REPORT

PUGWASH WORKSHOP ON HYPERSONIC WEAPONS

9 – 10 December 2019, Geneva

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1. Introduction

On 9 – 10 December 2019 the Pugwash Conferences held a workshop in Geneva on hypersonic weapons. The meeting, organised by the Pugwash Geneva office, was held under Chatham House rules and brought together 30 participants from various regions, including current and former government officials, scientists, engineers, academics and think tank/NGO experts. It aimed at fostering a constructive exchange of views and deepening common understanding of hypersonic weapons. Participants discussed technical aspects, factors driving the development, roles and purposes of hypersonic weapons, as well as risks associated with their deployment and use. The following is a summary of the discussions prepared by the rapporteurs[1].

2. What is a hypersonic weapon?

While in recent years hypersonic weapons have featured prominently in various media, academic publications and official statements, publicly available information about those weapons is still scarce. Their characteristics, the consequences of their introduction into the arsenals of major military powers and their eventual proliferation need to be better understood. Today, it is still unclear what precisely « hypersonic weapons » means. In order to get closer to a working definition, the following criteria were identified :

2.1 <u>Speed</u>

Speed can be used to categorize and distinguish between different types of vehicle.

1 This report was prepared by two rapporteurs, Amb. (ret.) Sergey Batsanov and Kevin Miletic. Please note that the views presented here represent a range of opinions expressed in the meeting, and they do not necessarily reflect the personal views of the rapporteurs, nor of the Pugwash Foundation, the Pugwash Conferences and the sponsors.

Speed regimes	Speed	Examples
Subsonic (M<1)	Lower than the speed of sound (Mach 1 = ~1200km/h or 0,33 km/s)	ALCMs, JASSM, Commercial jet airplanes
Supersonic (M>1)	Greater than Mach 1	BrahMos, Concorde (M=2)
Hypersonic[2] (M>5)	Greater than Mach 5 (1,7 km/s or ~6100km/h)	Kinzhal, X-15, X-51A, Hypersonic Cruise Missiles such as Zircon
	Greater than Mach 20 (6,86 km/s or ~24696 km/h)	ICBM/SLBM such as Minuteman III and Trident II in the descent phase Hypersonic Glide Vehicles such as Avangard (M=20)
	Mach 28 (9,6 km/s or ~34574 km/h)	Re-entry of orbiting stations and spacecraft
	Mach 36	Returns from lunar missions

However, if speed were the sole criterion for defining « hypersonic weapons », traditional ballistic missiles would also fall into this category.

2.2 Trajectory

a) The trajectory can be used to differentiate between traditional ballistic missiles and hypersonic weapons. Traditional ballistic missiles follow a ballistic or quasi-ballistic trajectory. Whereas hypersonic weapons, such as Hypersonic Glide Vehicles (HGVs) and Hypersonic Cruise Missiles (HCMs), follow a non-ballistic atmospheric trajectory.

Hypersonic Glide Vehicles (HGVs) are launched from a ballistic missile booster stage into a sub-orbital trajectory. They are released either in Near Space (20km and 100km in altitude) or Outer Space (above 100km), depending on the target location. The gliding vehicle re-enters the atmosphere with its flat lower surface exposed to atmospheric forces. The large drag force and minimal lift generated will slow the gliding vehicle down. It will then undertake a pull-up manoeuvre by rotating into a high lift, low drag

2 These are maximum speeds and not a speed that will be sustained for most of the flight time. For example an hypersonic Glide Vehicle (HGV) launched at Mach 20+ would, in a long-range strike, be slowed to speeds well below this for much of its flight time due to physical perturbations explained in the next section.

orientation. After the pull-up phase, the gliding vehicle will reach a gliding equilibrium and can glide at more than Mach 20. However, HGVs cannot sustain a Mach 20+ speed for the entire duration of their mid-course flight. The longer the atmospheric flight time, the greater the HGV will decelerate before hitting its target. Gliding is made possible thanks to the aerodynamic features of the vehicle which create extremely high compression waves of great amplitude. At the end of this gliding phase, when the gliding vehicle is close to the target, it uses atmospheric forces to exit the glide and hit the target.

b) The trajectory cannot be used to differentiate between a traditional cruise missile and a Hypersonic Cruise Missile (HCM). Indeed, both have the same flightpath. HCMs also cruise at an altitude of 10-40 km except that they reach hypersonic speed of up to Mach 10. In order to reach hypersonic velocity, they use different types of engines i.e. scramjet and ramjet engines.

2.3 Manoeuvrability

Manoeuvrability refers to the capacity of a delivery vehicle to change its course. It can be used to differentiate between traditional ballistic missiles, ballistic missiles fitted with manoeuvrable re-entry vehicles (MaRVs), and Hypersonic Glide Vehicles (HGVs).

Traditional ballistic missiles are not manoeuvrable. Ballistic missiles fitted with manoeuvrable re-entry vehicles (MaRVs) have limited manoeuvrability capability in their terminal phase only. HGVs have greater manoeuvrability over their mid-course and terminal phases. However, their manoeuvrability comes at the cost of speed and range. When HGVs deviate from their trajectory kinetic energy is lost. Drag forces generated by the change of course will slow them down and therefore reduce their range too.
As for Hypersonic Cruise Missiles (HCMs), their hypersonic speed makes them less manoeuvrable than the current generation of traditional cruise missiles. Similarly to HGVs, HCMs' manoeuvrability comes at the cost of speed, range and weight. In order to withstand high G-force and frictions generated by the change of course, the airframe needs to be reinforced. The more reinforced the airframe becomes, the less speed, range and room for payload and fuel the HCM will have. In other words, their manoeuvrability is the result of a trade-off between airframe, payload, fuel, speed and range.

2.4 Target accuracy

For HGVs and HCMs to be considered more effective than traditional ballistic and cruise missiles, they should be as or more accurate than traditional missiles. However, due to the lack of open source information, the difference in target accuracy is hard to assess. A number of factors could positively or negatively influence their accuracy.

For example, HGVs will hit their target at lower speed than traditional ballistic missiles because atmospheric forces slow them down. This may enhance their accuracy. On the other hand, the deleterious effects of aeroshell damage caused by a relatively long atmospheric flight time may undermine their accuracy. In addition, plasma may interfer with their on-board systems which would further reduce their accuracy (see section 3. for further information).

As for HCMs, they will hit their target at higher speed than traditional cruise missiles. This may make it more difficult to hit their target with high accuracy. In addition, the impact of physical phenomena on their on-board systems and aeroshell may further undermine their accuracy (see section 3. for further information).

Criterion	Hypersonic Weapons
Speed	Hypersonic (Greater than Mach 5)
Trajectory	Non-ballistic atmospheric for part or all of the flight
Manoeuvrability	Higher than traditional missiles
Target accuracy	Equal or higher than traditional missiles

Taken separately those criteria are necessary but not sufficient to define what a hypersonic weapon is. What distinguishes Hypersonic Cruise Missiles (HCMs) and Hypersonic Glide Vehicles (HGVs) from traditional cruise and ballistic missiles is the combination of all those criteria: a) hypersonic speed, b) high manoeuvrability, c) equal or higher target accuracy than traditional missiles, and d) a non-ballistic atmospheric trajectory for part or all of their flight. These characteristics are according to the laws of physics not easily reconcilable. Combining them within the same system draws a line between traditional missiles and hypersonic delivery vehicles such as HCMs and HGVs.

3. What technical challenges do hypersonic weapons raise?

Developing weapons systems with hypersonic speed ; sustained atmospheric flight time ; high-manoeuvrability ; and high-accuracy ; raise a set of technical challenges requiring specific advanced systems, materials, designs and test facilities:

3.1 Hypersonic Glide Vehicle (HGV)

HGVs undergo serious stress during their mid-course and terminal phases. The very high temperatures generated by the interaction with the atmosphere and the high G-loading generated by any manoeuvring can damage the vehicle and interfer with its aerodynamic properties. Aeroshell materials must therefore withstand temperatures of 2'200 Celsius, have good tensile strength to prevent the frame from breaking under high G-force, have low-density to make the frame as light as possible, and have good resistance to oxidation. The aeroshell must maintain the structural integrity of the vehicle to ensure stability throughout the long gliding phase. It must also ensure that the on-board instrumentation and payload remain functional. The only known materials that cumulate all those advantages are certain composites such as carbon fibre reinforced carbon (CFRC) which have been used for the nose cone of intercontinental ballistic missiles and space shuttles. Even carbon composites cannot fully maintain their integrity for a long time in hypersonic conditions. They will last longer than other materials, but will still degrade (ablation and oxidation). The question then is whether one can somehow actively cool the missile or whether the deleterious effects of aeroshell damage, such as reduced accuracy, are acceptable.

In addition to heat and G-force, chemical alterations of the airflow poses another significant challenge to HGVs. An object moving at increasing hypersonic speed will generate a staged chemical alteration of the airflow surrounding it, thereby triggering an ionization process. At the end of this ionization process, the object will be surrounded by a layer of plasma. Guidance systems – GPS, electro-optical and RF seekers – can be affected by the plasma which could undermine the accuracy and navigation control of the vehicle. Moreover, sensors upon which the guidance systems rely are exposed to elevated temperatures and high G-forces which can also undermine their performance and hence the accuracy of the vehicle.

3.2 Hypersonic Cruise Missile (HCM)

Cruise missiles with standard turbojets cannot reach hypersonic speed. HCMs need to employ advanced scramjet and ramjet propulsion systems to reach hypersonic speed. However, scramjets and ramjets are very delicate systems to operate. They become functional only within a certain speed range. They require a high initial speed through an airplane or a rocket booster stage. Once HCMs reach a certain speed scramjets and ramjets can be turned on. Switching in-flight from turbojet to scramjet or ramjet is technically challenging. Those propulsion systems also require special fuels. There are two types of fuel that can be used with scramjets and ramjets: hydrogen fuel and hydrocarbon fuel. While traveling at lower hypersonic speeds than HGVs, HCMs are nevertheless exposed to high temperatures, aerodynamics forces and chemical alterations of the airflow (as they typically fly in lower denser part of the atmosphere than HGVs). Those physical phenomena raise similar issues of airframe solidity, cooling system, and signal and sensor distortion which have an impact on navigation, flight stability and accuracy.

Advanced testing facilities are required to ensure that the designs, materials, and many critical navigation, guidance (and propulsion for HCMs) systems are well-integrated. Standard wind tunnels cannot reproduce conditions to test hypersonic weapons. Only few facilities can reproduce those conditions but for a very short time. Most development is done through computer modelling which is not sufficient to validate a weapon. The only way to make sure the weapon is working correctly is through flight tests.

Due to the lack of open data on HCMs and HGVs testing, it is unclear whether those technical issues have been resolved. **There is a need to further examine the impact of those technical issues on HGVs and HCMs':**

- **speed**
- **range**
- **flight stability**
- **manoeuvrability**
- **accuracy**
- **penetration**
- **detection**

Without this technical understanding it is rather risky to make assumptions and predictions over the real capabilities of HCMs and HGVs.

4. What are the current hypersonic weapons development programmes?

Hypersonic programmes are not new. The US and the Soviet Union did work with discontinuity on hypersonic programmes during the Cold War. Those old programmes almost never materialized, with a very few exceptions like the X-15 (US), but they helped inform and guide current HCMs and HGVs developments.

According to open source reporting, several countries have embarked on HCMs and HGVs development programmes. Those programmes vary in their developmental phase and include (in alphabetical order) but are not limited to:

4.1 China

Name	Description
DF-17	ballistic missile capable of delivering a glider
DF-ZF	gliding vehicle that can be mounted onto ballistic missiles (possibly the DF-17, DF-21 and DF-31)
Starry Sky-2/Xingkong-2 Waverider	glide vehicle that can be mounted onto ballistic missiles
Lingyun-1	hypersonic cruise missile

DF-17 and DF-ZF have been reported as already operational. Other programmes are in their design or experimental and testing phase.

4.2 India

Name	Description
BrahMos II	hypersonic cruise missile, jointly developed with Russia
Shourya	ballistic missile capable of delivering a glide vehicle

Indian programmes are all in their design or experimental and testing phase. They intend to produce operational prototypes but no procurement has been made yet.

4.3 Russia

Name	Description
Avangard (also known as Objekt 4202/Yu-71/Yu-74)	glider that can be mounted onto ballistic missiles such as SS-19
RS-28/Sarmat	hypersonic ballistic missile
Kinzhal	Air-launched ballistic missile
3M-22 Tsirkon	hypersonic cruise missile
Land-based intermediate range hypersonic programmes	rockets and platforms capable of delivering a glider
GZUR	hypersonic cruise missiles

Avangard and Kinzhal have been reported as already operational. Other programmes are in their design or experimental and testing phase.

4.4 USA

Name	Description
Advanced Hypersonic Weapon (AHW)	glider that can be mounted onto ballistic missiles such as Polaris A3/STARS
Falcon Hypersonic Technology Vehicles (HTV-1 and HTV-2)	gliders that can be mounted onto ballistic missiles such as Minautor IV
AGM-183A Air-Launched Rapid Response Weapons (AARW)	rocket boosters capable of delivering a hypersonic glider
Land-Based/Long-Range Hypersonic Weapons (LHRW)	rockets and platforms capable of delivering a hypersonic glider
Intermediate Range Conventional Prompt Strike Weapons (IRCPS)	rockets and platforms capable of delivering a glider
Air-launched Hypersonic Conventional Strike Weapons (HCSW)	hypersonic cruise missiles
Tactical Boost Glide (TBG)	gliding systems

Advanced Full Range Engines (AFRE)	aircraft propulsion systems that could operate over the full-range of speeds required from low-speed takeoff through hypersonic flight
Operational Fires (OpFires)	ground-launched systems enabling hypersonic boost glide systems
Hypersonic Air-breathing Weapon Concept (HAWC)	hypersonic cruise missiles
X-51A Waverider	hypersonic cruise missile

Those programmes are all in their design or experimental and testing phase. They intend to produce or have already produced operational prototypes, but no procurement has been made yet. The Missile Defense Agency (MDA) also started a Hypersonic Defense Programme.

4.5 Other development programmes

Others have also been reported as developing some hypersonic capabilities, including but not limited to: France, Japan, Australia and the EU.

It is public knowledge that certain countries are working on hypersonic programmes but technical information on range, speed, types of payload, types of platform and deployment date are very scarce. That information is absolutely crucial for accurate assessment of a country's hypersonic capability. While secrecy around hypersonic programmes is understandable, some transparency could inject a little dose of predictability in a field where mistaken assumptions about technical aspects of a newly introduced weapon may have negative consequences. **The need to overcome this lack of information and foster transparency and predictability was highlighted. Although no specific ways to achieve this were identified, some suggested to develop an open source-based hypersonic weapons register with a mechanism for interested countries to contribute on a voluntary basis.**

Several countries are also working on hypersonic programmes for civilian purposes. Civilian cooperation on hypersonic technology has potential and should follow in the footpath of existing cooperation on subsonic and supersonic technologies.

5. Why do States develop hypersonic weapons?

Reasons behind the development of hypersonic weapons seem to be manifold and specific to each country. Without any attempt to attribute more importance to one reason over another, the following have been identified as key drivers:

5.1 <u>The techno-military context</u>

A conducive R&D environment in government agencies, academia and private sector, combined with progress in spacecraft and ballistic missile technologies, and the reduction of their relative cost over time, created opportunities for hypersonic weapon development.

5.2 <u>Geopolitical tension</u>

The increasingly tense geopolitical and security climate may have prompted some countries to invest more in their overall military capabilities. As a by-product, hypersonic weapons programmes, have benefitted from a general shoring up of military capabilities.

5.3 <u>Security dilemma</u>

Certain decisions taken by some countries that were deemed hostile to one's national security, such as the development of ballistic missile defence systems, may have triggered an interest in developing HCMs and HGVs. This, in turn, may have prompted other countries to invest more in similar programmes and upgrade their missile defence systems.

5.4 <u>Strategic calculations</u>

Some countries may have considered that their current nuclear deterrent capability was not sufficient to guarantee strategic stability. In this regard, the acquisition of HGVs and HCMs may boost confidence in the effectiveness of one's second-strike capability, thereby enhancing their nuclear deterrent capability. (See section 6. for further information)

5.5 <u>Tactical calculations</u>

Some countries may consider that HGVs and HCMs will provide them with an advantage in certain theatres of operation. In this regard, the acquisition of HGVs and HCMs may give extra-confidence in the effectiveness of one's anti-access/area-denial capabilities and in the ability to hit protected high-value targets or “fleeting targets” deep into another country's territory. (See section 6. for further information)

5.6 Status

Hypersonic weapons may be perceived as a new, albeit perhaps limited, currency of power and providing their owners with an exclusive status of more advanced powers. Subsequent « fear of missing out » and being left behind in technological advances may contribute to the decision of developing hypersonic weapons.

6. What are the roles and missions of hypersonic weapons?

Most HCM and HGV programmes are still in their design and experimental phases and will not be operational for some time, especially longer-range systems which are more technically challenging. But building an understanding of their potential roles and missions ahead of their deployment could give policymakers and practitioners a head-start in dealing with possible future problems.

There is very few official information on how HGVs and HCMs feature in military doctrines. This makes it difficult to understand for what purposes they are developed and deployed. At the moment, it seems that HCMs and HGVs are not being built to fulfil new missions. Rather, they are integrated in existing operational framework to support already existing missions, although this may change in future. Some countries may believe that HCMs and HGVs can support those existing missions more effectively than traditional ballistic and cruise missiles.

6.1 Hypersonic Glide Vehicle (HGVs)

a) Strategic missions:

- Defence

  Long-range HGVs are not faster than traditional intercontinental ballistic missiles (ICBM), both travel at a maximum speed of Mach 20+. The main differences between ICBMs and long-range HGVs reside in their trajectory and manoeuvrability. HGVs usually flight at lower altitudes than ICBM re-entry vehicles after ascent phase. Thus HGVs will enter a ground-based radars' field of view later than ICBM re-entry vehicles because of the earth's curvature. Space-based sensors can detect both ICBM and HGV launches equally well in their boost phase, because both emit identical rocket plumes. However, their greater manoeuvrability and lower altitude make tracking and intercepting an HGV after its boost phase more challenging than an ICBM. (HGVs' manoeuvrability being an advantage to evade missile defence systems only if the approach of interceptors is detected in time.) In sum, the late detection time and greater manoeuvrability of an HGV carrying a nuclear payload could boost confidence in the effectiveness of a second-strike capability, thereby enhancing deterrence capabilities and contributing to strategic stability, if deployed on survivable platforms. A HGV carrying a conventional payload would not be considered as contributing to second-strike capability.

- Offence

  For essentially the same reasons (late detection time and greater manoeuvrability), HGVs could be considered as weapons of choice to conduct a decapitating first strike. Many factors would determine the success of such a strike, including undetected preparations, accuracy, number and payload of HGVs, amongst others. But in theory HGVs could be seen as providing its owners with a potential first strike capability. For conventional HGVs to be used in a first strike, their accuracy must be extremely high. Whereas, nuclear HGVs would not need to be as accurate.

  Alternatively, some countries might also consider them in a more selective manner to take out targets deep into other countries' territory that represent a major risk to national security. However, the use of both conventional or nuclear HGVs for this kind of mission taking place in the territory of another nuclear weapon State would risk triggering a nuclear war. It is hard to imagine what reasons could lead to the use of a nuclear HGV for this kind of mission in the territory of a non-nuclear-weapon State. Although conventional HGVs could be used for this kind of mission in the territory of a non-nuclear-weapon State, their cost and the fact that non-hypersonic systems have proven their effectiveness, makes their use very unlikely.

b) Tactical missions:

- Defence

  Over shorter distances, the difference in detection time between short-/intermediate-range ballistic missiles and HGVs tends to be reduced. Some countries may still consider the deployment of short-/intermediate-HGVs as enhancing their anti-access/area denial capabilities. The use of nuclear HGVs for anti-access/area denial mission would immediately escalate the conflict to a nuclear one. Unless there is an overwhelming attack that can only be stopped with nuclear weapons, conventional HGVs are more likely to be used for anti-access/area-denial missions.

- Offence

  While short-/intermediate-HGVs do not seem to provide greater tactical offensive advantages over traditional short-/intermediate-ballistic missiles, some countries might us them to take out protected high-value targets or "fleeting targets" visible for only a short amount of time at the beginning or during a conflict, in an attempt to gain the upper hand in a given theatre of operations. However, the use of both conventional or nuclear HGVs for this kind of mission taking place in the territory of another nuclear weapon State would risk triggering a nuclear war. It is hard to imagine what reasons could lead to the use of a nuclear HGV for this kind of mission in the territory of a non-nuclear-weapon State. Although conventional HGVs could be used for this kind of mission in the territory of a non-nuclear-weapon State, their cost and the fact that non-hypersonic systems have proven their effectiveness, makes their use very unlikely.

6.2 Hypersonic Cruise Missile (HCM)

a) Strategic missions:

- Defence

  HCMs have greater manoeuvrability and fly at lower altitude than traditional ballistic missiles or HGVs which makes them more difficult to detect and intercept. They have a shorter range too. But the deployment of HCMs on mobile sea-/air-/land-platforms could offset the initial lack of range. In which case, some countries may consider the deployment of nuclear HCMs on forward-based mobile platforms as adding to the effectiveness of their second-strike capability, thereby enhancing deterrence capabilities and contributing to strategic stability, if deployed on survivable platforms. A HCM carrying a conventional payload would not be considered as contributing to second-strike capability.

- Offence

  There are limits to where forward-based mobile platforms can go. It means that HCMs cannot cover a wide territory. This makes the use of HCMs for decapitating first strike unlikely, unless used in conjunction with other weapon systems such as HGVs. Indeed, they cannot hit as deep into other countries' territory as ballistic missiles and HGVs. But, due to their greater manoeuvrability and lower altitude, some countries might also consider them to take out targets within range that represent an immediate risk to national security. However, the use of both conventional or nuclear HCMs for this kind of mission taking place in the territory of another nuclear weapon State would risk triggering a nuclear war. It is hard to imagine what reasons could lead to the use of a nuclear HCM for this kind of mission in the territory of a non-nuclear-weapon State. Although conventional HCMs could be used for this kind of mission in the territory of a non-nuclear-weapon State, their cost and the fact that non-hypersonic systems have proven their effectiveness, makes their use very unlikely.

b) Tactical missions:

- Defence

  Although slightly less manoeuvrable due to their hypersonic speed, HCMs can hit a target faster than traditional cruise missiles regardless of distance. They fly at slightly higher altitude which makes them more visible to radars but the plasma layer may absorb or deflect radars' electromagnetic waves (depending on the radar frequency). Even if they are detected, their speed makes them harder to intercept than traditional cruise missiles. This may prompt some countries to consider the deployment of short-/intermediate-HCMs as enhancing their anti-access/area denial capabilities. The use of nuclear HCMs for anti-access/area denial mission would immediately escalate the conflict to a nuclear one. Unless there is an overwhelming attack that can only be stopped with nuclear weapons, conventional HCMs are more likely to be used for anti-access/area-denial missions.

- Offence

  For essentially the same reasons, some countries might us them over traditional cruise missiles to take out protected high-value targets or "fleeting targets" in an attempt to gain the upper hand in a given theatre of operations. However, the use of both conventional or nuclear HCMs for this kind of mission taking place in the territory of another nuclear weapon State would risk triggering a nuclear war. It is hard to imagine what reasons could lead to the use of a nuclear HCM for this kind of mission in the territory of a non-nuclear-weapon State. Although conventional HCMs could be used for this kind of mission in the territory of a non-nuclear-weapon State, their cost and the fact that non-hypersonic systems have proven very effective in conducting this kind of mission, makes their use very unlikely.

More than their speed and manoeuvrability, it is actually their range and payload that define what HCMs and HGVs might be used for and what their consequences may be. In that sense, they are no different from traditional ballistic and cruise missiles. In theory, HCMs and HGVs should be able to carry out the above mentioned missions. However, there are a lot of question-marks that need to be answered before most countries feel confident in acquiring and using them. In particular the effects of physical phenomena on their navigation and guidance systems. Thus, HCMs and HGVs should not be considered as immediate replacement for traditional cruise and ballistic missiles. On the contrary, it is more likely that traditional ballistic and cruise missiles will be preferred over hypersonic ones in the near to medium term.

The most likely scenario where HGVs and HCMs might feature prominently is in a conflict involving two or more countries with advanced missile defence systems and missile programmes. The use of HGVs and HCMs in conflicts involving countries with less technologically advanced missile and anti-missile programmes would represent a waste of resources (unless it is for testing purposes), given that traditional missiles have proven their effectiveness, and HGVs and HCMs are very expensive and few in numbers, for the time being. In addition, their limited numbers would probably mean that for most, if not all, of the above mentioned missions, HCMs and HGVs would need to be used in conjunction with other weapon systems. However, the scarce official information on how HGVs and HCMs feature in military doctrines makes it difficult to understand for what purposes they are developed and deployed. **In order to overcome this lack of information and foster transparency and predictability, it is recommended to further examine the purposes of hypersonic delivery vehicle in tactical and strategic contexts.**

The use of HCMs and HGVs would also require a number of supporting sub-systems including launch-platforms, satellites, C4ISTAREW (Command, Control, Communication, Computer, Intelligence, Surveillance, Target Acquisition, Reconnaissance and Electronic Warfare). **It is unclear how much HCMs and HGVs are compatible with existing sub-systems and whether they require an upgrade of existing or the development of new sub-systems. Therefore it is worth further examining the level of compatibility between existing sub-systems, and HCMs and HVGs.**

The use of hypersonic technology for Intelligence, Surveillance and Reconnaissance (ISR) missions was also considered. The speed, aerodynamic forces and high temperatures were seen as significant challenges to the gathering of accurate and exploitable information. While there is a potential for using hypersonic vehicles to conduct ISR missions, at the moment, it was considered that conventional aircrafts and satellites could conduct ISR missions more effectively.

7. What are the risks associated with hypersonic weapons?

The introduction of HCMs and HGVs may enhance a country's second strike capability (which will depend, inter alia, on types, numbers and modes of deployment), thereby contributing to strategic stability. But HCMs and HGVs may have some destabilizing effects too:

7.1 Increasing nuclear risks

There is a number of ways HCMs and HGVs could contribute to increasing nuclear risks:

- Warhead and target ambiguity
  "Warhead ambiguity" refers to the possibility of having HCMs and HGVs capable of carrying both nuclear and conventional payloads. Warhead ambiguity is not unique to HCMs and HGVs, it also applies to traditional ballistic and cruise missiles. In practice, a HCM or HGV fitted with a conventional payload could be confused with an incoming nuclear attack. This may prompt a country to respond to an incoming conventional hypersonic strike with a nuclear retaliation. But regardless of the type of warhead, some countries may decide to respond with nuclear retaliation anyway. Conventional HGVs and HCMs may be perceived as capable to exploit the vulnerabilities of nuclear deterrents and to disrupt military infrastructures and networks on which the functioning

of key defence assets is based.

In addition to this, their higher manoeuvrability than traditional missiles would make the identification of the target more difficult. This "target ambiguity" may prompt a country to assume that its strategic assets are being targeted by an incoming hypersonic strike and decide that a nuclear retaliation was warranted. Conventional and nuclear entanglement heightens the risks associated with target ambiguity. Ultimately, warhead and target ambiguities have a strong potential of lowering the nuclear threshold and of increasing the likelihood of nuclear use whether by intent or accident.

- Heightening threat perceptions

  Threat perceptions would probably be influenced by numbers and locations of deployed HCMs and HGVs. A limited number of HGVs and HCMs deployed in few locations may not change the overall threat perception. It is difficult to anticipate at which point, numbers and locations start making a difference in threat assessment process. The threat assessment process would also probably be different for strategic stability and regional stability. Forward-based forces being more vulnerable than the nuclear deterrence capability of a country, a lower number of HGVs and HCMs deployed in a given theatre of operations may upset the regional balance of power. Whereas a large number deployed across a wide-range of forward and rear bases would be required to upset the strategic balance of power. The perceived ability of HCMs and HGVs to hold a country's nuclear or strategic conventional forces at risk creates additional pressures to use (or threaten to use) nuclear weapons for fear of losing them. Therefore some countries may take measures to mitigate the risks of a decapitating first strike, including but not limited to, delegation of authority over nuclear weapons to low-level officers, launch-on-warning posture, nuclear build up to enhance nuclear deterrence survivability and investment in advanced defence systems. Those measures would in turn lower the nuclear threshold and increase the likelihood of nuclear use whether by intent or accident.

In order to anticipate the action-reaction dynamics that might ensue the deployment of HCMs and HGVs, it is recommended to further examine how threat perception may be affected by numbers and locations of HCMs and HGVs and what changes in posture would such a modification of perceptions generate.

- Shortening reaction time

  It is unclear if and how much would the use of HCMs and HGVs compress the timeline across the detection, assessment and response process. If the boost phase of a long-range HGV is picked up, other countries will be immediately on alert and the difference in reaction time between HGVs and traditional ballistic missiles will be reduced. If one loses track of a HGV after its boost phase, they may not have sufficient warning time to prepare for defence effectively. If the boost phase of a long-range HGV is not picked up, the reaction time for HGVs would shrink. Due to the earth's curvature and HGVs low trajectory, ground-based radar will be able to pick up HGVs very late in their mid-course phase which would compress the reaction time. Even within reach of ground-based radars, the layer of plasma may make them unidentifiable, depending on the radars' frequency, in which case the reaction time would be even further compressed. HCMs fly at lower altitude than HGVs which makes them stealthier than HGVs. Reaction time for a HCM would then be lower than a HGV. Their higher cruising altitude makes HCMs slightly easier to detect than traditional cruise missiles (provided that the layer of plasma does not inhibit detection). But their hypersonic speed may offset the fact that they fly higher, leading to a reduction in reaction time in the end.

  This possible compression of reaction time would be more acutely felt by commanders in theatres of operations who will have a few minutes to decide how to react to an incoming HGV or HCM. Even if it is only a matter of minutes, a lower reaction time would provide less time for accurately assessing the origin, destination and payload of a HCM or HGV. This information is crucial for the type of response that will be selected. With even less time at their disposal analysts and decision-makers would be more at risk of misreading a situation and taking a decision that could lead to the use of nuclear weapons. This also begs the question of the role Artificial Intelligence (AI) may play in assisting in the decision process. AI involvement in this process would in turn raise a number of important questions of political, military and moral nature.

In sum, there is uncertainty around the reaction time to an incoming HGV or HCM and how a potentially compressed reaction time would affect the different stages of the reaction process. There may be a need therefore to conduct a comparative analysis of the detection, assessment and response processes for traditional ballistic and cruise missiles, and HCMs and HGVs.

7.2 Increasing political risks

The deployment of HCMs and HGVs could indirectly increase political risks in a number of ways:

- Encouraging nuclear brinkmanship

  The characteristic of hypersonic missiles, in particular the fact that they are hardly observable by early warning systems and difficult to defend against, could exacerbate the way in which nuclear States engage in nuclear brinkmanship. Hypersonic missiles may aggravate the so-called "competition in risk taking" in which nuclear States could engage, with unpredictable consequences.

- Fuelling an arms race

  Because of the security dilemma, the introduction of HCMs and HGVs, even if only for defensive purposes, may be interpreted by other countries as threatening. This may prompt other countries to further develop their own HCMs and HGVs, and upgrade or expand their missile defence systems. In which case, the potential initial stabilizing effects with regards to strategic stability could be short-lived.

7.3 Increasing proliferation risks

Developing HCMs and HGVs requires prior knowledge and infrastructure for advanced traditional cruise and ballistic missile programmes. It would therefore be very difficult for a country without advanced cruise and ballistic missile capabilities to develop and/or operate HCMs and HGVs. This makes vertical proliferation the most likely type of proliferation in the near to medium term.

Even if horizontal proliferation was considered less likely than vertical proliferation in the near to medium term, there nevertheless are risks of horizontal proliferation, including but not limited to :

– development of indigenous hypersonic programmes which would be immensely challenging
– downhill transfer of hypersonic technology to lower-tier military countries with already established missile programmessales of hypersonic systems to allies
– sales of hypersonic systems to allies

– transfer of commercial hypersonic technology to lower-tier military countries with already established missile programmes. Private companies develop hypersonic technology for rocket launches and space shuttles (e.g. ESA IXV, Dream Chaser and REL Skylon) which may make the technology cheaper and more accessible in the medium to long term.

It is important therefore that States and private actors developing hypersonic technologies abide by the strictest standards of export control and non-proliferation.

8. What can be done to mitigate risks?

A number of non-proliferation, confidence-building, arms control and countermeasures, presented by different participants, were considered in order to mitigate the risks associated with the introduction of HCMs and HGVs:

8.1 Non-proliferation

Technology used in the development, production and maintenance of HGVs and HCMs is to a certain extend covered by some multilateral export control regimes (MECRs):

- Wassenaar Arrangement
  Founded in 1996 by a voluntary group of countries, the Arrangement's purpose is to contribute to regional and international security and stability by promoting transparency and greater responsibility in transfers of conventional arms, and military and dual-use (i.e. those having civil and military uses) goods and technologies to prevent destabilizing accumulations of those items. The Wassenaar Arrangement establishes two lists of items for which member countries are to apply export controls:

At least six provisions of the Munitions List may apply to HGVs and HCMs:

ML4 – covers rockets and missiles

ML8b. - covers propellants

ML10 – covers Aircraft, Unmanned Aerial Vehicles and aero-engines

ML11 – covers electronic equipment e.g. guidance and navigation equipment

ML21 and ML22 – cover software and other technologies designed for development, production, operation, maintenance, repair, overhaul of items in the Munitions List

At least four provisions of the dual-use list may apply to HGVs and HCMs:

Technology required for the development, production or use of items in the Dual-Use List:

Category One – covers special materials and related equipment including carbon matrix and equipment related to their development and production

Category Two – covers electronics and equipment related to their development and production

Category Nine – covers aerospace and propulsion, and equipment related to their development and production.

- Hague Code of Conduct (HCoC)

  HCoC members voluntarily commit themselves politically to provide pre-launch notification on ballistic missiles and space launch vehicles, and test flights. Since HGVs are mounted on top of ballistic missiles, relevant provisions of HCoC could also apply to them, including:

  Provision 4.a).i – make an annual declaration providing an outline of their HGV policies and provide annual information on the number and generic class of HGVs launched during the preceding year (HGV references added)

  Provision 4.a).iii – exchange pre-launch notifications on HGV launches and test flights (HGV reference added)

- Missile Technology Control Regime (MTCR)
  The MTCR participating governments have commit themselves politically to apply restrictions on the transfer of technology capable of being used for the delivery of weapons of mass destruction. These restrictions apply to complete rocket systems (including ballistic missiles, space launch vehicles and sounding rockets) and unmanned air vehicle (UAV) systems (including cruise missiles systems, target and reconnaissance drones); production facilities for such systems; and major sub-systems including rocket stages, re-entry vehicles, rocket engines, guidance systems and warhead mechanisms. The transfer of the most sensitive Category I items (with capabilities exceeding a 300km/500kg range/payload threshold) are subject to an unconditional "strong presumption of denial" regardless of the purpose of the export and are licensed for export only on rare occasions. Category II items are systems capable of a maximum range equal to or greater than 300km (regardless of payload) and are not subject to a "strong presumption of denial" and partners have greater flexibility in the treatment of Category II transfer applications.
  While MTCR guidelines apply to HGVs and HCMs, it depends on the vehicle whether they fall under Category I or II, depending on their range/payload. Moreover, there is an argument as to whether HGVs should be classified either as re-entry vehicle or unmanned air vehicle (UAV) due their lift generation and prolonged atmospheric flight.

Whilst the bulk of technologies required for HCMs and HGVs are controlled by Wassenaar, and the MTCR, there are still some issues to be addressed, including but not limited to:

- HCMs are UAVs (cruise missiles) according to MTCR, and are missiles under the Wassenaar Munitions List.
- HGVs could potentially be considered either as re-entry vehicles or UAVs under the MTCR (depending on national interpretation)
- Accounting for commercial/civilian use of hypersonic technology
- Effective non-proliferation can hardly be achieved without the participation of key hypersonic weapons developers, especially (in alphabetical order) China, Russia and the US.

It is recommended therefore to address the definitional aspects of hypersonic technology within the appropriate fora. Additionally, because of relatively limited politicisation and strong emphasis on technical aspects, it my be fruitful to use Multilateral Export Control Regimes as initial platforms to hold informal discussions with relevant stakeholders on HCMs and HGVs to better understand the technology and its effects.

8.2 Confidence-Building and Arms Control

A number of confidence-building and arms control measures were considered. It was noted that some measures would require a certain level of political will which may be lacking at the moment. However, it was deemed useful not to limit the field of possibilities and consider a wide-range of measures for policymakers to choose from depending on present and/or future interests and level of political will:

- Enhancing transparency and predictability:

  Communication – Better communication could contribute to fostering transparency and predictability around the defensive and offensive purposes of HGVs and HCMs. **It may be useful to explore adoption of appropriate measures to communicate each other's views on the intended use of HCMs and HGVs, such as the adoption of a more explicit definition of roles and missions of HGVs and HCMs in public documents such as Defence White Papers.**

  Notifications – Drawing from the HCoC's provision on test launches, notifications on HCM and HGV tests could allow for a more accurate assessment of another country's hypersonic arsenal and its operational level, thereby contributing to transparency and predictability. Other types of notifications could also be communicated such as the number, range, type of platforms (land, sea or air-based), and area of deployment of HCMs and HGVs. **It is recommended to consider adopting notification measures including but not limited to, HGV and HCM test-launches (possibly under HCoC umbrella); and an open source-based hypersonic weapons register, reflecting numbers, range, platforms and areas of deployed HCMs and HGVs, with a mechanism for interested countries to contribute on a voluntary basis.**

Warhead clarifications – Clarifying the nature of the warhead carried by HCMs and HGVs could help mitigate the risk of warhead ambiguity, thus reducing threat perceptions and the likelihood of miscalculations. Voluntary measures to clarify the nature of the warhead could include communicating what type of payload can each hypersonic system carry and how many will be fitted respectively with nuclear and conventional payload. While politically challenging, verification mechanisms would greatly improve confidence in the accuracy of the information communicated. **It would be advisable to identify ways to exchange information on the nature of warheads that HCMs and HGVs can carry as well as the type fitted onto deployed HCMs and HGVs.**

De-targeting - Agreement not to target certain vital assets such as command and control centres, and radars and satellites needed for early warning, could reduce the incentive for a first strike and enhance strategic stability. **It is recommended to adopt measures on de-targeting vital assets.**

Numerical and geographical limits – Agreed limitations of the number and area of deployment of HCMs and HGVs could contribute to reducing the incentive to embark on an arms race and reduce the perception of vulnerability that an otherwise uncontrolled deployment of HCMs and HGVs would generate. **It is recommended to explore adoption of numerical and geographical limitations on the deployment of HGVs and HCMs.**

- Establishing dialogue at institutional level:

New START – While existing HCMs and non-strategic HGVs are clearly outside the framework of New START, there is a strong argument for the application of New START to strategic nuclear HGVs as a variant of ICBMs. HGVs are neither cruise or ballistic but they are mounted on top of ballistic missile booster stages and follow a ballistic trajectory up until their pull-up manoeuvre. Strategic HGVs could therefore count towards the limits established by New START. **It is recommended to make use of the mechanisms provided under the New START Treaty to consider including strategic HGVs under its limits (provided the Treaty is extended).**

Multilateral Export Control Regimes – Given the relative limited politicisation and strong emphasis on technical aspects compared to other fora, **it is recommended to use Multilateral Export Control Regimes as platforms to hold informal discussions with relevant stakeholders on HCMs and HGVs to better understand the technology and its effects.**

Test Ban – a test ban would prohibit all flight testing of HCMs and HGVs suitable as weapons (commercial HGVs would stay outside the remit of a test ban). As a result current testing programmes would be frozen and future tests prohibited. It would not require scrapping existing HGVs and HCMs. However, confidence in the performance of those existing systems would decline in the medium to long term, if left untested. **It is recommended that all relevant parties consider the feasibility of a test ban for HCMs and HGVs.**

Given HCMs and HGVs' connections with other weapon systems which provide reasons for their development, support for their use, or response to their use, there is also an argument for taking into account other relevant weapon systems when dealing with HCMs and HGVs. Following this logic, putting HCMs and HGVs on the table alongside other relevant weapon systems in the contexts of either strategic and/or regional stability talks or nuclear risk reduction talks may provide another possible way to address risks associated with these systems. **In parallel to stand alone measures, it is recommended to consider HCMs and HGVs in a broader context of confidence building/arms control, strategic/regional stability and nuclear risks reduction.**

8.3 Countermeasures

Countermeasures were also considered as potential risk mitigators. It was noted that countering HCMs and HGVs was a two-step process. The first step is to detect and track the missile either before it is launched or during its flight, and the second step is to intercept the missile.

- Detection and Tracking:

  There was doubt regarding the capacity of existing systems to detect and track a HCM or HGV for the entire duration of their flight.

  Ground-based radars – Due to the earth's curvature, the low cruising and gliding altitude of HCMs and HGVs make them visible to ground-based radars only a few minutes before arriving on the target. Even within reach, the layer of plasma around the missile could absorb and deflect some electro-magnetic waves and reduce the effectiveness of ground-based radars to detect and track HCMs and HGVs depending on the frequency of the radars.

  Over-the-horizon radars – Over-the-horizon radars may prove more effective at detecting and tracking HCMs and HGVs as they are not as much affected by the earth's curvature as traditional ground-based radars. However, the layer of plasma around the missile which could absorb and deflect some electro-magnetic waves could reduce the effectiveness of over-the-horizon radars to detect and track HCMs and HGVs depending on the frequency of the radars.

  Space-based sensors – Space-based sensors could detect HGV launches because they emit as much rocket plumes in their boost phase as traditional ballistic missiles. However, the HGV could disappear from « sight » when it starts gliding. In fact, the infrared radiation (IR) of a HGV or HCM in flight (that is, in the mid-course phase) is likely about $1/10^{th}$ that of a ballistic missile rocket plume in its boost phase. Although, in the mid-course phase, IR emission from a HGV or HCM would be greater than that of a traditional ballistic missile, it was not clear whether existing space-based sensors would be able to pick up such a dim signal or whether new sensors, especially in the infrared spectrum, would be needed.

  The possible discrepancy in the efficacy of ground-based and space-based sensors in detecting and tracking HGVs and HCMs during the mid-course portion of flight could incentivize States that lack space-based capabilities to develop them. **It is therefore recommended to further examine the effectiveness of over-the-horizon radars and space-based sensors at detecting and tracking HCMs and HGVs.**

- Interception

  In-flight interception of HCMs and HGVs would also present some serious technical challenges:

  Kinetic means – Existing ground-based interceptors are supposed to be able to intercept ballistic missile re-entry vehicles flying at Mach 26. It is thus not the speed of HCMs and HGVs that would pose problems to missile defence systems, rather it is their manoeuvring capabilities that would allow them to evade incoming interceptors (with the caveat that incoming interceptors be detected and that the manœuvre be initiated in time). Space-based interceptors could be an option but they are technically very challenging to do in practice, given that the intercepting warhead needs to de-orbit and such manœuvre would need to be undertaken at the correct point of the interceptors orbit and would require the accurate prediction of the target well in advance. Also, such systems would have limited temporal coverage due to orbital mechanics unless there is a large number in orbit to provide full temporal coverage. In addition to this, space-based systems would raise several legal and strategic issues, and they would also have a high cost and be very vulnerable.

  Non-kinetic means – While a laser would be fast enough to intercept HCMs and HGVs, it was noted that there are too many question-marks around their accuracy, mobility and power to contemplate laser-technology as a reliable countermeasure to HCMs and HGVs. Moreover, the aerothermal protection required by the hypersonic vehicles would also provide thermal protection from a directed energy weapon such as a laser.

  Spoofing and jamming of navigation and guidance systems would also be technically challenging, especially considering that the layer of plasma around the missile may reduce the effectiveness of any spoofing or jamming attempt.

In light of the above, there does not seem to be, at this moment, any effective defence against HCMs and HGVs. Given the difficulties existing missile defence systems face with traditional ballistic and cruise missiles, developing effective defence systems against HCMs and HGVs would require an enormous and sustained investment with speculative guarantees of success. For this reason alone, not to mention many others, it is highly advisable that States possessing hypersonic capabilities and those working to achieve them, should start discussions on cooperative measures to prevent a new dimension of the arms race in this particular area and to mitigate or limit possible negative consequences of their uncontrolled deployment.

9. Abbreviations

MaRVs – Manoeuvrable Re-entry Vehicles
MiRVs – Multiple Independently-targetable Re-entry Vehicles
HGV – Hypersonic Glide Vehicle
HCM – Hypersonic Cruise Missile
CFRC – Carbon Fibre Reinforced Carbon
ICBM – Intercontinental Ballistic Missile
C4ISTAREW – Command, Control, Communication, Computer, Intelligence, Surveillance, Target Acquisition, Reconnaissance and Electronic Warfare
ISR mission – Intelligence, Surveillance, Reconnaissance mission
AI – Artificial Intelligence
MECRs – Multilateral Export Control Regimes
HCoC – Hague Code of Conduct
MTCR – Missile Technology Control Regime
UAV – Unmanned Aerial Vehicle
IR emission – Infrared emission

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