presumption of denial. All other exports of Category II items are subject to licensing procedures and are to be assessed with consideration of the criteria outlined in the guidelines.

The MTCR takes decisions—for example, on admitting new partners or making amendments to the annex—by consensus and these decisions are politically rather than legally binding. The main decision-making body of the MTCR is the plenary that is convened every year, usually in October, and is hosted by the annually rotating chair. The MTCR has several subsidiary bodies which cover different topical areas and operational functions: the technical experts meeting (TEM), the information exchange meeting (IEM), the licensing and enforcement experts meeting (LEEM), point of contact (POC) meetings, and reinforced point of contact (RPOC) meetings.

Sources: MTCR, 'Objectives of the MTCR', [n.d.]; and MTCR, 'Frequently asked questions (FAQs)', [n.d.].

reduced warning times and ineffective defences.[8] As the capabilities of most of the hypersonic missile systems currently deployed or under development would enable them to carry different types of payloads, they could be used as delivery systems for both nuclear and conventional payloads—so-called dual-capable delivery systems.[9] States are increasingly exploring how they could address and mitigate these risks through various international forums, instruments and regimes. A key aspect of these efforts focuses on the non-proliferation of hypersonic missile technology, to slow the spread of complete hypersonic missile systems and the required technology and to prevent destabilizing arms race dynamics that may arise from the perceived capabilities of these missiles. One instrument to prevent proliferation—or at least make it more costly, slow it down, and make its detection more likely—is export control. The Missile Technology Control Regime (MTCR) is the main multilateral export control regime through which states seek to prevent the proliferation of missiles and uncrewed aerial vehicles (UAVs). Next to the MTCR, several other instruments also address missiles, including the Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies (Wassenaar Arrangement) export control regime, the Hague Code of Conduct against Ballistic Missile Proliferation (HCOC) and United Nations Security Council resolutions on North Korea and Iran.[10]

[8] United Nations Office for Disarmament Affairs (UNODA) and United Nations Institute for Disarmament Research (UNIDIR), *Hypersonic Weapons: A Challenge and Opportunity for Strategic Arms Control* (United Nations: New York, 2019).

[9] 'Hypersonic weapons and strategic stability', *Strategic Comments*, vol. 26, no. 1 (Mar. 2020), p. xi.

[10] Wassenaar Arrangement, 'Control lists', Updated 23 Dec. 2021; Hague Code of Conduct against Ballistic Missile Proliferation, 'Description of HCoC', Updated Oct. 2020; Arms Control Association, 'UN Security Council Resolutions on North Korea', Fact Sheets & Briefs, Updated Jan. 2022; and UN Security Council Resolution 2231, 14 July 2015, Annex B.

The MTCR aims to prevent the proliferation of missiles and other uncrewed delivery systems capable of delivering chemical, biological or nuclear (CBN) weapons.[11] The 35 states participating in the MTCR (referred to as the partners) set common guidelines for missile technology exports and maintain the Equipment, Software and Technology Annex (the annex), a control list of complete missile systems, other uncrewed delivery systems and relevant dual-use items—that is, goods, software and technology that could be used for both military and civilian applications—to which they extend controls through export licensing requirements (see box 1.1).[12] The MTCR has an important function as a forum for technical deliberations to maintain the annex and stay up to date on relevant technological developments, such as advances in hypersonic missile technology; for the exchange of information on denials and procurement attempts; and for licensing and enforcement experts to share experiences and good practices.[13] The MTCR follows technical developments in missile technology including those that have enabled the recent advances in hypersonic missile technology. Particularly in recent years, the MTCR has discussed hypersonic missiles in its technical experts meeting (TEM) and plenary, and received briefings on the topic.[14]

This paper seeks to help improve understanding of the capabilities, required technology, and strategic and tactical implications of hypersonic boost-glide systems and HCMs, with a particular focus on mitigating resulting risks through non-proliferation-focused export controls. It combines an exploration of these aspects with a more detailed analysis of the applicability of the export controls prescribed by the MTCR and related instruments and regimes. This detailed analysis has several aims: informing the ongoing technical discussions within the MTCR, increasing awareness among policy makers and licensing and enforcement officers, and promoting nuanced discussion in the media and political discourse.

Following this introduction, section 2 explores the definitional issues related to hypersonic speed and the characteristics and technical challenges of hypersonic boost-glide systems and HCMs. It also outlines the drivers and status of hypersonic missile development programmes and deployments. Section 3 discusses the implications of conventional–nuclear entanglement in the case of hypersonic missile systems and how MTCR controls apply to nuclear, dual-capable and conventional delivery systems. Section 4 then analyses the application of MTCR export controls to hypersonic boost-glide systems and HCMs by exploring definitional ambiguities concerning HGVs, discussing current coverage of HGV and HCM subsystems and related items, and exploring hypersonic missile proliferation challenges posed by civilian space programmes. The paper concludes with section 5, which provides concrete recommendations on what steps the MTCR should take to strengthen its efforts to limit the proliferation of HGV and HCM technology.

[11] Missile Technology Control Regime (MTCR), 'Objectives of the MTCR', [n.d.]. The MTCR refers to chemical, biological and nuclear (CBN) weapons as 'weapons of mass destruction' (WMD). However, the term WMD lacks a generally recognized definition and, even if used to describe CBN weapons, implies their use for 'mass destruction', which is often less appropriate for describing the capabilities of many chemical or biological weapons. This paper therefore refers instead to CBN weapons or only nuclear weapons where appropriate.

[12] MTCR, Equipment, Software and Technology Annex, MTCR/TEM/2021/Annex, 8 Oct. 2021.

[13] MTCR, 'Frequently asked questions (FAQs)', [n.d.].

[14] See e.g. MTCR, *Missile Technology Control Regime Newsletter*, 3 Sep. 2020.

2. Hypersonic boost-glide systems and hypersonic cruise missiles

Hypersonic speed, manoeuvrability and hypersonic flight trajectories

Three key characteristics and the way they affect the overall capability of the delivery system need to be considered when analysing hypersonic missile systems: speed, endoatmospheric manoeuvrability and precision. Speed allows the delivery system to reach its target faster; manoeuvrability during atmospheric flight enables circumvention of defences and provides unpredictability; and precision is especially crucial for targeted strikes using conventional payloads.

The common focus on hypersonic speed as the key quality of HGVs and HCMs is misleading for several reasons. First, it is not speed itself but rather the combination of speed with endoatmospheric manoeuvrability that distinguishes HGVs and HCMs from other missile systems. Second, hypersonic speed is not achieved immediately nor kept indefinitely. While HGVs and HCMs are usually designed to enable manoeuvrability at high speeds, their manoeuvres come at the cost of speed and range; they are, therefore, typically slower than ballistic missiles. Third, the term 'hypersonic' implies a relation to the speed of sound, which is not constant but depends on atmospheric conditions (see figure 2.1).[15] Therefore, hypersonic speed is not always an exact and generalizable unit of speed. Hypersonic boost-glide systems or HCMs are often not the 'fastest' or most 'secure' strike option available. Traditional intercontinental-range ballistic missile (ICBM) re-entry vehicles can cover the distance faster, especially when launched on a depressed trajectory, and they can carry countermeasures or penetration aids, be launched in numbers, and may already be largely invulnerable to current missile defences.

Both HGVs and HCMs are designed to be manoeuvrable throughout their flight, particularly to be able to penetrate air and missile defences at high speeds or circumvent (ground-based) missile defence radars. Their manoeuvrability also means that their specific target is not clear from their trajectory and they can adjust to moving targets. HGVs can also use their manoeuvrability to perform pull-up or dive terminal manoeuvres to gain additional speed and reduce detectability, which can limit the ability of the defending party to target the incoming missile.[16] The majority of the flight profiles that HGVs travel usually occur inside the atmosphere. However, depending on the trajectory of the ballistic missile booster carrying the HGV, a (small) portion of it may also be exoatmospheric (see figure 2.2). If an HGV is carried by a fractional orbital bombardment system (FOBS), a significant portion or the majority of the trajectory may be exoatmospheric. There are also several trajectories that can extend range, retain speed and—possibly—enable the updating of position and target information.[17] One relevant trajectory is a so-called 'skip-glide' trajectory. This involves several dive and pull-up manoeuvres near the atmospheric border which allow the vehicle to 'skip' on the shockwave it generates, much like a pebble on a lake. Skip-glide trajectories are considered to be more usable by HGVs; however, some research suggests a possibility of using skip-glide trajectories to increase the range of high-speed air-breathing (cruise) missiles and decrease thermal loading.[18]

[15] Brockmann and Schiller (note 1).

[16] Tracy, C. L. and Wright, D., 'Modeling the performance of hypersonic boost-glide missiles', *Science & Global Security*, vol. 28, no. 3 (2020), pp. 137 and 147–48.

[17] Oelrich, L., 'Cool your jets: Some perspective on the hyping of hypersonic weapons', *Bulletin of the Atomic Scientists*, vol. 76, no. 1, pp. 41–42.

[18] Fomin, V. M., Aulchenko, S. M. and Zvegintsev, V. I., 'Skip trajectory flight of a ramjet-powered hypersonic vehicle', *Journal of Applied Mechanics and Technical Physics*, vol. 51 (10 Aug. 2010).

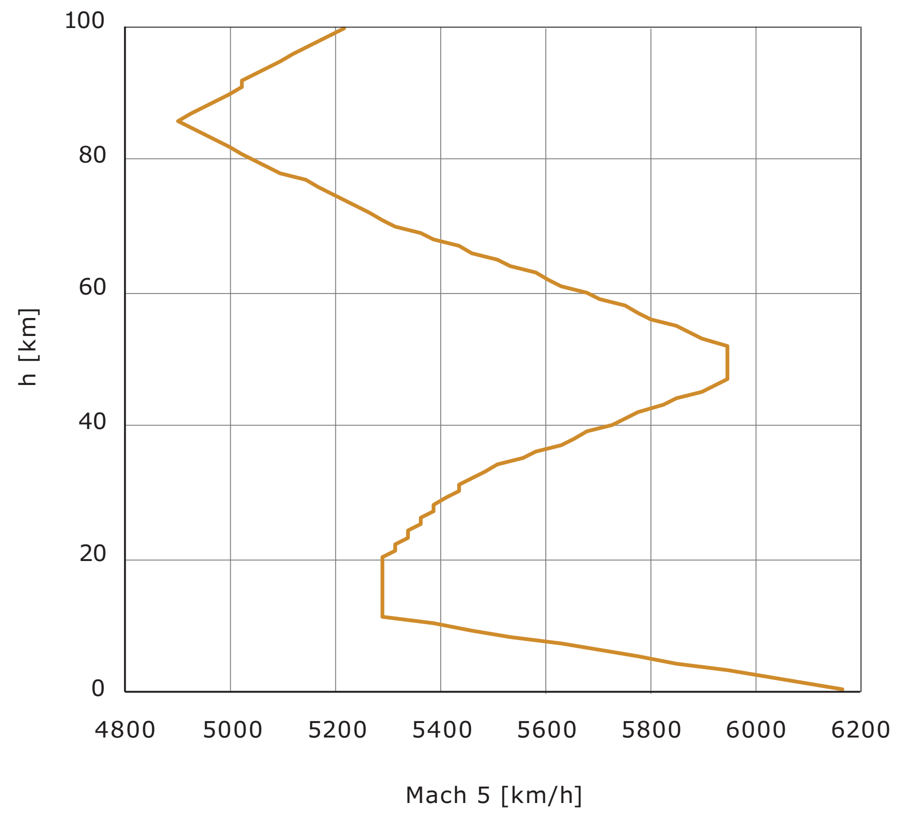

Figure 2.1. True speed by altitude at Mach 5

Source: Brockmann, K. and Schiller, M., 'A matter of speed? Understanding hypersonic missile systems', SIPRI Topical Backgrounder, 4 Feb. 2022.

Despite the manoeuvrability of HGVs and HCMs, a high degree of precision is not easily ensured. First, the 'cost' of mistake by the guidance system or within the pre--planned flight trajectory is ever-increasing with higher speeds and increases in the number of manoeuvres. Nevertheless, these same abilities can increase terminal precision, or what is often referred to as 'kill probability'. A mobile target would have less time to leave the area held at risk. Second, manoeuvrability can be used for terminal guidance—that is, adjustment of the flight path in the terminal approach to the target. However, achieving precision depends either on the capability to continuously communicate with the hypersonic weapon during its flight or for it to have highly sophisticated inertial guidance that enables the system to know exactly where it is, even without a communications link. The latter is particularly important, as a number of particular physical effects, including the generation of a plasma cloud of ionized air around the vehicle, may interfere with incoming and outgoing signals.[19] These effects also limit the usability of assorted on-board guidance sensors. The physical effects can be reduced by deceleration during the terminal stage; however, this could also make the vehicle more vulnerable to defences.

[19] Tambovtsev, V., Shevyakov, I. and Barinov, A., 'Characteristic of wingtip vortices formed around the hypersonic vehicle in the mesosphere', *Physics of Wave Processes and Radio Systems*, vol. 19, no. 1.

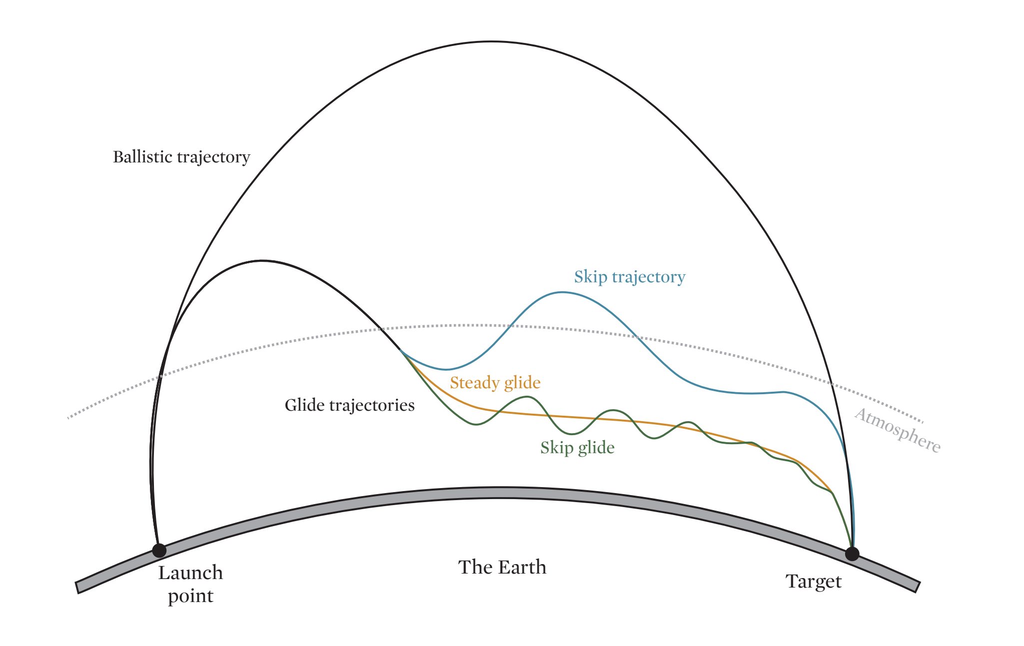

Figure 2.2. Notional trajectories of ballistic missiles, hypersonic boost-glide systems and aeroballistic missiles

Source: Zhao, P., Chen, W. and Yu, W., 'Analytical solutions for longitudinal-plane motion of hypersonic skip-glide trajectory', *Nonlinear Dynamics*, no. 96 (Mar. 2019), adapted with permission.

Hypersonic boost-glide systems

Most hypersonic weapons currently deployed, or nearing deployment, are hypersonic boost-glide systems of various types, ranges and payloads. Launched by ballistic missile boosters, HGVs are sophisticated manoeuvrable glide vehicles that travel a significant (although undefined) part of their flight path inside the atmosphere. These 'gliders' come in a range of different shapes (most commonly wedge-shaped or conical) and, compared to regular re-entry vehicles, rely on a higher lift-to-drag ratio to maintain flight in the atmosphere and reach their target. Such vehicles experience extreme and sustained thermal loading. Therefore, one of their most important characteristics is to have a heat-resistant or ablative coating. Any horizontal manoeuvre of such a vehicle leads to speed reduction—and, consequently, increased vulnerability to missile defences and a longer time to target. However, under certain circumstances, vertical manoeuvres can have a positive effect on speed, including skip-glide or 'inverted dive' manoeuvres that exploit the same lift-to-drag ratios but 'turn those around' to achieve a terminal speed increase.[20]

A similar type of missile to consider is the so-called aeroballistic missile—often conflated with HGVs, and to a lesser extent with HCMs. These are ballistic missiles (sometimes without detachable warhead or re-entry vehicles) that travel most of their flight path in the atmosphere and use aerodynamics to perform (some) manoeuvres. Their design is comparable with that of manoeuvrable re-entry vehicles (MaRVs). Some definitions consider all HGVs and aeroballistic missiles to be subtypes of MaRVs, while others classify aeroballistic missiles, MaRVs and HGVs as three separate types within the category of missile systems with aerodynamic capabilities.[21]

[20] Tracy and Wright (note 16), pp. 140 and 147.

[21] Lysenko, L. N., [Ballistic rocket guidance] (Bauman MSTU Publishing House: Moscow, 2016), p. 445 (in Russian); and Dunham, S. T. and Wilson, R. S., *The Missile Threat: A Taxonomy for Moving beyond Ballistic* (Aerospace Corporation: El Segundo, CA, Aug. 2020).

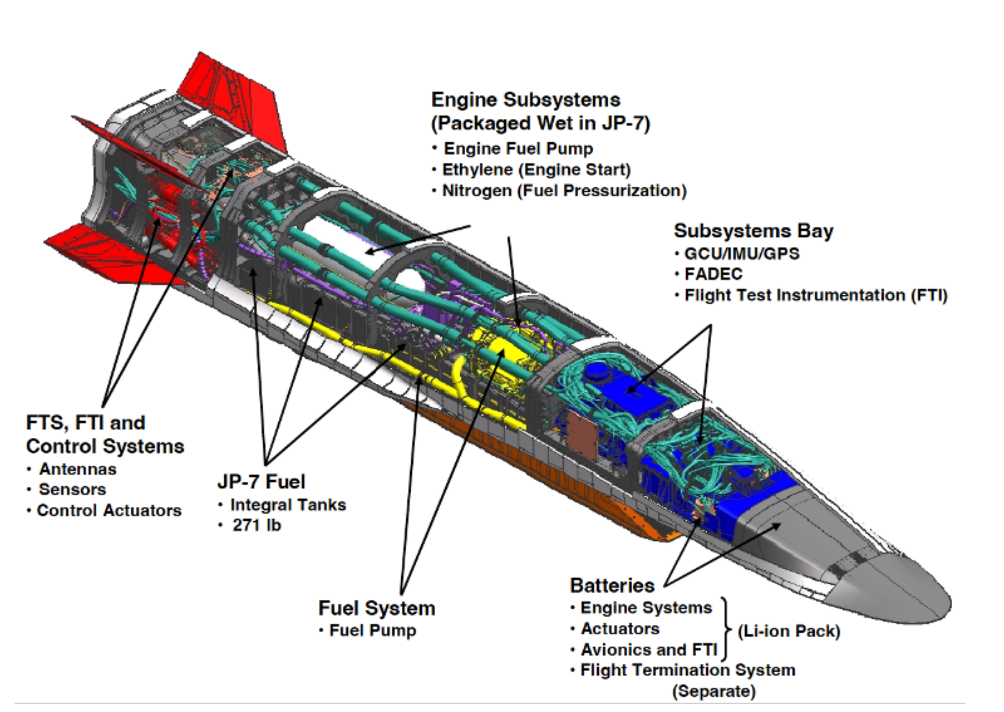

Figure 2.3. A cutaway diagram of subsystems packaging of an X-51A scramjet engine demonstrator

Source: Hank, J. M., Murphy, J. S. and Mutzman, R. C., 'The X-51A scramjet engine flight demonstration program', 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, May 2008, p. 7.

Hypersonic cruise missiles

Hypersonic cruise missiles are a specific type of cruise missile, usually using air-breathing engines, that can reach and maintain hypersonic speeds throughout much of their flight. Their main advantage, compared to ballistic missiles and boost-glide systems, is sustained and 'self-propelled' hypersonic flight combined with manoeuvring capability and flight at low altitudes—although, the average speed of HCMs may be lower than that of a HGV. While some advanced ramjet engines can reach lower hypersonic speeds, most HCM programmes seek to develop cruise missiles powered by scramjet engines, which are much more sophisticated and technically challenging (see figure 2.3). Despite the fact that many different HCM programmes have been under development for a long time, none of them appear to be nearing deployment.[22] The main technical challenge is developing a scramjet engine that works at the necessary altitude and when air flows into its intake at supersonic speed, such that its fuel actually combusts under these conditions.[23] HCMs appear to be particularly suited for launch not only from aircraft but also from ships and submarines, and for shorter ranges compared to HGVs.[24]

Drivers and status of hypersonic missile development and proliferation

Research on the types of weapon systems that are now considered hypersonic missiles began in the mid-20th century, but only in recent years have the first hypersonic

[22] Russia's Tsirkon missile is nearing deployment on surface warships; however, despite various reports claiming its use of a scramjet engine, its propulsion mode has not been credibly disclosed in public sources.
[23] Oelrich (note 17), p. 43.
[24] Tirpak, J. A., 'Hypersonic HAWC missile flies, but details are kept hidden', *Air Force Magazine*, 27 Sep. 2021.

boost-glide systems been deployed. Over the last decade, the number of states with hypersonic missile programmes and research and development efforts in key areas of related technology has grown significantly. Leading actors are currently China, Russia and the USA. In addition, Australia, France, India, Japan, North Korea and South Korea, among others, also have, or participate in, hypersonic missile programmes (see table 2.1). All of these states are MTCR partners, with the exception of China and North Korea. This is particularly important when considering the risk of further proliferation and the effectiveness of MTCR export controls.

There are at least three main enablers and drivers of recent progress in states' HGV and HCM programmes. First, there have been numerous and continuous advances in relevant technologies, including in heat-resistant and ablation materials, supercomputing simulation, miniaturization of electronics, and in the use of artificial intelligence (AI) by on-board guidance systems.[25] Second, increased capabilities and proliferation of air and missile defence systems have fuelled the search for new ways of overcoming or evading such defences. In particular, US deployment of both naval and ground-based anti-ballistic missile defences is a key reason cited by several states for their pursuit of hypersonic missiles.[26] Third, particularly in the context of the public and political hype around hypersonic missiles, it has rapidly become a sign of prestige to deploy, or at least test, such weapons—especially for states seeking the status of a strong military power.[27] The combination of technology, military and status considerations contributed to the current state of competitive dynamics, if not a 'hypersonic missile arms race'. There are now ever-increasing investments in hypersonic weapons technology, often without a full understanding or clear vision of their military missions and of the consequences that their development and deployment might have for regional and global security.

Russia was the first state to field missiles that it describes as hypersonic weapons with both 'theatre-range' (the medium-range air-launched aeroballistic missile Kinzhal) and 'strategic range' (the intercontinental-range silo-based boost-glide system Avangard). It will likely also be the first to operate a 'hypersonic triad' once Tsirkon, its sea-based HCM, formally enters service. Since 2019 China has reportedly deployed the DF-17, an intermediate-range hypersonic boost-glide system on road-mobile launchers that uses a ballistic missile booster to carry an HGV.[28] China has reportedly also tested another HGV on a FOBS, but little information is available on the glide vehicle and delivery system.[29] Russia and China are credited with currently enjoying a lead over other states developing hypersonic missiles, likely driven by their concerns over US missile defences. However, while this lead does not reflect military or technological superiority, it provides advantages through their ability to gain operational experience in day-to-day planning and maintenance operations, exercises and deployment to distant staging areas, that is, where final preparations for launch are made. The USA continues its long-standing pursuit of hypersonic missiles with up to a dozen different ongoing hypersonic weapons programmes across its major service branches.[30] The USA has not yet deployed any hypersonic boost-glide system or HCM. The main

[25] Saalman, L., 'China's artificial intelligence-enabled offense: Hypersonic glide vehicles and neural networks', ed. N. D. Wright, *Artificial Intelligence, China, Russia, and the Global Order: Technological, Political, Global, and Creative Perspectives* (Air University Press: Maxwell Air Force Base, AL, Oct. 2019), pp. 164–65.

[26] Putin, V., 'Presidential address to the federal assembly', Kremlin events, 1 Mar. 2018; and Sayler (note 4), pp. 4–9.

[27] Stone, R., '"National pride is at stake." Russia, China, United States race to build hypersonic weapons', *Science*, 8 Jan. 2020.

[28] Gertz, B., 'China shows DF-17 hypersonic missile', *Washington Times*, 2 Oct. 2019.

[29] Sevastopulo, D. and Hille, K., 'China tests new space capability with hypersonic missile', *Financial Times*, 16 Oct. 2021; and Saalman, L., 'Multidomain deterrence and strategic stability in China', SIPRI Insights on Peace and Security no. 2022/2 (Jan. 2022).

[30] United States Government Accountability Office (GAO), 'Hypersonic weapons: DOD should clarify roles and responsibilities to ensure coordination across development efforts', GAO report, GAO-21-378, Mar. 2021.

Table 2.1. Selected current hypersonic missile systems and development programmes

Designator/ programme	Type	Booster/propulsion	Payload	Range (km)	Status	MTCR Partner
Australia and United States						*Yes*
SCIFiRE (prog.)	HCM	Scramjet engine and rocket booster	Conventional	. .	Under development since 2021; speed of Mach>5; builds on HIFiRE prog.	
China						*No*
DF-ZF	HGV	. .	. .	(Inter-continental range)	First flight tested in 2014	
DF-17	HGV	DF-16 ballistic missile booster	(dual-capable)	1 600–2 400	Deployed since 2019; last flight-tested in 2017	
. .	HGV	Fractional orbital bombardment system	. .	Global range	First flight-tested in Aug. 2021	
Starry Sky-2	HCM	Air-breathing engine	Nuclear	. .	Experimental system; flight-tested in 2018	
North Korea						*No*
Hwasong-8	HGV	Boost-glide system; ground-launched; road-mobile	(nuclear or dual-capable)	. .	First flight-tested in Sep. 2021	
. .	Aero-ballistic	Boost-glide system; ground-launched; road-mobile	(nuclear or dual-capable)	. .	First flight-tested in Jan. 2022	
France						*Yes*
ASN4G	HCM	Air-breathing engine; air-launched	Nuclear	. .	Under development	
V-MAX (prog.)	HGV	Boost-glide system	(nuclear)	. .	Under development	
India						*Yes*
HSTDV (prog.)	HCM	Air-breathing engine; Agni-1 missile booster	. .	. .	Demonstrator tested in 2019	
Japan						*Yes*
HVGP	HGV	Boost-glide system; ground-launched	Conventional	. .	Under development since 2020; planned deployment in 2026	
HVGP (prog.)	HCM	Air-breathing engine; air- and ground-launched	Conventional	. .	Under development since 2020; planned deployment in 2028	
South Korea						*Yes*
‘Hycore’	HCM	Air-breathing engine	Conventional	. .	Under development	
Russia						*Yes*
‘Avangard’	HGV	Boost-glide system; ground-launched; silo-based	Nuclear; 2 000–4 000 kg warhead	6 000–11 000	Declared operational in Dec. 2019	
‘Gremlin’ (GZUR)	HCM	Scramjet engine; air-launched	. .	. .	Under development since 2018; testing planned for 2023; ~Mach 6	
‘Kinzhal’	Aero-ballistic	Solid-propellant rocket motor; air-launched	Dual-capable; ~480 kg warhead	≤2 000	Declared operational in Dec. 2018	
‘Ostrota’	HCM	Scramjet engine; air-launched	. .	. .	Testing since 2022	

Designator/ programme	Type	Booster/propulsion	Payload	Range (km)	Status	MTCR Partner
‘Tsirkon’	(aero-ballistic or HCM)	(aeroballistic solid-propellant rocket motor or scramjet engine); sea-based; air-launched version under development	(dual-capable)	1 000–1 500	Testing since 2019; production since 2021; declared operational (for surface ships) in 2022	
United States						*Yes*
Air-launched Rapid Response Weapon	HGV	Boost-glide system; air-launched	Conventional	>1 600	Under development by the US Air Force	
Hypersonic Attack Cruise Missile	HCM	Air-breathing engine; air-launched	Conventional	. .	Under development by the US Air Force	
Hypersonic Air-breathing Weapon Concept	HCM	Air-breathing engine; air-launched	Conventional	. .	Under development by DARPA	
Long-Range Hypersonic Weapon ‘Dark Eagle’	HGV	Boost-glide system; ground-launched; road-mobile	Conventional	>2 700	Under development by the US Army	
Intermediate-Range Conventional Prompt Strike	HGV	Boost-glide system; ground-launched; road-mobile	Conventional	. .	Under development by the US Navy	
Standard Missile-6 Block IB	. .	Interceptor-derived; ground-launched; road-mobile	Conventional	. .	Under development by US Army and DARPA	
Operational Fires	HGV	Boost-glide system; ground-launched	. .	. .	Under development by DARPA	
Tactical Boost Glide	HGV	Boost-glide system; air-launched	. .	‘tactical range’	Under development by DARPA and the US Air Force	
‘Project Mayhem’	HCM	Air-breathing engine; air-launched	. .	‘extended range’	Under development since 2020	

. . = data not available or not applicable; ( ) = data uncertain; DARPA = Defense Advanced Research Projects Agency; HCM = hypersonic cruise missile; HGV = hypersonic glide vehicle; HIFiRE = Hypersonic International Flight Research Experimentation Program; GZUR = Gremlin hypersonic guided rocket; kg = kilogram; km = kilometre; prog. = programme; SCIFiRE = Southern Cross Integrated Flight Research Experiment.

Sources: Sayler, K. M., ‘Hypersonic weapons: background and issues for Congress’, Congressional Research Service, Updated 17 Mar. 2022, pp. 4–17; Speier, R. H. et al., *Hypersonic Missile Nonproliferation: Hindering the Spread of a New Class of Weapon* (RAND Corporation: Santa Monica, CA, 2017), Appendix B; Bugos, S. and Reif, K., ‘Understanding hypersonic weapons: managing the allure and the risks’, Arms Control Association Report, Sep. 2021, pp. 8–14; Henrotin, J., ‘Hypersonic weapons: what are the challenges for the armed forces?’, Briefings de l’Ifri, 18 June 2021, pp. 7–9; various government reports and press releases; and authors’ estimates and assessments.

military missions intended for the missiles under development are time-sensitive targeted strikes, penetration of missile and other air defences, and holding targets in the strategic depth at risk. Several other countries are currently at different stages of development of domestic hypersonic weapon programmes. *France* plans to have hypersonic delivery systems as the backbone of its next-generation nuclear arsenal by developing both the air-launched HCM ‘ASN4G’ (air–sol nucléaire de 4e génération) and a HGV, reportedly for its submarine-launched ballistic missile (SLBM), under the ‘V-MAX’ (véhicule manoeuvrant experimental) programme.[31] *India* notably carried out a number of tests of scramjet technology using its hypersonic technology demon-

[31] Wright, T. and Decis, H., ‘Counting the cost of deterrence: France’s nuclear recapitalisation’, IISS Military Balance Blog, 14 May 2021; and Charpentreau, C., ‘France to test V-MAX hypersonic glider in coming months’, *AeroTime Hub*, 12 May 2021.

strator vehicle (HSTDV).[32] *North Korea* claims to have successfully tested HGVs, both aeroballistic and gliding types, which use boosters with rocket motors similar to those of its Hwasong-12 intermediate-range ballistic missile.[33] *Japan* and *South Korea* are also pursuing hypersonic weapons-related programmes. Japan's future long-range strike capability specifically aims at protecting its remote islands and providing an anti-ship capability. Japan plans to initially deploy its hyper velocity gliding projectile (HVGP) on a boost-glide system by 2026 and to develop a scramjet-powered missile for deployment in 2028 or later.[34] South Korea is currently developing the 'Hycore' HCM, primarily to strengthen its military capabilities vis-à-vis North Korea.[35] Notably, their programmes seem to be more focused on counterforce applications of their respective hypersonic weapons under development. *Australia* is a rare example of advanced military–technical cooperation in the hypersonic domain. The current Southern Cross Integrated Flight Research Experiment (SCIFiRE) programme is based on the long-running Hypersonic International Flight Research Experimentation Program (HIFIRE) joint research project with the USA, which was focused on testing different designs of hypersonic aerospace vehicles. The project is currently maturing with the intention to develop 'a solid-rocket boosted, air-breathing, hypersonic conventional cruise missile, air-launched from existing fighter or bomber aircraft, through the completion of a preliminary design review'.[36]

[32] Indian Ministry of Defence, 'DRDO successfully flight tests Hypersonic Technology Demonstrator Vehicle', Press release, 7 Sep. 2020.

[33] Savelsberg, R. and Kawaguchi, T., 'North Korea's hypersonic missile claims are credible, exclusive analysis shows', *Breaking Defense*, 16 Feb. 2022.

[34] Tanabe, Y., 'Japan mulls anti-aircraft carrier gliding missiles for remote island defense', *The Mainichi*, 25 Feb. 2020.

[35] Kwon, H.-C., 'S. Korea may put hypersonic missile into service by late 2020s', *The Hankyoreh*, 7 Jan. 2022.

[36] Hitchens, T., 'Joint US–Australian hypersonic cruise missile moves ahead', *Breaking Defense*, 3 Sep. 2021.

3. Conventional–nuclear entanglement and MTCR controls on dual-capable delivery systems

Conventional–nuclear entanglement and the case of HGVs and HCMs

The perceived capabilities and possible missions of hypersonic weapons, and the possible dual-capable nature of many of them, means that they are a prime example of so-called conventional–nuclear entanglement and of broader trends in the development of strategic non-nuclear weapons.[37] Some of the missions considered for hypersonic weapons, both at strategic and theatre levels, can be fulfilled by conventional payloads due to the speed and precision of the weapons. The USA reiterates that it has no plans to equip its future hypersonic missiles with nuclear payloads. In contrast, Russia explicitly declared its Avangard missile to exclusively be a nuclear weapon delivery system and its Kinzhal missile to be explicitly dual-capable. Nevertheless, Kinzhal (and Tsirkon) is mentioned by some scholars as part of non-nuclear strategic capabilities that can be used in conflict that has not yet escalated to include nuclear use.[38] As with several other Russian long-range precision weapons, their dual-capable nature means that they are often labelled as part of non-nuclear deterrence forces. China has explicitly hedged its bets on what role it intends for its DF-ZF hypersonic glide vehicle, including whether its roles and types of payloads may vary depending on which ballistic missile booster (and with what range) carries it.[39] As with many other intermediate-range weapons in the People's Liberation Army Rocket Force inventory, the system could well be dual-capable, but there is a lack of robust public data to corroborate this.

Conventional–nuclear entanglement could apply in the case of these and future hypersonic missile systems, both with potentially stabilizing or destabilizing effect. Another aspect of the challenges posed by entanglement is that non-nuclear hypersonic weapons could be used as a deterrent against adversary nuclear capability or as a counterforce capability. Similarly, nuclear-tipped hypersonic weapons could be deployed as a deterrent against superior conventional threats or aimed at strategic but non-nuclear anti-ballistic missile assets. While these different missions could be argued to enable more stable deterrence relationships in which mutual vulnerability is ensured, without significant confidence-building measures and mutual verification, misperception and misinterpretation would continue to be a significant threat. It seems to be a common fallacy to overestimate the capabilities of adversaries and underestimate one's own. A particularly problematic scenario that could arise from misperception, misinterpretation or a combination thereof is a 'use it or lose it' situation where one party fears that the perceived capability of its adversary could disarm it and that if it does not strike first, it would lose its ability to launch its strategic weapons or retaliate. The party may even choose to strike with nuclear weapons because of its doubts about the capabilities of its non-nuclear options.

Several of the states developing HGVs and HCMs do so to be able to overcome advanced missiles defences. However, the development and deployment of HGVs and HCMs is also used to justify continuous development of new missile defence systems.[40]

[37] Acton, J. M., 'Escalation through entanglement: How the vulnerability of command-and-control systems raises the risk of inadvertent nuclear war', *International Security*, vol. 43, no. 1 (2018), pp. 97–98.

[38] Massicot, D., 'Lengthening the bridge: The role of current weapons and emerging technologies in expanding the pre-nuclear phase of conflict', NATO Defence College Russian Studies Series no. 4/21, July 2021.

[39] Saalman, L., 'Factoring Russia into the US–Chinese equation on hypersonic glide vehicles', SIPRI Insights on Peace and Security no. 2017/1, Jan. 2017, p. 5.

[40] Putin, V., 'The updated air and space defence system must detect hypersonic and ballistic targets of all types at long distances and then be able to destroy them along the entire trajectory of their flight', Kremlin news, 1 Nov. 2021;

It is unclear whether such dynamics might eventually lead to a dramatic increase in missile defence capabilities that could also better defend against 'traditional' missile threats. They do, however, result in a vicious cycle, where missile defences lead to more missiles with an ability to defeat defences, which in turn lead to the development of more sophisticated defences. The impact of this dynamic can spiral if it also reduces the secured strike capability of other strategic forces and can thus threaten strategic stability and result in destabilizing arms race dynamics, particularly between nuclear-armed states. However, this does not mean that there are no solutions. Increased transparency about intended missions and procedures required to switch from non-nuclear to nuclear payloads could be a good first step, and, eventually, proper arms control measures could be put in place. At the same time, if arms control is going to be a serious option, it should go hand-in-hand with addressing a broader category of long-range precision weapons.[41] Nonetheless, arrangements for hypersonic weapons would be a good first step.

MTCR controls on nuclear and dual-capable delivery systems

The primary focus of the MTCR is to prevent the proliferation of nuclear weapon delivery systems. The threshold parameters of a capability to deliver a payload of at least 500 kilograms to a range of at least 300 kilometres were set in accordance with requirements for delivering a notional nuclear warhead of an emerging nuclear power in a notional strategic theatre.[42] The 500 kg payload weight parameter chosen when the MTCR was created may be less applicable to modern nuclear warheads, and a range of at least 300 km can be more or less relevant depending on the situation of particular possessor states and theatres of operation where such missile systems may be deployed. However, these parameters have nevertheless established a useful threshold so that most potentially destabilizing missiles and UAVs are covered by MTCR controls.

The issue of dual-capable delivery systems—that is, delivery systems capable of delivering both a nuclear weapon or a conventional payload—is not new to the MTCR. The MTCR guidelines and annex intentionally refer to missiles and UAVs 'capable of' delivering CBN weapons. This means that they neither require the delivery systems to be specially designed for a CBN weapon end-use, nor that sufficient information or concern about such an end-use would have to be established, for them to fall under controls and thus a licensing requirement.[43] Similarly, the MTCR annex covers equipment and technology 'relevant to' missiles and UAVs that meet or exceed the payload and range parameters.[44] Accordingly, while dual-capable delivery systems may pose particular challenges to strategic stability, influence nuclear postures, and be particularly destabilizing if they have the characteristics of highly capable hypersonic missile systems, from the MTCR perspective of non-proliferation export control, such delivery systems are captured by controls regardless of whether they are destined for a nuclear or conventional weapon end-use.[45] Complete missiles and UAVs with the stated parameters and complete subsystems that can be used for them are covered by category I of the MTCR annex; the partners commit to applying a 'strong presumption

and Karako and Dahlgren (note 2).

[41] Williams, H., 'Asymmetric arms control and strategic stability: Scenarios for limiting hypersonic glide vehicles', *Journal of Strategic Studies*, vol. 42, no. 6 (2019).

[42] Ozga, D. A., 'A chronology of the Missile Technology Control Regime', *Nonproliferation Review*, vol. 1, no. 2 (Winter 1994), p. 67.

[43] MTCR, Guidelines for Sensitive Missile-Relevant Transfers, [n.d.], para. 1; and MTCR (note 12), p. 15.

[44] MTCR (note 43), para. 1.

[45] Pollack, J. H., 'Boost-glide weapons and US–China strategic stability', *Nonproliferation Review*, vol. 22, no. 2 (Feb. 2016).

of denial' to transfers of such items and to complete production facilities. This strong presumption of denial is also extended to dual-use goods and technology covered by category II and non-listed items that may be covered through the application of a catch-all control if the exporting state has information or sufficient concerns that the items could be used in CBN weapons delivery systems. This regime establishes particularly strong controls not only on complete system and nuclear (and chemical and biological) weapon end-uses but also on conventional missiles that meet or exceed the threshold parameters, while also casting a wide net around missile technologies where states require export licensing and can take decisions on a case-by-case basis.[46]

The implementation of the MTCR guidelines and the annex by the partners, and their use as the basis of non-partners' export controls on delivery systems and related goods and technologies, enable states to apply a restrictive policy on relevant transfers; however, this also leaves a certain leeway for sovereign decision-making. The 'minimum common set of criteria' for licensing decisions set out by the MTCR not only heavily emphasizes the prevention of transfers to possible nuclear weapon end-uses but also seeks to take into consideration legitimate civilian space programmes and crewed aircraft applications.[47] However, the guidelines also refer to binding end-use assurances and responsibility for necessary steps to ensure these as possible mitigating measures for rare occasions when partners may choose not to issue a denial or make an exception to the strong presumption of denial.[48] The MTCR provides the elements of a strong system of controls, but its effectiveness and the level of restraint that partners and non-partners implementing it apply to particular types of delivery system—in this case, hypersonic boost-glide systems and HCMs—depends on a common understanding of their classification in the annex categories and the comprehensive coverage of relevant subsystems, goods and technologies.

[46] MTCR, 'MTCR guidelines and the equipment, software and technology annex', [n.d.].
[47] MTCR (note 43).
[48] MTCR (note 43), para. 2.

4. Applying MTCR export controls to hypersonic boost-glide systems and hypersonic cruise missiles

The export controls prescribed by the MTCR already create extensive controls on key missile technologies that are required for hypersonic boost-glide systems and HCMs. In most cases, the parameters of these controls mean that the types of subsystems, items and technology required for HGVs and HCMs are already covered. However, there is some ambiguity over when HGVs would fall under controls within category I or within category II of the annex—which category determining how restrictive states' controls on their transfers would be. This is particularly significant as the restrictiveness and extent of some of the controls on related dual-use goods and technologies are linked to whether the complete system is covered by category I of the annex. There is an ongoing discussion among the partners about clarifying the coverage of HGVs and whether any amendments or additional controls on relevant dual-use technologies may be required.

Definitional ambiguities concerning HGVs and HCMs

The definitional issues pertaining to speed, trajectory and manoeuvrability of hypersonic missile systems, and the spectrum of these capabilities that exists across different missile types, means that there is some ambiguity over the coverage of hypersonic boost-glide systems and specifically HGVs by the MTCR annex. The MTCR guidelines and the annex do not provide technical definitions for many important terms such as 'ballistic missile', 'unmanned aerial vehicle' and 're-entry vehicle'. Instead, the annex often provides a non-exhaustive list of examples of such items. For example, according to the annex, 'unmanned aerial vehicle systems' include 'cruise missiles, target drones and reconnaissance drones'.[49] As neither HGVs nor HCMs are explicitly mentioned by the annex, exporters and licensing authorities need to interpret whether they fall in—or outside—the control list items in the annex. This classification is particularly important because the payload definition differs for ballistic missiles, cruise missiles and other UAVs. In the case of ballistic missiles with separating re-entry vehicles, the entire weight of a re-entry vehicle, munitions and other components count towards the 500 kg threshold.[50] For cruise missiles, only the munitions, separating mechanisms and some other elements such as countermeasures are counted towards the payload weight parameter.[51] Depending on the specific design of the vehicle and the weight of the nuclear warhead or explosive munition—or if a HGV relies only on its kinetic energy at impact—at least some HGVs could fall outside of category I and thus would not generally be subject to a strong presumption of denial.

HGVs are designed to maintain a certain level of aerodynamic lift and usually have some type of aerodynamic control surfaces or cold gas thrusters that enable them to perform manoeuvres throughout their flight, both down-range and cross-range.[52] In contrast, traditional re-entry vehicles typically have near-zero lift, which would speak for defining HGVs as UAVs. However, well before the recent advances in HGV programmes, a whole class of re-entry vehicles—MaRVs—was designed to enable certain degrees of manoeuvrability, and so the partners have agreed to classify MaRVs as ballistic missile re-entry vehicles. The unofficial MTCR annex handbook, which is produced and periodically updated (last in 2017) by the USA and published on the

[49] MTCR (note 12), p. 16.
[50] MTCR (note 12), pp. 10–12.
[51] MTCR (note 12), p. 11.
[52] Acton, J. M., 'Hypersonic boost-glide weapons', *Science & Global Security*, vol. 23, no. 3 (2015).

Table 4.1. Coverage of selected items required for hypersonic missile systems by the MTCR Equipment, Software and Technology Annex

Type of equipment	Category	List item
Complete delivery systems		
Complete rocket systems (including ballistic missiles, space launch vehicles, and sounding rockets)	I	1.A.1
Complete unmanned aerial vehicles (including cruise missiles, target drones and reconnaissance drones)	I	1.A.2
Complete subsystems usable for complete delivery systems		
Complete subsystems	I	2.A.1
Individual rocket stages	I	2.A.1.a
Re-entry vehicles	I	2.A.1.b
Rocket propulsion subsystems	I	2.A.1.c
Guidance sets	I	2.A.1.d
Thrust vector control subsystems	I	2.A.1.e
Propulsion components and equipment		
Ramjet/scramjet/pulse jet/combined cycle engines	II	3.A.2
Instrumentation, navigation and direction finding		
Integrated flight instrument systems	II	9.A.1
Gyro-astro compasses	II	9.A.2
Linear accelerometers	II	9.A.3
All types of gyros	II	9.A.4
Accelerometers or gyros	II	9.A.5
Inertial measurement equipment or systems	II	9.A.6
Integrated navigation systems	II	9.A.7
3 axis magnetic heading sensors	II	9.A.8
Flight control		
Pneumatic, hydraulic, mechanical, electro-optical or electromechanical flight control systems	II	10.A.1
Attitude control equipment	II	10.A.2
Flight control servo valves	II	10.A.3
Avionics		
Radar and laser radar systems including altimeters	II	11.A.1
Passive sensors	II	11.A.2
Receiving equipment for navigation satellite systems	II	11.A.3
Test facilities and equipment		
Vibration test equipment	II	15.B.1
Aerodynamic test facilities (incl. wind tunnels)	II	15.B.2
Test benches/stands	II	15.B.3
Environmental chambers	II	15.B.4
Accelerators	II	15.B.5
Aerothermodynamics test facilities	II	15.B.6

Note: Each list item in the annex also includes a section D, which covers software, and a section E, which covers technology.

Source: Missile Technology Control Regime, Equipment, Software and Technology Annex, MTCR/TEM/2021/Annex, 8 Oct. 2021.

MTCR website, also specifically mentions HGVs as 'one potential type of MARV' in this category.[53] HCMs naturally fall within the category of cruise missiles, and their payloads would exceed the 500 kg threshold in most current specific HCM programmes and most other conceivable designs.[54] While many of the technical arguments and references to established practices and interpretations point to classifying HGVs as

[53] MTCR, *Annex Handbook 2017* (2017), p. 24.
[54] Government senior adviser on export technical policy, Interview with authors, 2 Feb. 2022.

ballistic missile re-entry vehicles, the decision by the partners is ultimately both a technical and a political one that will also reflect whether there is consensus around the need to apply particularly restrictive controls to HGVs.

There are several options for how the MTCR could clarify the definitional ambiguity concerning HGVs and ensure restrictive controls on them. First, the partners could agree to amend the annex to explicitly include boost-glide systems in the list of types of 'Complete rocket systems' provided in category I, list item 1.A.1.[55] The types currently included are 'ballistic missiles, space launch vehicles, and sounding rockets'. Hypersonic boost-glide systems could be interpreted to fit into the wider category of ballistic missiles, as they usually rely on a ballistic missile booster to accelerate and carry the glide vehicle to its sub-orbital or near-orbital release point. They could also be added in their own right. Explicitly listing them with the other types would prevent their coverage by the control list being left open to interpretation. To the same effect, the partners could add an explanatory 'note' to the list item clarifying that hypersonic boost-glide systems are understood to be 'complete rocket systems' or 'ballistic missiles'. Second, the partners could amend the annex to explicitly include HGVs within the scope of 're-entry vehicles' which are controlled as 'Complete subsystems' usable for complete rocket systems in category I. The partners could also add a 'note' to the relevant list item (category I, item 2.A.1.b.) clarifying that HGVs are understood to be 're-entry vehicles' covered by the list item.

Current coverage of hypersonic missile technology by the MTCR annex

Complete rocket systems and rocket boosters

The MTCR annex includes control list items covering complete rocket systems and individual rocket stages within category I (see table 4.1). Hypersonic boost-glide systems generally use a ballistic missile booster or rocket stage—usually using a solid-propellant rocket motor—to carry a HGV to its release (or re-entry) point. The broad formulation of controls on these items means that the MTCR already applies restrictive controls on this key subsystem of a boost-glide system. Notably, a HGV could also be carried to its release point by other types of propulsion systems, for example a scramjet engine, but current and planned designs almost exclusively use a (modified) ballistic missile booster or a different type of rocket booster. HCMs may also rely on a small rocket booster to boost their initial acceleration or to reach the necessary air speed and pressure required for supersonic combustion in a scramjet engine.[56] These smaller boosters are also covered by category I controls as complete subsystems if they can be used in a HCM that is beyond the 500 kg payload and 300 km range threshold. The annex also covers propellants, as well as chemicals and production equipment required for different types of solid-propellant rocket motors and liquid-fuelled rocket engines, as these are the same for ballistic missiles and other rocket-propelled delivery systems traditionally covered by MTCR controls.[57]

Air-breathing engine systems, including scramjet engines

Advanced air-breathing engines that can achieve hypersonic speeds are key components of HCMs, and mastery of this technology is a key hurdle to HCM development. While some very sophisticated ramjet engines can reach hypersonic speeds of up to approximately Mach 6, most hypersonic missile systems currently

[55] MTCR (note 12), p. 16.
[56] Oelrich (note 17), p. 43.
[57] See category II, item 6 in the MTCR annex. MTCR (note 12), pp. 38–45.

under development aim to use scramjet engines.[58] Depending on the design of the HCM, it may also use two cycles of different engine technologies. For example, it may integrate an additional ramjet engine or rocket motor to reach the speed required for initiating supersonic combustion in its scramjet engine—a so-called 'combined cycle' engine.[59] The MTCR annex covers ramjet, scramjet and 'combined cycle' engines, and devices for combustion regulation and other specially designed components for these types of engines, in category II (see table 2).[60] The annex also covers a wide range of propellants, fuels, oxidizers and required chemicals, as well as other components (see category II, item 4) that could be used in future HCMs.

Inertial guidance systems and flight controls

The annex includes controls on complete 'guidance sets' usable in category I systems with a certain accuracy that integrate 'the process of measuring and computing a vehicle's position and velocity (i.e. navigation) with that of computing and sending commands to the vehicle's flight control systems to correct the trajectory'.[61] It also includes list items that cover individual dual-use equipment, assemblies and components required for 'instrumentation, navigation and direction finding' (i.e. gyros, accelerometers, inertial measurement equipment and integrated navigation systems), various flight control systems and attitude control equipment, and avionics (i.e. radar and laser radar systems, passive sensors and receiving equipment for navigation satellite systems, including antennae).[62] Inertial guidance systems that are integrated with other sensors, the on-board computing capabilities and the flight control system are particularly important for hypersonic missile systems because the conditions experienced during hypersonic flight can blind sensors and severely impede communication with ground control and satellite navigation. An inertial guidance system relies on instruments that precisely measure any acceleration, deceleration and turns of the hypersonic vehicle during its flight and provide these to an on-board computer to calculate its exact position. Based on these continuous calculations, the flight control system can adjust or correct course.[63] Notably, the computing solutions explored to improve the performance of guidance and flight control systems during the difficult conditions of hypersonic flight include the integration of neural networks.[64]

Heat shields and special materials for heat management

One of the key technical challenges for hypersonic missiles is managing the sustained extreme thermal loads experienced by both HGVs and HCMs during their flight. MTCR controls cover 'Heat shields, and components therefor, fabricated of ceramic or ablative materials' and 'Heat sinks and components therefor, fabricated of light-weight, high heat capacity materials'.[65] The annex also covers several types of high-temperature ceramic composite materials usually used for missile nose tips, re-entry vehicles, leading edges and control surfaces that bear significant thermal loads during endo-atmospheric manoeuvres.[66] Ballistic missile re-entry vehicles experience even higher temperatures than HGVs and HCMs due to their higher peak speeds; however, they

[58] Brockmann and Schiller (note 1).

[59] A 'combined cycle' engine is an 'engine that employs two or more cycles of the following engine types: Gas-turbine (turbojet, turboprop, turbofan and turboshaft), ramjet, scramjet, pulse jet, detonation or rocket motor or rocket engine'. MTCR (note 12), p. 23.

[60] MTCR (note 12), p. 23.

[61] MTCR (note 12), pp. 18–19.

[62] MTCR (note 12), pp. 48–59.

[63] Oelrich (note 17), p. 42.

[64] Saalman (note 25), pp. 162–65.

[65] MTCR (note 12), p. 18.

[66] MTCR (note 12), p. 42.

generally do so for a much shorter period between their re-entry into the atmosphere and reaching their target.[67] HGVs may experience lower peak temperatures but for a longer time and thus higher total thermal loading. The specific requirements and therefore the characteristics of the materials and thermal management approach often differ for HGVs and HCMs.[68] The partners should monitor the development of special materials and composites specially designed for use in HGVs and if necessary amend the annex to ensure adequate coverage of such composites.

Hypersonics test facilities and equipment

The significant technical challenges and the very specific conditions under which HGVs and HCMs have to operate require extensive simulation and testing. A hypersonic missile programme requires test facilities that can be used during design, prototyping and testing phases, and that are able to adequately simulate the conditions at various altitudes, hypersonic speeds and types of trajectories and manoeuvres. The MTCR annex controls a range of test facilities and equipment, including 'vibration test equipment', test benches and test stands, 'environmental chambers' and 'accelerators'.[69] Wind tunnels for hypersonic speeds are particularly important as test facilities in which the aerodynamics of glide vehicles and cruiser modules can be tested under relevant conditions. The annex covers aerodynamic test facilities, including all wind tunnels for hypersonic speeds, and certain 'aerothermodynamics test facilities'. As the number of wind tunnels for testing at higher hypersonic speeds is currently rather limited and in high demand, controls on relevant technical data on tests and technical assistance are particularly important.

Technology and technical assistance

The export controls prescribed by the MTCR can also apply to transfers of technology and technical assistance related to the specific goods listed in the annex. In this context 'technology' is defined by the annex as 'specific information which is required for the "development", "production" or "use" of a product'. The annex distinguishes between 'technical data' (i.e. 'blueprints, plans, diagrams, models, formulae, tables, engineering designs and specifications, manuals and instructions written or recorded on devices such as disk, tape, read-only memories') and 'technical assistance' (i.e. 'instruction, skills, training, working knowledge, consulting services').[70] Technical data can be tangible and in a physical form, but it can also be transferred in an intangible way; for example, if it is in the form of electronic data, through electronic file sharing or transfers.[71] Technology transfers, particularly technical assistance, can also take the form of know-how transfers through training, instruction and apprenticeship, but also through consulting services. Intangible transfers of technology are especially challenging for export controls as these transfers take place independent of national borders and physical customs controls.

The development of hypersonic missiles requires knowledge and experience in a series of engineering fields, material science and physics. It also requires the skills and know-how necessary for a development effort that includes the simultaneous development of multiple subsystems, sensor packages, the airframe and payload, and their integration and packaging into a complete system that meets military specifications. Therefore, controls on technical assistance to prevent the illicit

[67] Speier et al. (note 7), pp. 100–101.
[68] MTCR (note 12), p. 18.
[69] MTCR (note 12), pp. 65–68.
[70] MTCR (note 12), pp. 13–14.
[71] Bromley, M. and Maletta, G., 'The challenge of software and technology transfers to non-proliferation efforts: Implementing and complying with export controls', SIPRI Research Paper, Apr. 2018.

acquisition of know-how—particularly tacit knowledge relating to overcoming specific technical challenges that continue to plague HGV and scramjet development programmes—are a key component of a holistic approach to the application of export controls to hypersonic missile technology. However, the implementation of controls on technical assistance, including what types of mechanisms are used to license, monitor and enforce controls on technical assistance, varies considerably between states.[72]

Catch-all controls

Catch-all controls are an export control mechanism that, under certain circumstances, allows states to impose licensing requirements on transfers of items that do not appear on their control lists. Since 2003 the MTCR guidelines require the partners to have catch-all controls as part of their national export control systems.[73] The MTCR guidelines stipulate that under such a catch-all provision, partners can impose licensing requirements if their competent authorities inform the exporter 'that the items may be intended, in their entirety or part, for use in connection with delivery systems for weapons of mass destruction other than manned aircraft'.[74] Catch-all mechanisms also rely on awareness and due diligence by industry and researchers because they create an obligation for exporters to notify the national licensing authority if they are 'aware that non-listed items are intended to contribute to such activities, in their entirety or part'.[75] Based on such a notification, the competent authority can determine whether to apply a licensing requirement. However, that also means that effective use of catch-all controls is highly dependent on access to relevant information and intelligence and on the strength of the due-diligence and compliance procedures of the exporting parties (individuals, companies and research institutions)—as well as on good cooperation and communication between these parties and the export control authorities.

Catch-all controls are a particularly versatile tool in the context of emerging technologies and technological developments more broadly. They enable states to intervene and impose a licensing requirement on transfers of otherwise uncontrolled items in situations where states have relevant intelligence about possible delivery system end-uses and want to deny the licence or deem it necessary to receive additional information and assurances through a licensing application. In the context of HCMs this could, for example, enable a state to impose licensing requirements on exports of new types of fuels for scramjet engines without their being listed in the annex, if they could contribute to a state's delivery system programme. Catch-all controls can also be applied to transfers of technical data and technical assistance related to unlisted items transferred as part of scientific collaboration, where the relevant state's authorities are aware that the end use could be in a CBN weapons or delivery system programme.

Export controls in the context of civilian space programmes, reusable rockets and crewed spacecraft

Civilian space programmes have long used technologies for atmospheric re-entry and endoatmospheric glide which could also be relevant for HGV programmes. The MTCR guidelines note that they are 'not designed to impede national space programs or international cooperation in such programs', but qualifies this commitment to apply only if 'such programs could not contribute to delivery systems for weapons

[72] For a more comprehensive analysis of controls on technical assistance see Bromley and Maletta (note 71).
[73] MTCR (note 13).
[74] MTCR, Guidelines for Sensitive Missile-Relevant Transfers (note 43).
[75] MTCR, Guidelines for Sensitive Missile-Relevant Transfers (note 43).

of mass destruction'.[76] Space launch vehicles (SLVs) are explicitly covered by the MTCR's category I controls on ballistic missiles if they exceed the payload and range thresholds or if they include a category I subsystem. The payload definition for SLVs includes spacecraft, which are not considered re-entry vehicles, and crewed aircraft are generally excluded from MTCR controls. However, spaceplanes—for example, the crewed spaceplanes developed as part of the US Space Shuttle programme and the Russian Buran programme, and the uncrewed spaceplanes developed in Boeing's X-37 programme—do not unambiguously fit these categories. Their reusable nature—a feature that is increasingly sought after in the new space industry—and their ability to re-enter the atmosphere and coast to their landing sites, distinguish them from weapon delivery systems. Reusable single-stage-to-orbit vehicles are another example of a space launch technology that does not readily fit the categories. They can be crewed, provide similar launch capabilities and are likely to incorporate many relevant technologies and subsystems.

It is these features and the technologies required for achieving them that also make them relevant in the context of HGVs. However, while many of the same technical challenges related to the physical phenomena that re-entering spaceplanes experience apply to HGVs, the requirements (e.g. concerning the vehicle's possible size and heat shielding) mean that engineering solutions and design features cannot readily be adopted. Nevertheless, the combination of know-how, technology and hardware used in such a programme could mean that key supplier relationships; design, simulation and test facilities; and a workforce with many transferable skills could make technology for hypersonic missiles more accessible and pose proliferation risks. Raising awareness, particularly among new actors in the space industry, and applying additional scrutiny to transfers of technology and especially know-how in the context of such programmes, could help mitigate proliferation risks. The MTCR should engage with the Wassenaar Arrangement to discuss technical developments and coordinate on how their controls apply to spaceplanes and other reusable spacecraft and whether such controls should be expanded in the future by either regime.

[76] MTCR, Guidelines for Sensitive Missile-Relevant Transfers (note 43).

5. Recommendations

The hype around hypersonic missiles has fuelled perceptions both of their invulnerability to missile defences and the possibility of developing future missile defences to effectively protect against them.[77] Combined with technological and status-related drivers, these developments have increasingly resulted in an arms race dynamic. Hypersonic boost-glide systems and HCMs may be perceived to create new nuclear and conventional military options, vulnerabilities and ambiguities that could destabilize strategic stability relationships. In this context, it is ever more important to strengthen efforts towards the non-proliferation of hypersonic missile technology, to slow the spread of complete hypersonic missile systems and the required technology. The following seven recommendations suggest ways to strengthen the role of the MTRC in preventing the proliferation of hypersonic boost-glide systems and hypersonic cruise missiles.

Clarify the coverage of hypersonic glide vehicles by the MTCR annex

The partners should clarify how the annex should be applied to possible transfers of hypersonic boost-glide systems and HGVs. To limit the proliferation of weapon systems using HGVs, the partners should agree on limited amendments to the annex to explicitly include hypersonic boost-glide systems in the definition of 'complete rocket systems' or to add an explanatory note that clarifies that HGVs should be treated as ballistic missile re-entry vehicles. These amendments would ensure that most HGVs fall within category I of the annex, and require partners to apply a strong presumption of denial to most transfers of complete hypersonic boost-glide systems and HGVs as complete subsystems thereof.

Use the MTCR's unique position as a technical policy forum

The partners should continue to make use of the unique nature of the MTCR as a technical policy forum in which technical experts from most states that currently deploy or develop hypersonic missiles discuss developments in missile and UAV technology. A shared understanding of what the meaningful characteristics, parameters and capabilities of HGVs and HCMs are could also help inform additional transparency and confidence-building measures (TCBMs) and initiatives for possible future arms control agreements that would either incorporate or focus on hypersonic missiles. The confidential nature of technical and policy discussions within the MTCR can be an advantage, particularly as the partners deliberate a common approach to applying MTCR controls to HGVs and HCMs. At the same time, increasing transparency by way of communicating some of the key outcomes of technical discussions beyond the rather technical control list amendments could go a long way in informing public, academic and political debates on hypersonic missiles.

Follow technical developments in hypersonic missile technology, and if necessary, update control list coverage of related dual-use technologies

The partners should continue to monitor technical developments and explore possible amendments to the annex where such technical advancements could create gaps in its coverage. A targeted review of materials and designs used in current approaches to thermal management under sustained heat loads experienced during atmospheric

[77] Karako and Dahlgren (note 2).

flight at hypersonic speed could help ensure adequate coverage, while related technical discussions could help enable all partners to apply additional scrutiny in assessing licensing applications for transfers of such materials and related technical know-how, particularly through technical assistance. As hypersonic propulsion technologies, especially scramjet engines, continue to advance and may over time be increasingly used for civilian applications and crewed air- and spacecraft, control list items may in the future require the addition or adjustment of technical parameters to ensure coverage of advanced engine technologies, without creating undue burdens or levels of restrictiveness of controls on legitimate end-uses.

Engage with adherents and other non-partners on hypersonic missiles

The partners should make the application of MTCR controls to HGVs, HCMs and related technology a key topic in outreach to and engagement with the MTCR adherents and non-partners. In particular, once there is agreement on the coverage of HGVs, this should be explicitly communicated in the next technical outreach meetings with MTCR adherents and during outreach missions conducted by the plenary chair to those non-partners that are developing—and, in the case of China, already deploying—hypersonic missiles and relevant technologies. Addressing the coverage of HGVs and HCMs in MTCR outreach to China would be particularly important. China has one of the most advanced hypersonic missile programmes; it is a non-partner but previously applied for MTCR membership and declared to follow the guidelines and use the annex.[78] Such wider engagement could help improve the comprehensive application of export controls and build a norm against the proliferation of hypersonic missile systems.

Engage in dialogue with the Wassenaar Arrangement on dual-use space launch technology that could enable hypersonic missile proliferation

The partners should engage in inter-regime dialogue with the Wassenaar Arrangement at the technical experts level on the coverage and application of export controls to dual-use space launch technologies. The MTCR and the Wassenaar Arrangement cover SLVs and a range of related subsystems, production equipment and dual-use items, some of which are increasingly relevant in the context of hypersonic missile proliferation. Therefore, both regimes must also deal with the growth of the new commercial space industry developing in many countries, a growing focus on reusable rockets and spaceplanes, and developments in single-stage-to-orbit vehicles. These discussions could both address specific engine technologies, including combined cycle engines incorporating rocket motors or engines, and the broader question of how exemptions related to end-uses in crewed vehicles should be applied or possibly adjusted in the future. The partners could prepare such a dialogue through the MTCR's informal mechanism for setting up technical inter-regime dialogues, drawing on lessons learnt from previous inter-regime dialogues on other technical topics.[79]

Engage with the Hague Code of Conduct on complementary measures for hypersonic missile non-proliferation

The partners should seek continued engagement with the HCOC, both through official MTCR functions, including outreach by the plenary chair and the chairs of the

[78] Xinhua, 'White paper: China's export controls', *Global Times*, 29 Dec. 2021.

[79] Brockmann, K., *Challenges to Multilateral Export Controls: The Case for Inter-regime Dialogue and Coordination* (SIPRI: Stockholm, Dec. 2019).

subsidiary bodies of the MTCR, and through the partners in their own national capacities. In particular, the discussion on the ambiguity over the classification of hypersonic boost-glide systems and HGVs could be of particular interest to the HCOC, as it also lacks a clear definition of 'ballistic missiles' and it is unclear whether hypersonic boost-glide systems fall within this category and would thus be subject to its TCBMs.[80] Including hypersonic missile policies and activities (including flight tests) in these TCBMs could also help inform the implementation of export controls. Increased transparency about missile programmes and space programmes helps states make nuanced assessments in their licensing decision-making and reduces the disruptive impact that export controls can have on legitimate scientific development, international scientific cooperation and civilian space programmes. This is particularly important in the context of the hype and emerging arms race dynamics around hypersonic missile systems.

Ensure strong commitment to the implementation of UN Security Council sanctions regimes targeting missile proliferation and related activities

The partners should, through their national export control systems, continue to support the rigorous implementation of UN Security Council resolutions that respond to destabilizing missile activities by establishing sanctions regimes which include trade restrictions. These types of sanctions regimes currently target North Korea and Iran. The MTCR is an important forum through which the partners can exchange information on illicit procurement activities and strengthen the implementation of strategic trade control measures by sharing best practices. This is particularly important in the context of North Korean missile activities and recent advances of its hypersonic boost-glide programme, which may have benefited from foreign assistance and is known to engage in illicit procurement activities. The mechanisms in the MTCR can help the partners apply additional scrutiny to transfers to non-members who run sanctioned missile programmes and reject a common goal of non-proliferation of CBN delivery systems.

[80] Brockmann, K., 'Controlling ballistic missile proliferation: Assessing complementarity between the HCOC, MTCR and UNSCR 1540', HCOC Research Papers, no. 7 (June 2020), p. 29.

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