

The implications of the advent of hypersonic weapon systems for strategic stability

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1. First things first: What are hypersonic missiles?

1.1 Hypersonic missiles are a new type of missile which possesses speed and manoeuvring capabilities that make them a game-changer in nuclear (and conventional) inter-state competition¹. They are much faster than existing cruise missiles and much more manoeuvrable than existing ballistic missile re-entry vehicles (RVs). They can reach and maintain hypersonic speeds, i.e. speeds exceeding Mach 5². However, this characteristic is not unique to them: ICBM RVs also travel at hypersonic speeds³.

Hypersonic missiles follow a non-ballistic trajectory, flying between 18 miles and 60 miles in altitude. Their manoeuvrability allows them to change course up to the last minutes of flight⁴ and achieve a high degree of targeting precision. These characteristics have implications for detection.

The unusual altitude and flight path of hypersonic missiles can result in their being invisible to existing missile early-warning radars for much of their trajectory. Some varieties⁵ will be

¹ RAND, *Hypersonic Missile Nonproliferation: Hindering the Spread of a New Class of Weapons* (RAND Corporation, 2017), p. 1; RICHARD R. HALLIONS, CURTIS M. BEDKE AND MARC V. SCHANZ, *Hypersonic Weapons and US National Security: a 21st Century Breakthrough* (The Mitchell Institute for Aerospace Studies, 2016), p. 2.

² JAMES ACTON, *Silver Bullet? Asking the Right Questions about Conventional Prompt Global Strike* (Carnegie Endowment for International Peace, 2013), p. 5;

³ RAND (n.1); The *terminal phase* is the portion of flight when the warhead reenters the atmosphere which lasts approximately thirty seconds. ROBERT CHEN, JASON SPEYER, *Terminal and Boost Phase Intercept of Ballistic Missile Defense* (AIAA Guidance, Navigation and Control Conference and Exhibit 18 - 21 August 2008) p.1. Nevertheless, once the RV reenters from outer space would be greatly slowed down by the Earth's atmosphere. It is estimated that an average ICBM RV would travel at more than 1,8 m/s (approximately Mach 8) at impact point. AMITAV MALLIK, *Technology and Security in the 21st Century: A Demand-side Perspective* (Oxford University Press, 2004), p. 110.

⁴ RAND (n.1), p. 8. See also 'Hyper-glide Delivery Systems and the Implications for Strategic Stability and Arms Reductions' (James Martin Center for NonProliferation Studies, 2015), p. 8.

⁵ At the time of this writing it is not certain if Hypersonic Cruise Missiles (HCM) will be detected by satellites during their boost-phase. HCMs are a two-stage weapon system, the first-stage is a small rocket booster that will accelerate the missile at the right supersonic speed needed for properly starting the second stage. During the firing of the first-stage there could be the possibility for a boost-phase detection. It is still not certain if the infrared signature of the first stage of HCM could be detected by infrared satellites used for missile warning. See JAMES ACTON (n.2), p. 68.

detectable by satellite early-warning systems during their boost-phase⁶, but after the boost-phase they may disappear from view⁷.

Ballistic missiles fly at much higher altitudes and follow relatively predictable trajectories. Mostly, it is possible to predict the destination of any given ballistic missile payload by using space-based and ground-based early-warning systems⁸. While currently the only nations that possess space-based early-warning systems are the United States and Russia⁹, ground-based early-warning radar technologies are wide-spread.

Space-based early-warning systems can track a ballistic missile in the boost-phase of its flight by detecting the intense heat generated by the first-stage engine. This allows an opponent to make a first assessment of the target of the missile and to calculate the warning-time at their disposal. After the detection by satellites systems, a ballistic missile would then be detected from thousands of miles away by powerful early-warning radars, which would further confirm the trajectory and the impact point¹⁰.

For example, it is estimated that space assets would guarantee a warning-time of approximately 30 minutes in the case of an ICBM travelling from the Russian bases of Dombrovsky or Tatischevo to U.S. Warren Air Force base¹¹. With that said, the travel-time of a forward-positioned ballistic missile could be much less than 30 minutes. For instance, the flight-times of SLBMs positioned 800 to 1,000 miles away from the U.S. coast could be as short as 10 to 12 minutes¹².

By contrast, the view of ground-based early-warning radars will be limited by the curvature of the Earth, and the warning-time they can provide will be shorter than that provided by space-based assets¹³. It is reported that a powerful radar, like the U.S. *Pave Paws* radars

⁶ The Boost phase is the portion of flight immediately after launch when the booster accelerates to lift the munitions into the air, see CHEN AND SPEYER (n.3), p. 1. Boost phase is relatively short in duration. For medium- and short-range missiles, the boost phase lasts at most only a couple of minutes, while for a missile of inter-continental range it may be as long as three to five minutes. "Missile Defense, the Space Relationship, & the Twenty-First Century" (The Institute for Foreign Policy Analysis, 2009), p. 16. Available at <http://www.ifpa.org/pdf/IWG2009.pdf>.

⁷ ACTON (n.2), p. 118; RACHEL WIENER, *The Impact of Hypersonic Glide, Boost-Glide and Air-Breathing Technologies on Nuclear Deterrence*, in MARK CANCIAN (ed.), *Project on Nuclear Issues* (CSIS, 2017), pp. 138-139.

⁸ MARK J. LEWIS, *Global Strike Hypersonic Weapons*, in Nuclear Weapons and Related Security Issues "AIP Conf. Proc." vol.1898, 2017, p. 2. See also "Hyper-glide Delivery Systems and the Implications for Strategic Stability and Arms Reductions" (n. 4), p. 27.

⁹ Though, there are reports, not officially confirmed, that China has begun testing the "TJSF" early-warning satellite in 2015. See <https://www.globalsecurity.org/space/world/china/warning.htm> and <https://www.nasaspacesflight.com/2018/12/long-march-3c-secretive-tjsw-spacecraft/>

¹⁰ BRUCE J. BLAIR, *The logic of accidental nuclear war* (The Brookings Institution, 1993) pp. 187-191.

¹¹ PAVEL PODVIG, *Reducing the Risk of an Accidental Launch in Science and Global Security*, vol. 14, 2006, pp. 83-85; BRUCE J. BLAIR, *The logic of accidental nuclear war* (The Brookings Institution, 1993) pp. 187-191.

¹² PAUL PODVIG, *The Operational Status of the Russian Space-Based Early Warning System*, in *Science and Global Security*, 1994, <http://scienceandglobalsecurity.org/archive/sgs04podvig.pdf>; BRUCE J. BLAIR, (n.41), p. 191.

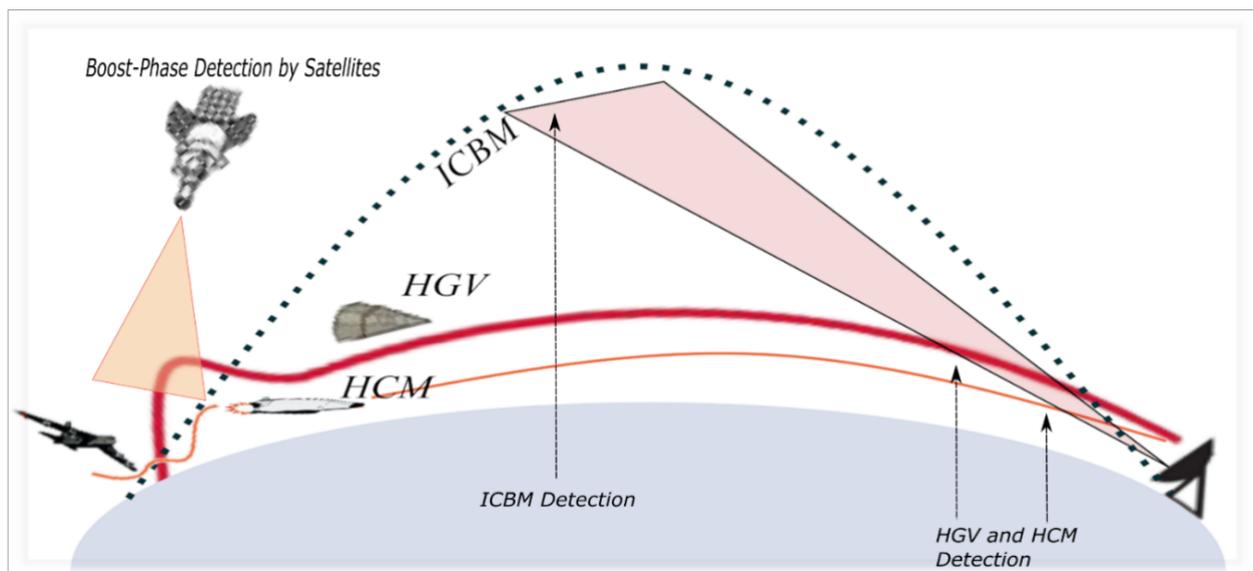
¹³ This is not always true, if a radar is positioned close enough to the launch point of the missile (about 250 miles to 340 miles), it could detect the missile during the boost-phase. See "Alternatives for Boost-Phase Missile Defense" (Congressional Budget Office, 2004), pp. 10-11, available at <https://apps.dtic.mil/dtic/tr/fulltext/u2/1001718.pdf>.

or the Russian *Voronezh* radars, can track a ballistic missile with a range of about 2000 miles from 1550 miles away, resulting in about 14 minutes of tactical warning¹⁴.

In the case of hypersonic missile, early-warning systems (space-based and ground-based) would not guarantee the same timelines of warning.

Hypersonic missiles, like ICBMs, will be detectable in their initial boost-phase by satellite early warning systems¹⁵. Thereafter, by flying at lower altitudes than ballistic missiles, they will cease to be detectable¹⁶. After the “unobservable” phase, hypersonic missiles flying at heights between 18 and 25 miles will become detectable when travelling within about 250 to 370 miles of a ground-based radar¹⁷. Even if detected by a ground-based radar, there will be a high degree of uncertainty about their destinations¹⁸. In a context in which an opponent believed that the radar in question was the target, the early-warning-time would be limited to two and a half minutes in the case of a hypersonic missile travelling at Mach 10.

Examples of HGVs and HCMs detection by existing early-warning architecture



In other words, States that do not possess a reliable satellite early-warning system can only expect to become aware of an approaching hypersonic missile during the latter part of its

¹⁴ ACTON (n.1), pp. 156-157.

¹⁵ As has been stated, it is still uncertain if satellites systems could detect the heat generated by the small boosters attached to HCMs. ACTON (n.1), p. 68.

¹⁶ ACTON (n. 1), p. 118. See also ALEXEY ARBATOV “New Global Strike Systems Create Serious Problems for Russia”, October 2013, available at <https://carnegie.ru/2013/10/24/new-global-strike-systems-create-serious-problems-for-russia-pub-53597>.

¹⁷ ACTON (n.1), p. 70, footnote “b”.

¹⁸ RAND (n.1), p. 8; *Conventional Prompt Global Strike Capability*, National Research Council’s Committee on Conventional Prompt Global Strike Capability, May 11, 2007; *U.S. Conventional Prompt Global Strike: Issues for 2008 and Beyond*, National Research Council’s Committee on Conventional Prompt Global Strike Capability, 2008, p. 126.

trajectory; and its manoeuvring capability will mean that even those who can detect its boost-phase will be unable to estimate its likely impact point with any certainty.

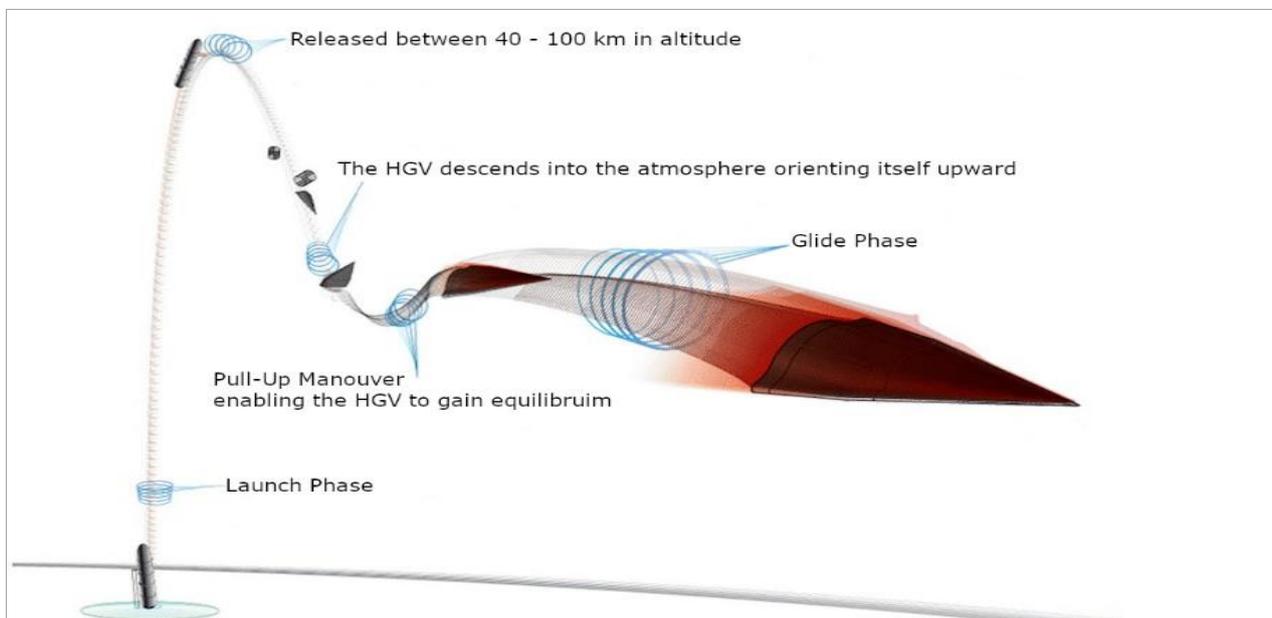
These characteristics make hypersonic missiles a suitable system for surprise long-range strikes. They also make hypersonic missiles able to penetrate the most advanced air defence systems.

There are two types of hypersonic missile that have already been well tested: the *hypersonic boost-glide vehicle* (HGV) and the *hypersonic cruise missiles* (HCM).

1.2. Hypersonic boost-glide vehicles

An HGV is an unpowered vehicle capable of gliding on the upper atmosphere at hypersonic speeds. *It is equipped with small propulsion system (so called RCS thrusters) for orientation and directional control*¹⁹. In order to reach hypersonic speeds, HGVs need to be propelled by a rocket, probably an existing type of ICBM²⁰. Release from the booster rocket can take place, depending on the target location, between 25 miles and 60 miles above the earth's surface. At this point the HGV descends into the atmosphere where a "pull-up" manoeuvre²¹ is executed to enable it to gain equilibrium and glide to its target along a relatively flat trajectory²².

Hypersonic glide vehicle



Source: adapted from DARPA graphics

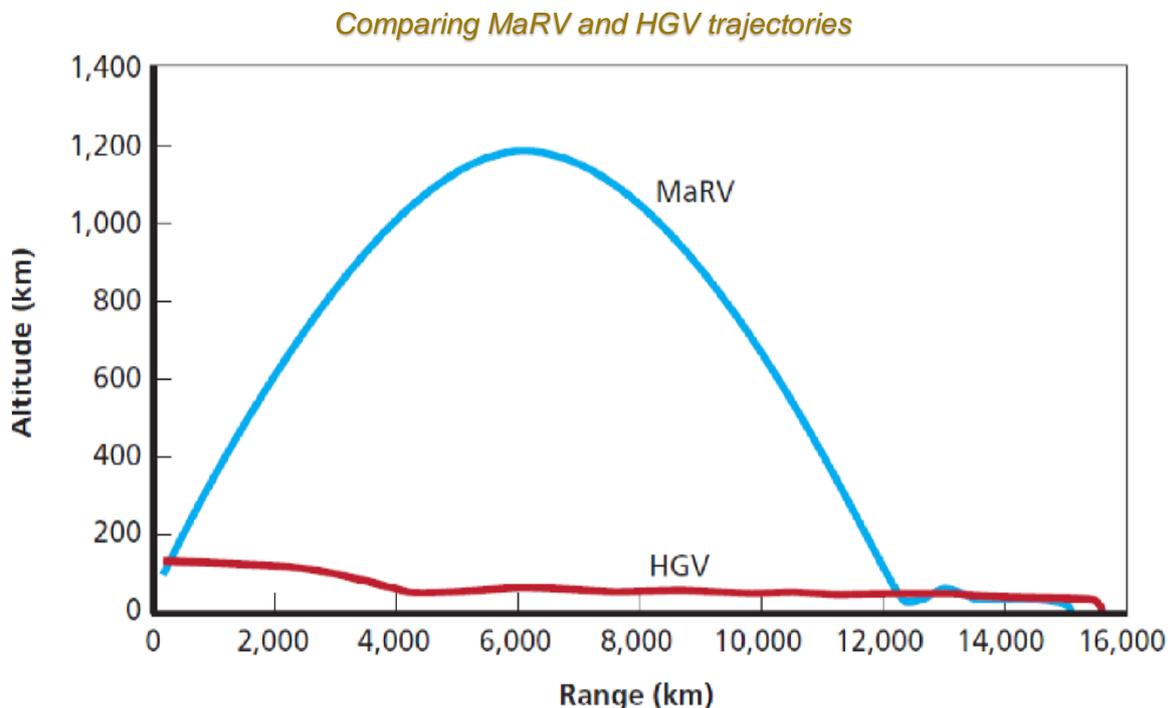
¹⁹ RAND (n.1), p. 9.

²⁰ WIENER (n.7), p. 142; AMY WOOLF, *Conventional Prompt Global Strike (PGS) and Long-Range Ballistic Missiles* (Congressional Research Service, 2019) p. 17.

²¹ In the pull-up phase, the HGV will orient itself upwards using small thrusters and will enter in the gliding phase by using the lift force generated by its shape. JAMES ACTON, *Hypersonic Boost-Glide Weapons*, in *Science and Global Security*, vol. 23(3) 2015, p. 194.

²² *Ibid.*, pp. 195-196.

In contrast to existing ICBM RVs, HGVs are capable of manoeuvring and changing the point of impact throughout all of their flights (ICBM RVs can only offer a change of direction in the post-re-entry phase²³ and are vulnerable to ballistic missile defences²⁴). The unpredictability of an HGV trajectory will hold extremely large areas at risk.



1.3 Hypersonic cruise missiles

An HCM is a cruise missile capable of operating at hypersonic speeds. It is equipped with a *scramjet engine* (supersonic ramjet) which generates thrust from a supersonic airflow. Before the scramjet enters into operation, an HCM needs to achieve a supersonic speed; this is usually done by the use of additional boosters and by launching the HCM from an aircraft²⁵. Existing cruise missiles are hardly detectable (flying at a very low altitude) and follow unpredictable trajectories; HCMs will offer, in addition, flight speeds capable of posing a complex defensive challenge²⁶. HCMs will fly at lower altitudes than HGVs, i.e. between 12 miles and 30 miles above the earth's surface, but still higher than most current surface-to-air missile systems are capable of reaching. Defensive missile systems could be designed

²³ The Midcourse phase of an ICBM is the longest portion of flight, where the munitions have separated from the booster and are flying un-powered. This phase offers the largest time window in which track and intercept the incoming warhead. See ROBERT J. CEPEK "Round-Based Midcourse Defense: Continue Testing, but Operational Fielding must take a Backseat to Theater Missile Defense and Homeland Security" (Joint Forces Staff College, 2005), p. 5. See also 'Mid-Course Phase' at <https://www.globalsecurity.org/space/systems/mid-course.htm>.

²⁴ RAND (n.1), p. 9.

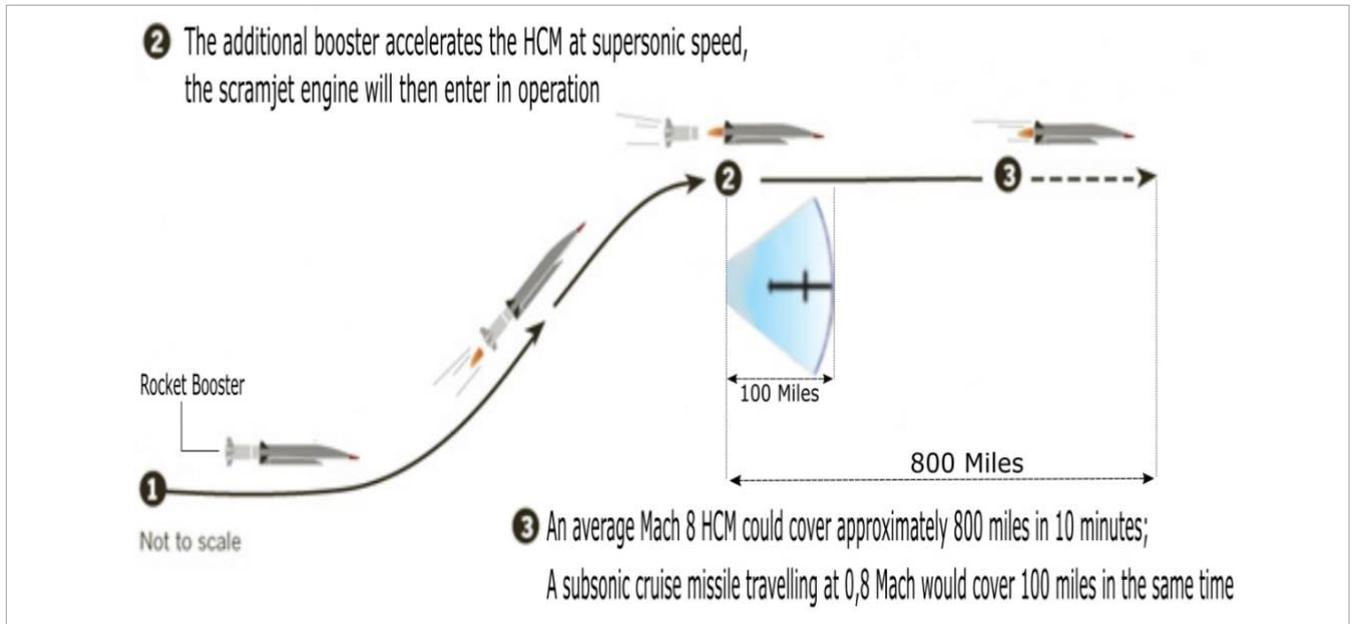
²⁵ RAND (n.1), p. 12.

²⁶ ACTON (n.2), p. 73.

to reach HCM altitudes, but the HCM's speed would still present a challenge for such interceptors.

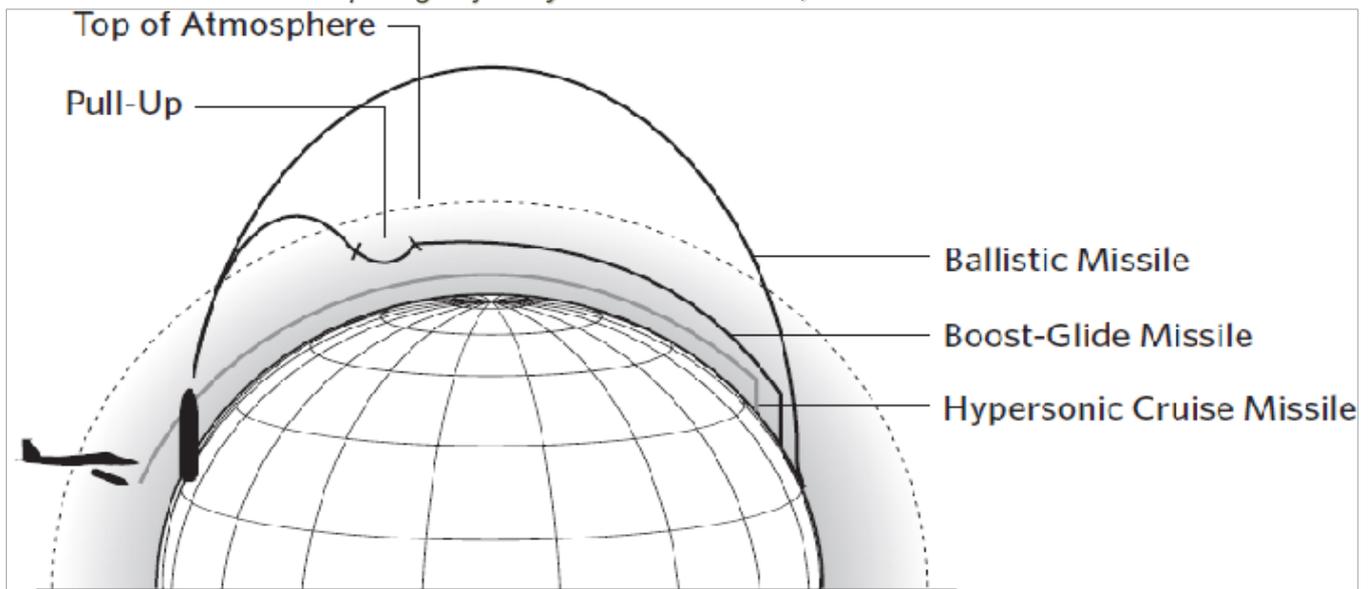
Both HCMs and HGVs may be used as either strategic or tactical systems, with conventional or nuclear warheads, introducing not only flexibility, but ambiguity of intent.

HCM Launch



Source: Adapted from Boeing Graphics

Comparing trajectory of Ballistic Missile, HGV and HCM



Source: Acton (n.1)

2. Overview of the hypersonic arms race

2.1. Studies of the military utility of hypersonic warhead delivery vehicles date back to the 1960s when the United States considered the development of the *Dyna-Soar* project, a piloted hypersonic spaceplane capable of inspecting satellites and bombing targets located on the Earth's surface from near-space²⁷. However, the *Dyna-Soar* was never realized. The recent resurgence of U.S. attempts to militarize hypersonic technologies are part of the *Conventional Prompt Global Strike* (CPGS) programme, initiated by the Bush administration in 2003, with the aim of developing fast, long-range, non-nuclear weapons capable of striking targets anywhere in the world "within one hour of time"²⁸. Hypersonic missiles are the most likely candidate for that mission²⁹. According to James Acton, CPGS objectives are to deny rogue states the ability to employ nuclear arsenals; destroy or disable anti-satellite capabilities; counter anti-access/area-denial capabilities; kill high-value terrorists and disrupt terrorist operations. Other important objectives seem to be the engagement of deep inland targets to "cripple an adversary's essential warfighting capabilities"³⁰, and to address "growing threats to forward-deployed forces and bases, ensuring U.S. power projection capabilities"³¹. Michael Griffin, undersecretary of defense for research and engineering, has stated that developing hypersonic weapons is the "highest technical priority" for the U.S. military.

Faced with the development of U.S. CPGS weapons, Russia and China have raised serious concerns about the programme's impact on strategic stability. Both countries have underlined the CPGS's destabilizing effects, especially in combination with the forward deployment of U.S. Ballistic Missile Defence (BMD)³². These concerns appear to be driving

²⁷ R. F. HOUCHIN, *The Rise and Fall of Dyna-Soar: A History of Air Force Hypersonic R&D, 1944-1963* (Auburn University, 1995) p. 137 and 196. See also M. LEITENBERG, *Studies of Military R&D and Weapons Development "Case Study 1 -- The History of US Anti-Satellite Weapons"*, 1984, pp. 89-90 available at <https://fas.org/man/eprint/leitenberg/index.html>

²⁸ ACTON (n.1) p. 4. See also WOOLF (n.11), pp. 1-2.

²⁹ Another prompt weapon that have been considered as a CPGS weapon were the U.S. D-5 nuclear submarine launched ballistic missile (SLBM) converted to carry a conventional warhead instead of a nuclear one, referred to as the "Conventional Trident Modification". Though this attempt raised the Congressional opposition as there is the real risk that an observing nation would mistake the launch as a nuclear attack. The program didn't receive funding and was eventually terminated. In addition, during the New START negotiations, Russia has expressed concern about the placement the Conventional warheads on strategic ballistic missiles. See Woolf (n.11), p.42-43

³⁰ *Conventional Prompt Global Strike Capability*, National Research Council's Committee on Conventional Prompt Global Strike Capability, May 11, 2007, p. 5.

³¹ WOOLF (n.11); As reported, some of the scenarios taken into account by the *Defense Science Board* that require a prompt response were: - A near peer competitor had used its emerging counter space capability to destroy a U.S. satellite. - The United States wanted to destroy a package of special nuclear materials that a terrorist organization had shipped to a neutral country. - A small package of weapons of mass destruction was located temporarily in a rural area of a neutral country. See WOOLF (n.11), pp. 5-6.

³² JOSHUA H POLLACK, 'Boost-glide Weapons and US-China Strategic Stability' in *The NonProliferation Review*, vol. 22 (n. 2), 2015, 157-158; JAMES M. ACTON, 'Russia and Strategic Conventional Weapons' in *The NonProliferation Review*, vol. 22 (n.2), 2015, 144-145. Despite this, the U.S. claimed that Although the doctrine underlying the CPGS programme is not intended to threaten Russian or Chinese nuclear or conventional forces. THOMAS SCHEBER, KURT GUTHE, *Conventional Prompt Global Strike: A Fresh Perspective*, in *Comparative Strategy* vol. 32, 2013, p. 20.

a series of Russian and Chinese strategic countermoves, including the development of their own hypersonic weapon systems.

The United States, China and Russia are by far the nations with the most developed hypersonic technologies. They are engaged in what can be regarded as a hypersonic arms race³³, though it should not be overlooked that, at least at this stage, hypersonic missiles are conceived as providing a “niche” capability³⁴. In fact, these nations have conducted several tests of hypersonic missiles in the last decade³⁵ and are near to deploying a limited hypersonic capacity³⁶.

United States

After 2003 the United States focused its efforts on two hypersonic glide vehicles which have undergone flight testing: the HTV-2 (Hypersonic Technology Vehicle 2) developed by DARPA, and the AHW (Advanced Hypersonic Weapon) developed by the Army. The HTV-2 was intended to reach a speed of 8000 miles per hour (close to Mach 11) and to have a maximum range of 10,000 miles³⁷. The HTV-2 was tested twice in 2010 and 2011, reaching a speed of Mach 20 (14,340 miles per hour) in the 2011 test. The programme was then defunded as in both tests the vehicle experienced flight anomalies³⁸. The AHW is intended to provide a range capability of the order of 3,700 miles within a flight-time of 35 mins, and to be accurate within a radius of 30 ft³⁹. The AHW has been tested three times - in 2011, 2014 and 2017. Only the 2014 test was not successful. In the 2017-test the AHW was launched from a submarine-launched ballistic missile. The Pentagon has indicated that the Army, Navy, and Air Force will work together to develop the AHW as a common system by the early 2020s⁴⁰. As regards hypersonic cruise missiles, the Air Force undertook several tests of the X-51 WaveRider between 2011 and 2013⁴¹. The weapon is being developed to operate at speeds in excess of Mach 7 (about 5,300 mp/h) at an altitude of 50,000ft and to have a range of about 430 miles.

³³ MARK GUBRUD 'Going too fast: Time to ban hypersonic missile tests? A US response' in *Bulletin of the Atomic Scientists*, vol. 71 (n.5), 2015, p.1; RAJARAM NAGAPPA 'Going too fast: Time to ban hypersonic missile tests? An Indian response' in *Bulletin of the Atomic Scientists*, vol. 71 (n.5), 2015, p. 9.

³⁴ ACTON (n.2), p. 139. As has been stated, Russia programmed a deployment of a total of 12 Avangard boost-glide hypersonic missile by the end of 2027. See “Avangard system is tested, said to be fully ready for deployment” at http://russianforces.org/blog/2018/12/avangard_system_is_tested_said.shtml.

³⁵ AJEY LELE, *Disruptive Technologies for the Militaries and Security* (Springer, 2019), pp. 71-74.

³⁶ See RAND (n.1), p. xii.

³⁷ Woolf (n.11), pp. 14-15.

³⁸ *Ibid.*

³⁹ See “Advance Hypersonic Weapon (AHW)” at <https://www.army-technology.com/projects/advanced-hypersonic-weapon-ahw/>.

⁴⁰ WOOLF (n.11), p. 17.

⁴¹ *Ibid.*, pp. 39-40.

Russia

Russia is working both on hypersonic glide vehicles and hypersonic cruise missiles. One of the most important development on the hypersonic glide side is the Avangard boost-glide vehicle. The system has been well tested. It is said to travel at Mach 20+⁴². After the latest test, on 26 December 2018, Deputy Prime Minister Yuri Borisov stated that: “The latest tests have shown that it has reached speeds close to Mach 30. Practically at these speeds, no anti-missile can knock it down”⁴³. According to Podvig, the Avangard will be deployed on top of the UR-100NUTTH missile by the end of 2019, and a total of 12 missiles will be deployed by the end of 2027. This suggests that Russian hypersonic missiles will, initially at least, amount to a “niche” capability. As regards hypersonic cruise missiles, Russia tested in 2017 the Zirkon, which is expected to fly between Mach 4 and Mach 6 travelling up to 250 miles in range. The Zirkon is expected to serve as a multi-purpose tactical weapon.

China

Traditionally, China has projected itself as a restrained nuclear power with a policy of no-first-use and moderate quantitative expansion of its nuclear capabilities. Its deployed nuclear arsenal is currently much smaller than those of Russia and the United States. China’s effort to develop hypersonic weapons is linked to the modernisation of its nuclear forces with the goal of their contributing to a ‘limited nuclear deterrent capability’. Since 2014, China has tested the WU-14, later re-designated then DF-ZF, more than seven times, with fruitful results. The conduct of several tests within a span of few years indicates China’s commitment to the development of this technology. Although there is little information about the capabilities of the DF-ZF, the speed of the missiles is said to be around Mach 10⁴⁴. Mounting it atop of certain ballistic missiles could extend its range⁴⁵.

3. Hypersonic missiles and strategic stability

3.1 As has been described, hypersonic missiles possess greater manoeuvrability than ICBM RVs and greater speed than existing cruise missiles. These characteristics have the potential to affect strategic stability relationships, especially between U.S., China and Russia which are near to deploying operational hypersonic strike capabilities.

⁴² See again “Avangard system is tested, said to be fully ready for deployment Russian forces” at http://russianforces.org/blog/2018/12/avangard_system_is_tested_said.shtml.

⁴³ “Avanguard/Vanguard” <https://www.globalsecurity.org/wmd/world/russia/avanguard.htm>.

⁴⁴ See “DF-ZF (formerly WU-14)” at <https://www.globalsecurity.org/wmd/world/china/df-21d.htm>.

⁴⁵ LELE (n.27), p. 63.

One way of formulating an aspect of the challenge to strategic stability is to ask whether hypersonic warhead delivery vehicles, once detected, would leave an opponent enough time to decide on and implement an adequate response⁴⁶.

Decision-makers, a hypersonic missile strike having been detected, would operate in a degraded environment of compressed timelines and destination/target uncertainty. In many cases⁴⁷, the chain of command following the detection of hypersonic missiles would be under even greater pressure than in the case of long-range ballistic missiles.

To mitigate this problem the United States is currently working on the development of a new satellite-sensor layer⁴⁸, which presumably would be positioned in low earth orbit (LEO)⁴⁹, in order to provide *birth to death tracking* of both ballistic missiles and hypersonic vehicles⁵⁰. This system may provide the United States with a significant “time-gaining” factor.

Meanwhile Russia and China are working on a new generation of over-the-horizon (OTH) radars⁵¹. These may prove able to detect hypersonic missiles from thousands of miles away. The Russian government has announced that the newly-constructed *Konteyner 29B6 OTH* radar will be able to detect hypersonic missiles from a distance of 1,860 miles⁵². In late 2017 China unveiled to the public a new large OTH radar, the “J27-A”, which is said to have a detection range of more than 1,800 miles. It is believed to be located on the Shandong Peninsula, its function being to monitor any ballistic launch from the east/south-east, i.e. a vast area between the Korean Peninsula and Guam⁵³.

⁴⁶ See ACTON (n.2), p. 22.

⁴⁷ See *infra* at p. 11.

⁴⁸ DEPARTMENT OF DEFENCE, *Missile defense review 2019*, p. xi.

⁴⁹ See, SANDRA ERWIN “Next steps for the Pentagon’s new space sensors for missile defense” at <https://spacenews.com/next-steps-for-the-pentagons-new-space-sensors-for-missile-defense/>; see also STEVE TRIBLE “MDA Plans Prototyping Phase For Space Sensor Layer” at <http://aviationweek.com/defense/mda-plans-prototyping-phase-space-sensor-layer>.

⁵⁰ The U.S. are committed to build a large constellation of military satellite leveraging on cheap commercial space buses. Darpa’s Blackjack Program is committed to physically add a military payload or a military software (“military mass-less payload”) to commercial satellites that will be launched in low earth orbit. The program is set to have 20 experimental satellites in 2021, and, if the experiment will prove successful, 90 satellites within 2022. In 2018, Blackjack Program received increased funding by the U.S. Congress with a total allocation of \$125 million. See MIKE WALL “US Military Aims to Launch Cheap New ‘Blackjack’ Spy Satellites in 2021” available at <https://www.space.com/41639-darpa-cheap-spy-satellites-2021-launch.html>. See also MONICA JACKSON “Senate Committee Proposes Additional \$110M to Accelerate Blackjack LEO Satellite Program” available at <https://www.executivegov.com/2018/06/senate-proposes-additional-110m-to-accelerate-blackjack-leo-satellite-program/>.

⁵¹ OTH radars are a type of radar systems which use the ionosphere to refract outgoing radar waves and return signals, enabling the system to detect and track targets that would otherwise be hidden by the curvature of the earth. See “Over the Horizon Backscatter Radar: East and West” at <https://www.acc.af.mil/About-Us/Fact-Sheets/Display/Article/199120/over-the-horizon-backscatter-radar-east-and-west/>

⁵² See “29B6 Konteyner Over The Horizon Radar (OTHR)” at <https://www.globalsecurity.org/wmd/world/russia/konteyner.htm>

⁵³ See “P-band Strategic early warning phased array radar” <https://www.globalsecurity.org/wmd/world/china/lpar-p.htm>.

Nonetheless, it seems likely that extended tracking of hypersonic missiles will prove difficult and that this will affect the “time” strategic factor⁵⁴. This and the impossibility of predicting their targets with any certainty (“*target ambiguity*”) and whether the threat they pose is conventional or nuclear (“*warhead ambiguity*”) in the absence of reliable intelligence will result in a degraded environment for the elaboration and communication of a response by decision-makers in the event of a hypersonic strike, since States are able to act on the basis of information only if it is timely and offers predictability, and any information is likely to be useless if received too late⁵⁵.

3.2. Hypersonic weapons in imaginary scenarios

A degraded decision-making environment is likely to have consequences for threat perceptions, the avoidance of accidental war and escalation management. It may be useful to illustrate this through two imaginary scenarios.

In the first scenario let us imagine a conventional U.S. HGV strike from a continental site which passes over the Arctic, the target being a site in Iran, following an escalation of U.S. opposition to Iranian nuclear activities (the scenario is rendered especially hypothetical by the fact that the current U.S. candidate for deployment as a hypersonic weapon, the AHW, is an HCM and is thought to have a maximum range of 3,700 miles, little more than half the distance from Wyoming to Tehran).

It is assumed that the U.S. strike would come several days after the start of the crisis. A fleet of HGVs travelling at Mach 10 would cover the distance between F.E. Warren Air Force Base (Wyoming) and a target near Teheran (about 6,900 miles) in approximately one hour and five minutes. At the time of launch Russian early-warning satellites would detect the infrared signature caused by the missiles’ boost-phases. Unable to track the HGVs after the boost-phase, Russian early-warning services would only pick them up when they came within range of Russian radars located in Russia’s far North, scanning the Arctic horizon⁵⁶. At that point the HGVs would be only two and a half or three minutes short of the Russian coast/air space.

How are Russian decision-makers likely to react? Presumably they will use a “hot-line” as soon as reports of the launch reach them, but will they feel able to trust their U.S.

⁵⁴ For an overview on the importance of time as a strategic element, see Andrew Carr, *It’s about time: Strategy and temporal phenomena*, in *Journal of Strategic Studies* (October 2018).

⁵⁵ BRUCE J. BLAIR, *The logic of accidental nuclear war* (The Brookings Institution, 1993) p. 252; ROBERT JERVIS, *The Meaning of the Nuclear Revolution: Statecraft and the Prospect of Armageddon* (Cornell University Press, 1989), p. 60.

⁵⁶ See “Evolution of the Russian early-warning radar network Russian nuclear forces” at http://russianforces.org/blog/2018/09/evolution_of_the_russian_early.shtml

counterparts' assurances that the HGVs' target is in Iran and that the missile warheads are non-nuclear, especially if relations between the two states have been marked by animosity during the preceding period? Will U.S. counterparts, knowing that Iran and Russia are aligned on the Iranian nuclear question, be ready to communicate target information to Russian counterparts? How can the Russians be sure that the purpose of the strike is not to "decapitate" Russia's leadership? Can they take the risk of merely tracking the HGVs as they pass over Russian territory, having spelled out to U.S. counterparts that any damage to Russian assets from the strike in question will trigger a counter-strike?

In another scenario a Chinese attack on Taiwan is imagined, leading to the U.S. launch of a small fleet of conventional air-launched HCMs from the Philippine Sea towards the Fujian Province (facing the Taiwan Strait). The Mach 8 HCMs would fly the 800 miles to their targets in about 10 minutes. Their mission would be the destruction of coastal defences, as well as communication nodes and power plants, in order to disable Chinese command-and-control capabilities. Several Chinese early-warning radars pointed at Taiwan⁵⁷ would detect the incoming HCMs flying as low as 12-15 miles in altitude from about 500 miles away. This would provide about 6 minutes warning-time.

Given that China has raised considerably the alert level of its nuclear forces and is building strategic early warning systems enabling the adoption of a launch-on-warning posture⁵⁸, how would the Chinese government cope with such a short decision time and with target and warhead ambiguities, especially with warhead ambiguity? Would they possess the means or have time to ask U.S. counterparts to clarify the nature of the incoming warheads? Would they trust any answer that they received? In the heat of the moment, could warhead and target ambiguities trigger a decision to launch nuclear missiles at U.S. military bases in the Asia-Pacific theatre? Could the use of hypersonic weapons at an early stage of a conventional conflict of a regional nature result in such damage to vital Chinese assets that Chinese decision-makers would decide to escalate to an all-out war?

3.3. Deterrence

The paradigms of deterrence dramatically changed with the advent of the nuclear age, shortly followed by the advent of the missile age⁵⁹. Deterrence can be regarded as an assurance of destructive retribution for acts of aggression, to influence the behaviour of

⁵⁷ See on this subject "OTH, GBR... Ces radars très longues portées chinois" at <http://www.eastpendulum.com/oth-gb-ces-radars-tres-longues-portees-chinois>.

⁵⁸ GREGORY KULACKI, *China's Military Calls for Putting Its Nuclear Forces on Alert* (Union of Concerned Scientists, 2016) at <https://www.ucsusa.org/sites/default/files/attach/2016/02/China-Hair-Trigger-full-report.pdf>.

⁵⁹ R. AYSON and CHRISTIN M. LEAH, "Missile strategy in a post-nuclear age", in *The Journal of Strategic Studies*, 2014, p. 1.

other actors⁶⁰. Missiles contract time and space, making the consequences of ignoring that assurance likely to be felt very rapidly⁶¹. Nuclear-tipped missiles exponentially heighten the role of deterrence by assuring an adversary that he risks nuclear devastation. If in the pre-nuclear world deterrence was based on the risk of losing territory as a consequence of losing a war, a risk that rested on an adversary's possession of superior military capabilities, in the nuclear-missile age deterrence is based on the risk of incurring a monstrous amount of damage in a small window of time, irrespective of whether an adversary possesses a superior (or any significant) conventional force⁶².

3.4. Hypersonic missiles and deterrence

As we have seen, in certain cases hypersonic missiles may compress the warning-time that will follow the detection of an incoming strike, the targets of that strike will be unpredictable, and the nature of the threat posed by any given strike – conventional or nuclear – will be ambiguous. All these factors can impact on the assumptions and calculations that have underpinned nuclear deterrence.

The deterrence provided by strategic ballistic missiles has been well explored in the context of strategic stability. Nuclear deterrence rests upon several pillars: for example, survivability of enough assets to ensure a second-strike capability, mutual vulnerability, effective communications to permit escalation control, and arms control measures in the broad sense of the term. These are fundamental tools for reducing as much as possible the risk of miscalculation or misperception of another possessor-state's intentions. Nuclear deterrence is linked to the idea of stability by the goal of war avoidance⁶³.

Let us consider the case of two States possessing nuclear-armed hypersonic missiles. An imbalance need not exist if both continue to respect agreed warhead deployment limits. But that balance will be unstable because the characteristics of hypersonic delivery systems will be perceived as enhancing first strike capabilities⁶⁴. Moreover, the super-accuracy of these weapons could lead one State to believe that a surgical low-yield nuclear attack ought to be acceptable to an adversary, while the other State would see any use of these weapons as

⁶⁰ CHRISTINE M. LEAH (n.38), pp. 20-24; ELBRIDGE A. COLBY MICHAEL, S. GERSON, "Strategic Stability: Contending Interpretations", pp. 56-58.

⁶¹ JERVIS (n.55) p. 6

⁶² THOMAS C. SCHELLING, *Arms and Influence* (Yale University Press, New Haven, Connecticut, 1966), p. 2 and 22.; LEAH (n.38); JERVIS (n.55), p. 6.

⁶³ As stated by Dan Smith: "A strategy of deterrence should be one which promotes the stability of that relationship" DAN SMITH, *Nuclear deterrence and strategic stability*, in *Arms Control*, vol. 5(2) 1984, p. 180. See also JOHN D. STEINBRUNER, *National security and concept of Strategic stability*, in *The Journal of Conflict Resolution*, vol. 22 (3) 1978, pp. 413-414.

⁶⁴ Acton (n.24), p. 144. See on this subject Thomas C. Schelling, *Surprise Attack and Disarmament*, in John Garnett (ed.), *Theories of Peace and Security: A Reader in Contemporary Strategic Thought* (Macmillan St Martin's Press, 1970), p. 180.

an existential threat⁶⁵. Equally, an irresponsible leadership could decide to use nuclear-armed hypersonic systems and accept a low-yield nuclear strike in return⁶⁶. And in the case of both sides being willing to accept hypersonic low-yield nuclear strikes, the one who then found himself at a disadvantage could decide to escalate. A lack of transparency about intentions and a limited understanding of reciprocal nuclear doctrines, both characteristic of the current international environment⁶⁷, could then multiply the complication of escalation management.

We may conclude that symmetry in hypersonic nuclear arsenals will not provide a rationale for stability between possessor-states. Instead it will create a *status quo* in which the fear of being pre-empted becomes the dominant factor.

By contrast, three factors would mitigate the threat to nuclear deterrence-based strategic stability if only conventionally-armed hypersonic missiles were present in the arsenals of two opposing States. The use of conventional hypersonic systems to degrade an opponent's nuclear forces would require the employment of hundreds of hypersonic missiles; preparations for their use would be hard to conceal, giving the opponent time to put nuclear forces on high alert; it is doubtful whether conventionally-armed hypersonic missiles could effectively destroy silo-based nuclear missiles⁶⁸.

In other words, it is not by looking at their first-strike potential that the core of the destabilizing potential of conventionally-armed hypersonic missiles become apparent. Instead, one needs to look at their potential to threaten early-warning radars, dual-use (nuclear/conventional) command and control nodes, air and missile defence assets, and time-critical or mobile targets⁶⁹ to put an adversary in a highly disadvantageous position at the outbreak of a conflict. The risk is that conventionally-armed hypersonic weapons could, intentionally or by

⁶⁵ LEAH (n.38) p. 192.

⁶⁶ An interesting example of the effect of irresponsible leadership is reported by Thérèse Delpech: "In 1962, Fidel Castro encouraged the Soviets to use nuclear weapons [against the U.S., during the Cuban missile crisis], knowing that it would lead to the destruction of Cuba. And in 1981, almost 20 years later, Castro asked the Soviets to reintroduce nuclear weapons to Cuba, while Mao expressed his readiness to accept massive Chinese casualties in a nuclear war over Taiwan", see THÉRÈSE DELPECH, *Nuclear Deterrence in the 21st century: Lessons from the Cold War for a New Era of Strategic Piracy* (RAND, 2012), p. 40. The effect of irresponsible leadership on strategic stability were also considered by Bernard Brodie: "To be willing to accept enormous destruction only for the sake of inflicting greater destruction on the enemy [...] argues a kind of desperation at the moment of decision which rules out reason" see BERNARD BRODIE, *The Anatomy of Deterrence* (RAND, 1958), p. 11.

⁶⁷ THÉRÈSE DELPECH (n.66), pp. 20-21.

⁶⁸ VLADIMIR DVORKIN "Preserving Strategic Stability Amid U.S.-Russian Confrontation" available at <https://carnegie.ru/2019/02/08/preserving-strategic-stability-amid-u.s.-russian-confrontation-pub-78319>; ACTON (n.2), pp. 84-87; DENNIS M. GORMLEY, 'US Advanced Conventional Systems and Conventional Prompt Global Strike Ambitions' in *The NonProliferation Review*, vol. 22 (n. 2), 2015, p. 133

⁶⁹ JAMES ACTON, *Escalation through Entanglement*, in *International Security*, vol. 43 (n.1), 2018, pp. 61-66. NATIONAL RESEARCH COUNCIL, *Conventional Prompt Global Strike Capability: Letter Report*, 2007, p. 2.

mistake, degrade the systems required for operating certain nuclear assets or destroy other vital assets, and that this could trigger an intentional or accidental nuclear response.

Illustrating these points, Russia and China see U.S. plans to deploy highly precise conventional hypersonic missiles as a U.S. attempt to cripple their nuclear retaliatory capabilities⁷⁰. A perception that hypersonic weapons could prove decisive in a military conflict is shaping the strategic posture of both Russia and China. The 2014 Russian Military Doctrine regards as a “military threat”, as well as a risk for their deterrent capability, the “deployment of strategic non-nuclear systems of high-precision weapons”. In other words, the doctrine considers conventional hypersonic weapons (or strategic non-nuclear high-precision weapons) to be equivalent to nuclear weapons in terms of their implications for deterrence. According to the doctrine, “within the framework of strategic deterrence measures of a forceful nature the use of high-precision weapons is envisaged by the Russian Federation”⁷¹.

These Russian perspectives are linked to perceptions of U.S. ballistic missile defence (BMD) deployments in Romania and Poland. At the St. Petersburg International Economic Forum in 2015, President Putin declared that U.S. abrogation of the ABM Treaty and successive actions have pushed the world to a new Cold War⁷². The Russian government believes that the interceptor launchers in question could be used to launch nuclear-tipped cruise missiles⁷³. In essence, it seems that Moscow believes that the deployment of U.S. ballistic missile defense systems in conjunction with the development of hypersonic weapon systems is increasing the potential for a successful U.S. preemptive strike against Russia’s land-based strategic nuclear forces⁷⁴.

The Chinese government shares the Russian view that hypersonic systems will pose a threat to opponents’ nuclear forces. In the *2013 Science of Military Strategy*, the Chinese Academy of Military Science argues that U.S. CPGS weapons could force China into a “disadvantaged, passive position” by weakening the Chinese nuclear counterstrike

⁷⁰ DENNIS M. GORMLEY (n.67), p. 125.

⁷¹ President Vladimir Putin personally emphasized concern about the development of “high-precision conventional weapons systems that in their strike capabilities come close to strategic nuclear weapons”. Quoted in ACTON ‘*Russia and Strategic Conventional Weapons*’ (n.24), p. 123. Deputy Defence Minister Anatoly Antonov was even more specific in an April 2013 interview, stating that “the destructive capabilities of [CPGS weapons] are increasingly getting closer to those of nuclear weapons[...] incoming information unequivocally testifies to the fact that the United States is looking for a considerable new segment of its strategic arsenal capable of solving a wide range of tasks that used to be assigned exclusively to strategic nuclear weapons”. *Ibid.*, p. 143.

⁷² “*Putin: Unilateral US Withdrawal from ABM Treaty Pushing Russia toward New Arms Race*,” *Russia Today*, June 19, 2015, <https://www.rt.com/news/268345-putin-west-russia-relations/>.

⁷³ Acton (n.2), p. 146.

⁷⁴ MATTHEW ROJANSKY, *Russia And Strategic Stability*, in ELBRIDGE A. COLBY MICHAEL, S. GERSON (eds.), *Strategic Stability: Contending Interpretations* (U.S. Army War College Press, 2013), pp. 318-325.

capability⁷⁵. Given the relatively small size of China's nuclear arsenal, a large U.S. hypersonic arsenal could undermine the Chinese nuclear deterrence capability⁷⁶. It is also reported that China is worried about the potential combination of high-precision warhead delivery methods with low-yield nuclear warheads; such weapons would be "tactically usable"⁷⁷. The U.S. decision to place BMD and radar systems in the Asia-Pacific region is also a driver for Chinese concern about hypersonic weapons⁷⁸. These factors are contributing to the Chinese decision to raise the alert of nuclear forces and build a launch-on-warning capability⁷⁹.

If in future conventionally-armed hypersonic systems are seen as capable of disarming first strikes, or even merely threaten the disabling of key defence assets such as C3I infrastructure and early warning radars, and if their deployment is coupled with increasing forward-deployment of missile defences, rendering effective retaliation problematic, they will be destabilising and may create an incentive for developing or enhancing asymmetric responses, e.g. the large-scale dissemination of low-yield nuclear weapons or anti-satellite capabilities.

3.5. Countering Hypersonic Weapons

It is thought that current missile defence systems will be incapable of destroying hypersonic systems⁸⁰. However, both Russia and the United States are reported to be seeking the means to intercept hypersonic missiles⁸¹. Russia is developing the S-500 missile interceptor system, and the United States is working on the THAAD-ER (Terminal High Altitude Area Defence-Extended Range) system. Both these systems have been conceived for area-defence⁸². It would be cost-prohibitive to deploy them to protect all possible hypersonic

⁷⁵ CHINESE ACADEMY OF MILITARY SCIENCE, *The Science of Military Strategy 2013* (Military Science Press, 2013), pp. 170-171.

⁷⁶ GREGOR KULACKI, *The Chinese Military Updates China's Nuclear Strategy* (Union of Concerned Scientists, 2015) pp. 5-8.

⁷⁷ MICHAEL S. CHASE, *PLA Rocket Force: Executors of China's Nuclear Strategy and Policy*, in JOE McREYNOLDS (ed.), *China's Evolving Military Strategy* (Brookings Institution Press; Jamestown Foundation 2017), p. 155.

⁷⁸ POLLACK (n.24), 148-149; WIENER (n.7), pp. 153-154.

⁷⁹ GREGOR KULACKI (n.70), pp. 5-8.

⁸⁰ RAND (n.1), pp. xi-xii; HALLIONS (n.1), p. 4; ELENI EKMEKTSIOGLOU, *Hypersonic Weapons and Escalation Control in East Asia*, in vol. 9(2) 2015, pp. 56-57.

⁸¹ See regarding the U.S. steps to counter hypersonic missiles: WOOLF (n.11), p. 45; AMY BUTLER, "*Thaad-ER In Search of a Mission*" at <http://aviationweek.com/defense/thaad-er-search-mission> The U.S. are also funding the Darpa's Glide Breaker project to explore other options for countering hypersonic missiles. See GRAHAM WARWICK, "*Darpa's Glide Breaker to Tackle Hypersonic Defense*" at <http://aviationweek.com/awindefense/darpa-s-glide-breaker-tackle-hypersonic-defense>. The Russia's S-500 system is said to be "the only air defense complex in the world capable of fighting hypersonic targets". See on this <https://www.globalsecurity.org/wmd/world/russia/s-500.htm>.

⁸² The *area-defence* concept refers to a system designed to protect a large area (radius: several hundreds of kilometres): this aim is achieved by a relatively long-range defensive missile designed to intercept the incoming missile at a distance of several hundred kilometres away from the defensive missile launch site. See FRANCESCO CALOGERO, *Anti-ballistic Missiles*, in PAOLO FORADORI, GIAMPIERO GIACOMELLO, ALESSANDRO PASCOLINI (eds.), *Arms Control and Disarmament 50 Years of Experience in Nuclear Education* (Palgrave Macmillan, 2018), p. 16.

targets⁸³. But it could be realistic to use them to protect critical facilities like command-and-control nodes and land-based nuclear assets, mitigating first strike vulnerability fears

Another way of defending against hypersonic weapons (as well as other types of missile) could be through directed-energy systems, in particular, laser weapons⁸⁴. However, the effectiveness of laser weapons against hypersonic missiles is yet to be seen and the probability is difficult to assess due to the technology being at an early stage of development; it is not clear that it will be possible to contrive that a laser beam tracks a hypersonic target without interruption for tens of seconds⁸⁵.

4. A challenge for arms control

4.1. Left unaddressed by arms control measure, the advent of hypersonic missiles is likely to be destabilising. There is potential for it to impact strategic relations between the United States, Russia and China, and there is a risk that regional powers will seek to acquire hypersonic capabilities because they feel threatened by neighbours or have regional hegemonic ambitions.

At this early stage in the development of hypersonic systems, with deployment still pending, the United States, Russia and China could take short-term steps to deal with the implications of hypersonic systems for strategic and tactical nuclear stability.

They could look for ways of reducing the ambiguities that this paper has highlighted. To this end, reciprocal transparency measures could be helpful. These might include data exchanges designed to build confidence in the survivability of land-based nuclear assets and early-warning radars and C3I capabilities. An expansion of “hot-line” communication options might reduce the risk of misinterpretation of ambiguities. Information concerning the military doctrines that underpin the deployment of hypersonic systems could be shared (the most recent U.S. Nuclear Posture Review expressly mentions non-nuclear strikes on U.S. or allied command and control, or warning assets as the precondition for the use of U.S. hypersonic nuclear systems⁸⁶). Additional reciprocal measures might include sharing information about “red lines”, to reduce escalatory risks, and exchanging assurances that early-warning radars and satellite will not be targeted.

⁸³ RAND (n.1), p. 14

⁸⁴ WIENER (n.7), p. 157. Directed energy weapons rely on direct transmission of energy to the target in order to temporarily or permanently damage it. See B. ZOHURI, *Directed Energy Weapons: Physics of High Energy Lasers (HEL)* (2016) pp. 80-81.

⁸⁵ RAND (n.1), p. 15.

⁸⁶ U.S. Nuclear Posture Review 2018, p. 21.

However, without a reliable verification mechanism for clarifying the nature of the warheads carried by hypersonic missiles, warhead ambiguity is likely to continue to pose a major challenge to threat perceptions, and a potential source of miscalculation, both in peacetime and after the outbreak of conflict. One short-term measure that might mitigate the warhead ambiguity risk would be to locate conventional hypersonic missiles and command-and-control infrastructures far away from the sites of nuclear hypersonic missiles and nuclear ballistic missiles. This would be a way of avoiding *entanglement* between nuclear and conventional forces and command-and-control infrastructures⁸⁷. This could be part of a broader programme to avoid entanglement by isolating all nuclear assets.

Other short-term measures could be of a unilateral nature. The United States, Russia and China could enhance the capacity and survivability of early warning assets and land-based nuclear and command-and-control assets,

Of course, any short-term reciprocal measure would imply the existence of political will to address the challenges posed by the advent of hypersonic systems through inter-state cooperation, and a determination to build the requisite level of reciprocal trust. It is not obvious that the United States President Donald Trump possesses such will or determination.

In the longer term, a treaty might better address the risks presented by hypersonic missiles. A “hypersonic treaty” could set numerical limits on the deployment of conventional and nuclear hypersonic missiles, to provide an assurance in relation to the survivability of nuclear and C3I assets, and to contribute to a better assessment of the threat-environment, lowering concerns about decisive first strikes. Specific attention could be paid to warhead ambiguity: the nature of hypersonic payloads could be the object of on-site inspections. The treaty could also provide for fixed places of deployment of hypersonic missiles following the model of the ABM treaty, which limited the sites of ABM systems⁸⁸.

Arms control agreements are vulnerable to changes in the fundamental interests of parties⁸⁹. But a treaty that would limit the deployment of hypersonic missiles and that would provide rights of inspection to the parties would seem set to be of long-term interest not only to the three possessor-states but also to all NPT parties, since it would coincide with their interest in the elimination of escalatory competition. That said, it should be recognized that such a

⁸⁷ JAMES ACTON (n.2), p. 133; James Acton (n.69), pp. 95-97.

⁸⁸ *Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Anti-Ballistic Missile Systems* (Moscow, 26 May 1972, 944 UNTS 13). The limits to the deployment of anti-missile systems were provided in Article I, Article III and Article V.

⁸⁹ CHRISTINE M. LEAH (n.38), p. 121.

treaty could do no more than reduce risks: in the event of the outbreak of a conflict involving hypersonic possessor-states, on-site inspections would surely be suspended, and conventional warheads could be replaced with nuclear warheads⁹⁰.

4.2. Non-proliferation

Another risk linked to the advent of hypersonic missiles is that of their proliferation and the proliferation of sub-systems useful for indigenizing the technologies⁹¹. At this point the United States, Russia and China, being the only hypersonic possessor-states, should take the lead in countering this proliferation risk. At present it seems that there are no political reasons for a proliferation of hypersonic missiles⁹² and there are significant technical challenges to the indigenous development of hypersonic military technology⁹³. Moreover, the weaponization of hypersonic technologies requires sophisticated facilities that would be cost-prohibitive for many States. But this could change in the future.

A complete ban on the diffusion of hypersonic technologies could be impractical, but some degree of export control could work well to minimize proliferation. A major problem in this regard is that hypersonic technologies have dual use potential. A recent RAND study⁹⁴ found that in several non-possessor-states work is already underway in governmental laboratories and academic institutions intent on researching both military and civilian applications. Nonetheless, a treaty binding parties other than the three-existing possessor-states to refrain from using hypersonic technologies for military purposes, and binding possessor-states to refrain from assisting non-possessors to acquire such technologies or systems for military purposes, might be achievable.

⁹⁰ WOOLF (n.11), pp. 36-37.

⁹¹ RAND (n.1), pp. xi-xii.

⁹² It is important to remark that hypersonic missiles are currently conceived as providing a limited “niche” capability.

⁹³ JAMES ACTON (n. 24), pp. 145-146; JAMES ACTON (n.2), pp. 59-61.

⁹⁴ RAND (n.1), pp. 22-28.