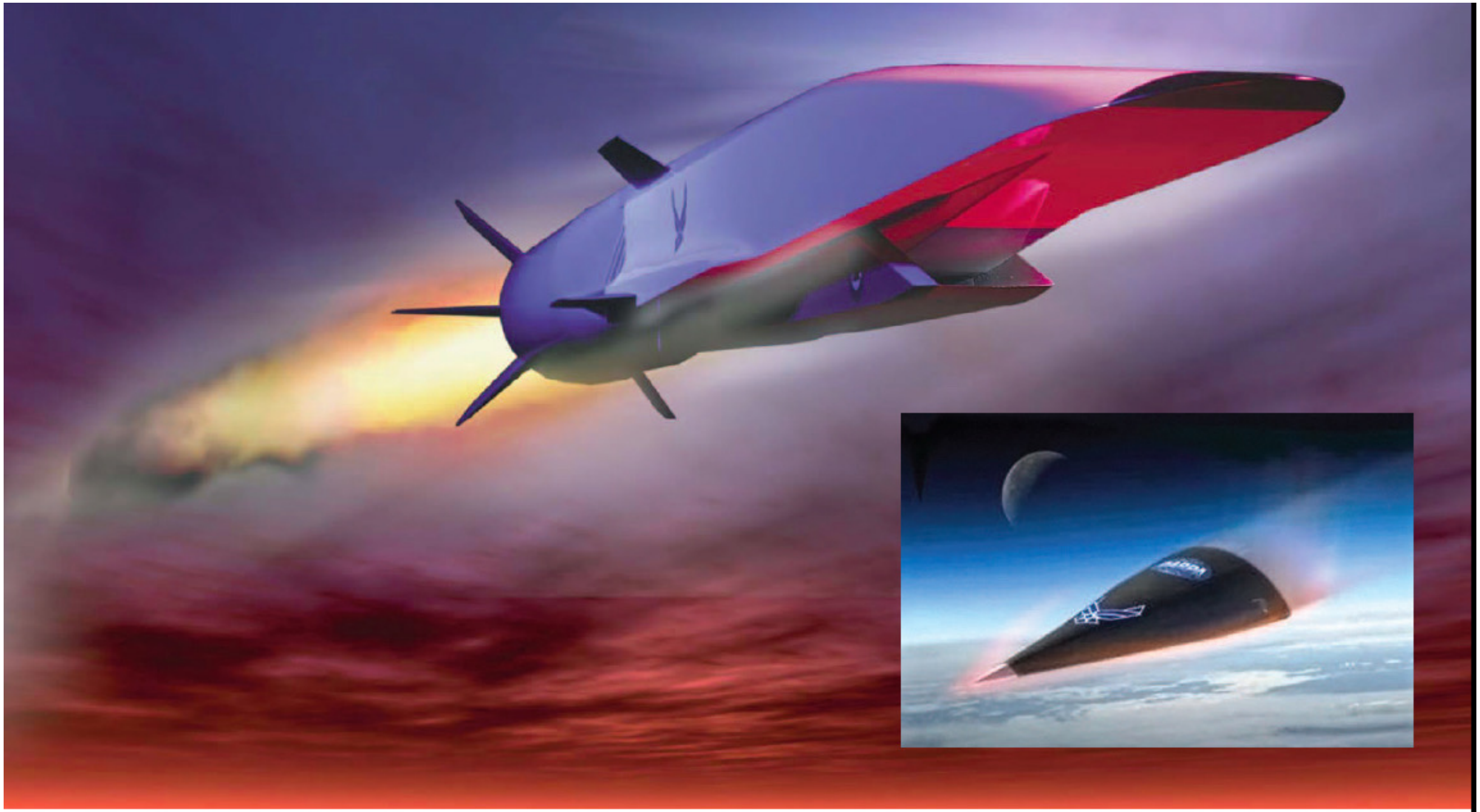


Hypersonic weapons the myth and beyond

January 2024 Alessandro Pascolini

The myth

Hypersonic missiles are depicted as a "game changer":

- **with "unmatched speed" they are said to "hit over-the-horizon targets in a fraction of the time it would take existing ballistic or cruise missiles"**
- **they got near-immunity to detection, being "nearly invisible" to existing early warning systems**
- **they are forces that cannot be intercepted by ABMs**

Together, these capabilities will leave those targeted with "insufficient time to confidently identify and confirm the nature of an incoming attack, let alone to decide how to respond"

6 May 2023 first distruction of hypersonic weapons by air defences

The Ukrainian Ministry of Defense announced on 6 May 2023 it had shooted down a Russian hypersonic missile Kinzhal in the skies over the capital region. Yet just 12 days afterward, Ukraine shot down six Kinzhals that Russia fired in an assault on Kyiv.

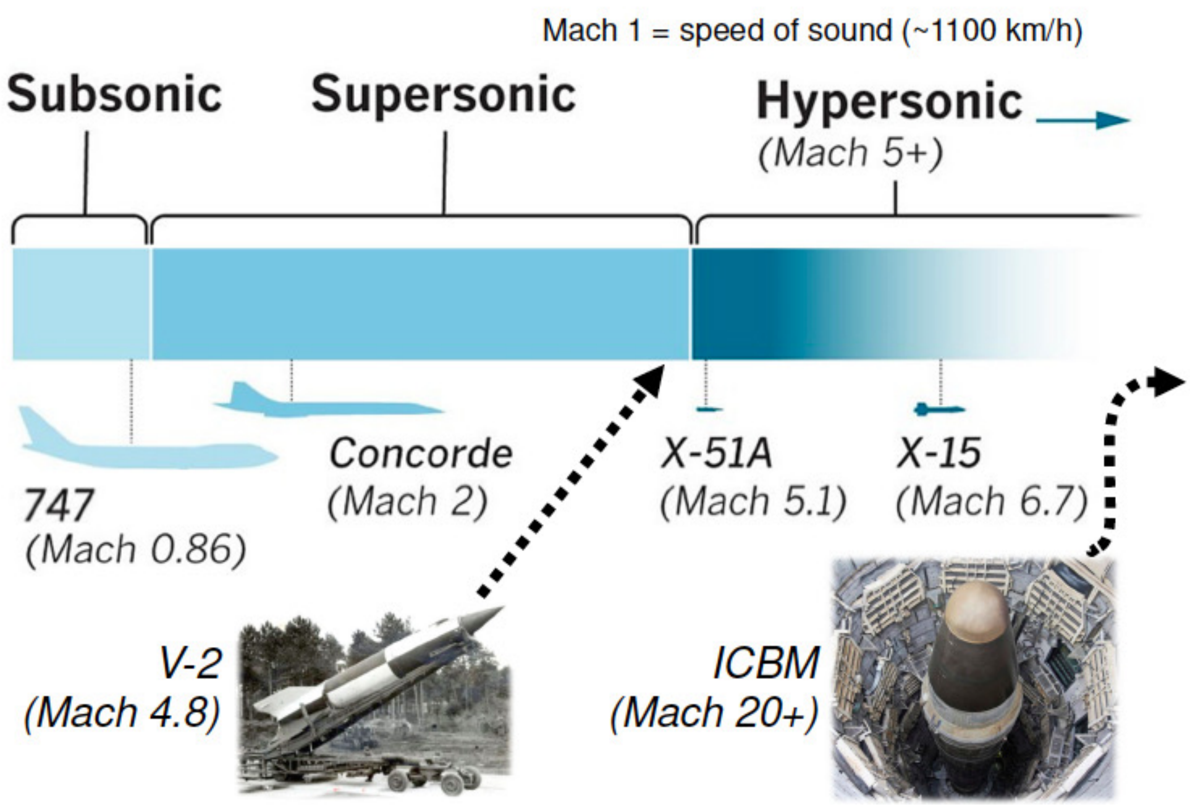
Could this be possible? Is it just propaganda?

The upright cylinder is what's left of a captured Kinzhal displayed in Kyiv on 12 May

hypersonic flight

Speed regimes

- subsonic: velocities lower than the speed of sound in the atmosphere (Mach 1 ≈ 1100 km/h ≈ 0.33 km/s)
- supersonic: velocity between Mach 1 and Mach 3
- hypersonic: velocities above Mach 5



ICBMs exceed Mach 20 velocity

Rehentering vehicles:

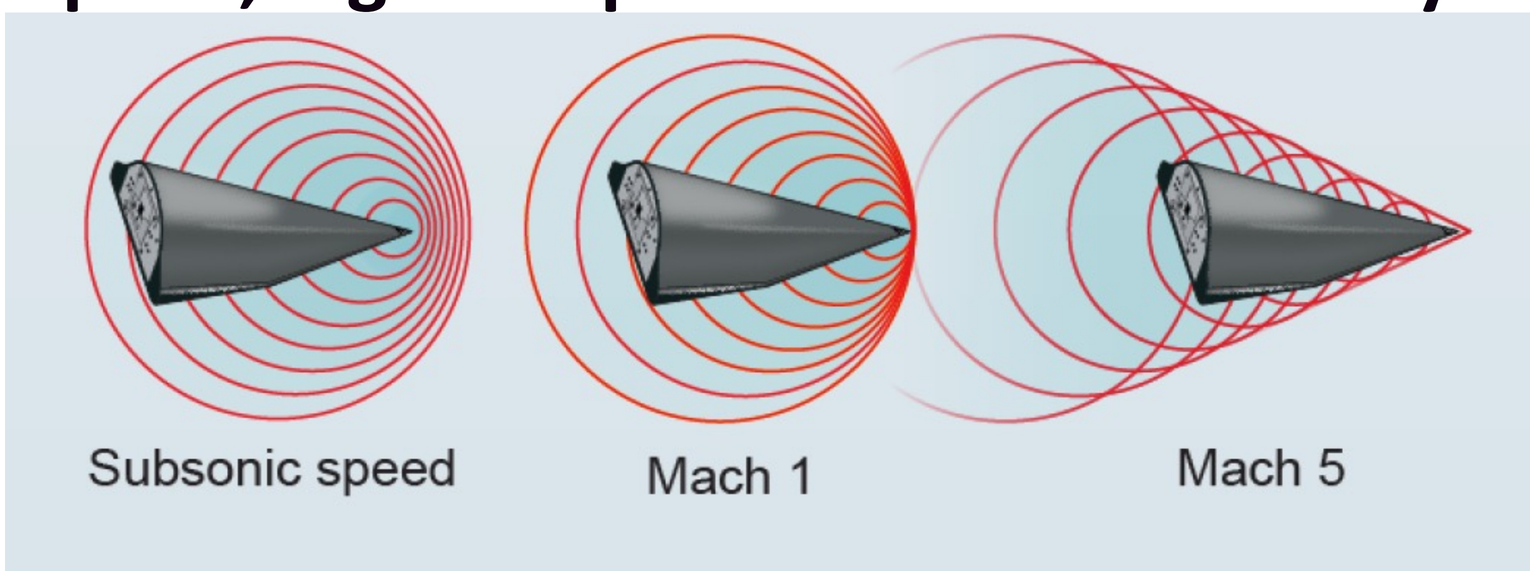
- from orbital stations reach Mach 28
- from Moon flights exceed Mach 32

Shock waves

An object flying faster than Mach 1 generates a shock wave, i.e. a moving layer of dense air.

At hypersonic speeds, the angle the shock wave makes with the direction of motion is very narrow and hugs the aircraft's body.

The thin region between the body and the shock wave contains high-speed, high-temperature and chemically unstable air.



The hypersonic regime poses more and more serious problems with increasing speed due to:

- **highly non-linear gas-dynamics**
- **thermodynamics far from equilibrium with critical entropy gradients**
- **chemical alterations of the air flow**
- **ionization processes and plasma formation**

All these phenomena are sharpened with the square of the Mach number

Physical effects are different on the various parts of the vehicle

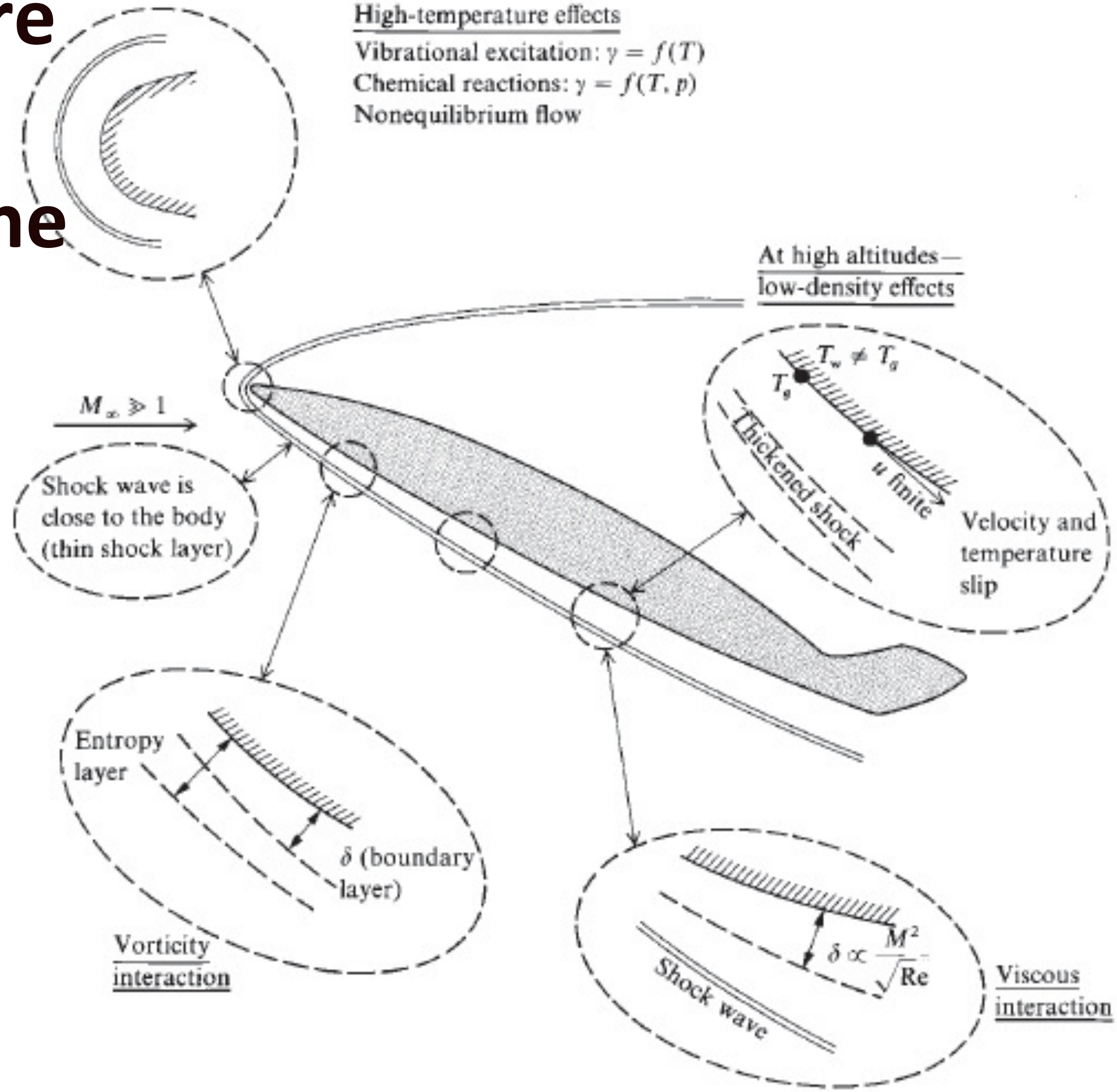
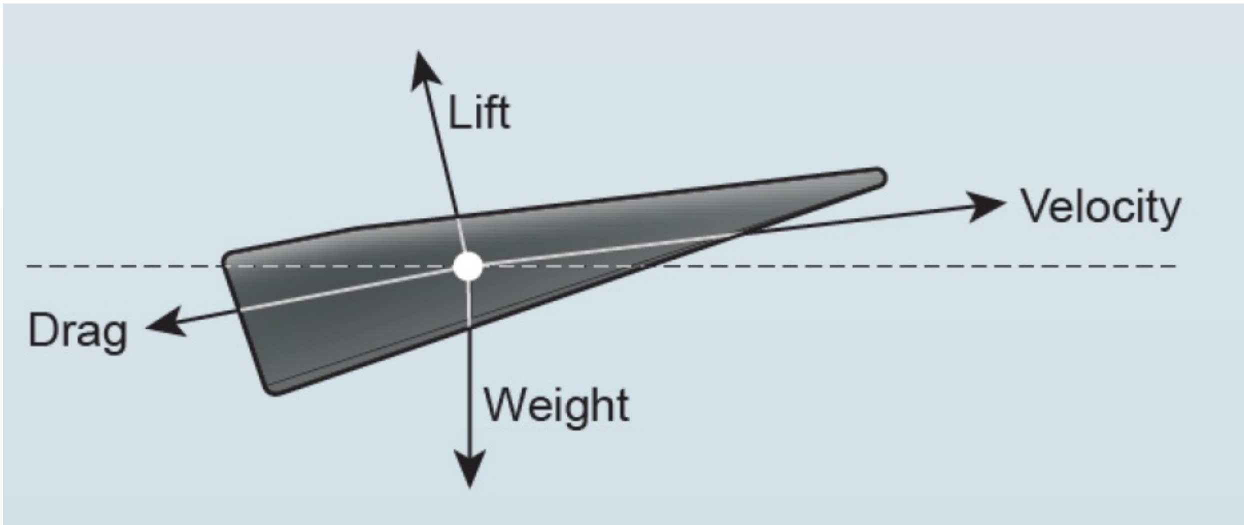


Fig. 1.20 Physical effects characteristic of hypersonic flow.

Gravity, lift and drag govern flight trajectories

An aircraft stays aloft and manoeuvres using lift L, a force perpendicular to the velocity vith respect to the air.



The lift L must be equal to the weight, and a slightly higher for manoeuvring vehicles

$$L \propto C_L \, \rho \, v^2$$

Therefore, for a given vehicle design and velocity *v*, a minimum density ρ (or maximum altitude) exists to maintain the needed vehicle lift. As the velocity decreases, the density must increase to maintain the same lift, i.e., the altitude decreases.

Drag

The drag D is the resistance faced by an object as it pushes through a fluid; it increases in proportion to the square of its speed

$$\mathrm{D} \propto C_D\, \rho\, v^2$$

It poses an enormous obstacle to hypersonic flight, slowing down gliders and making them harder to manoeuvre.
Making matters worse, drag drains kinetic energy from the vehicle, converting it to shock waves and thermal energy in the surrounding air; temperatures up to several thousand degrees are reached.

Aerodynamic efficiency

The fundamental parameter for gliding and slowing down is aerodynamic efficiency, i.e. the L/D ratio between lift and drag

- ▻ **the maximum value of L/D = 4 + 12/M**
- ▻ **for subsonic aircraft (M < 0.3) L/D reaches 30 – 40**
- ▻ **for supersonic aircraft L/D < 4.5**
- ▻ **for hypersonic vehicles L/D < 3?**

Such low L/D ratios for hypersonic vehicles mean low lift and high drag—which limits the speed and range of a hypersonic glider, reduces its manoeuvrability and increases surface heating.

Aerodynamic efficiency and glide range

The glide range from altitude *h* at subsonic velocities is

$$\text{L/D} \times \left(h + \frac{v^2}{2g}\right)$$

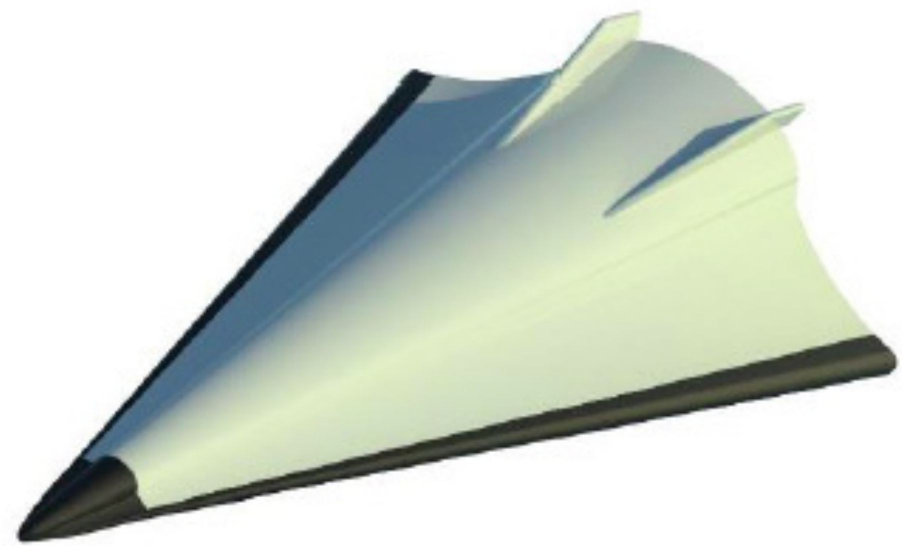
An airliner with L/D about 20 can glide at least 20 times the initial altitude: over 200 km from an altitude of 10 km (at Mach 1 the kinetic term is about 4.5 km)

"Waveriders" for higher aerodynamic efficiency

A wedge shape can match the shock-wave pattern of the airflow around the glider, enclosing part of the shock wave under the vehicle itself to provide additional lift and to improve vehicle performance by increasing its lift-to-drag ratio (*L*/*D*).
Since the shock pattern depends on the vehicle's speed and altitude, which can change significantly during the glide phase, applying directly this concept to long-range vehicles requires delicate attention.

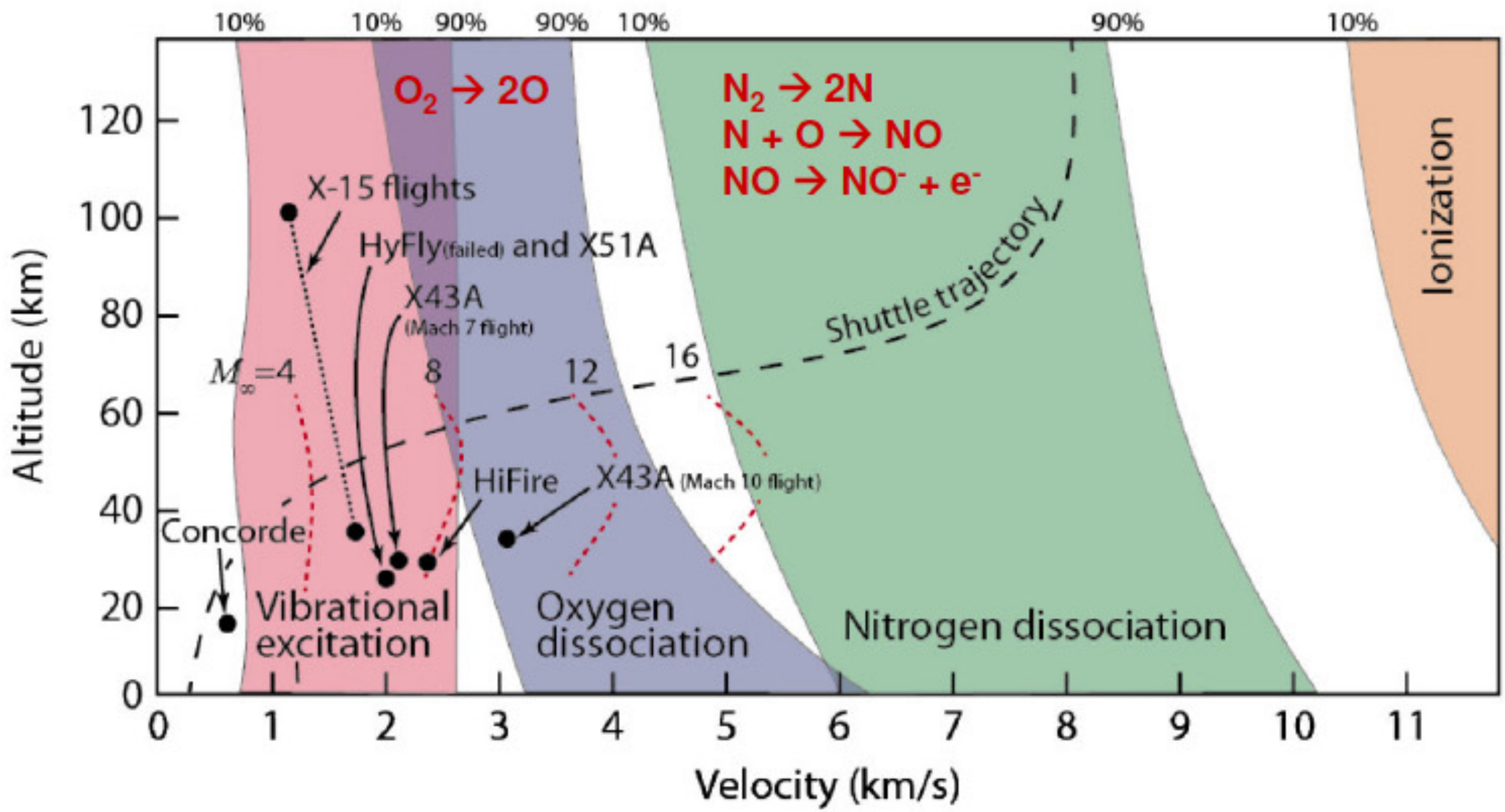
The US HTV-2 demonstrated *L*/*D* of about 2.6 in tests.

the Russian Avangard waverider



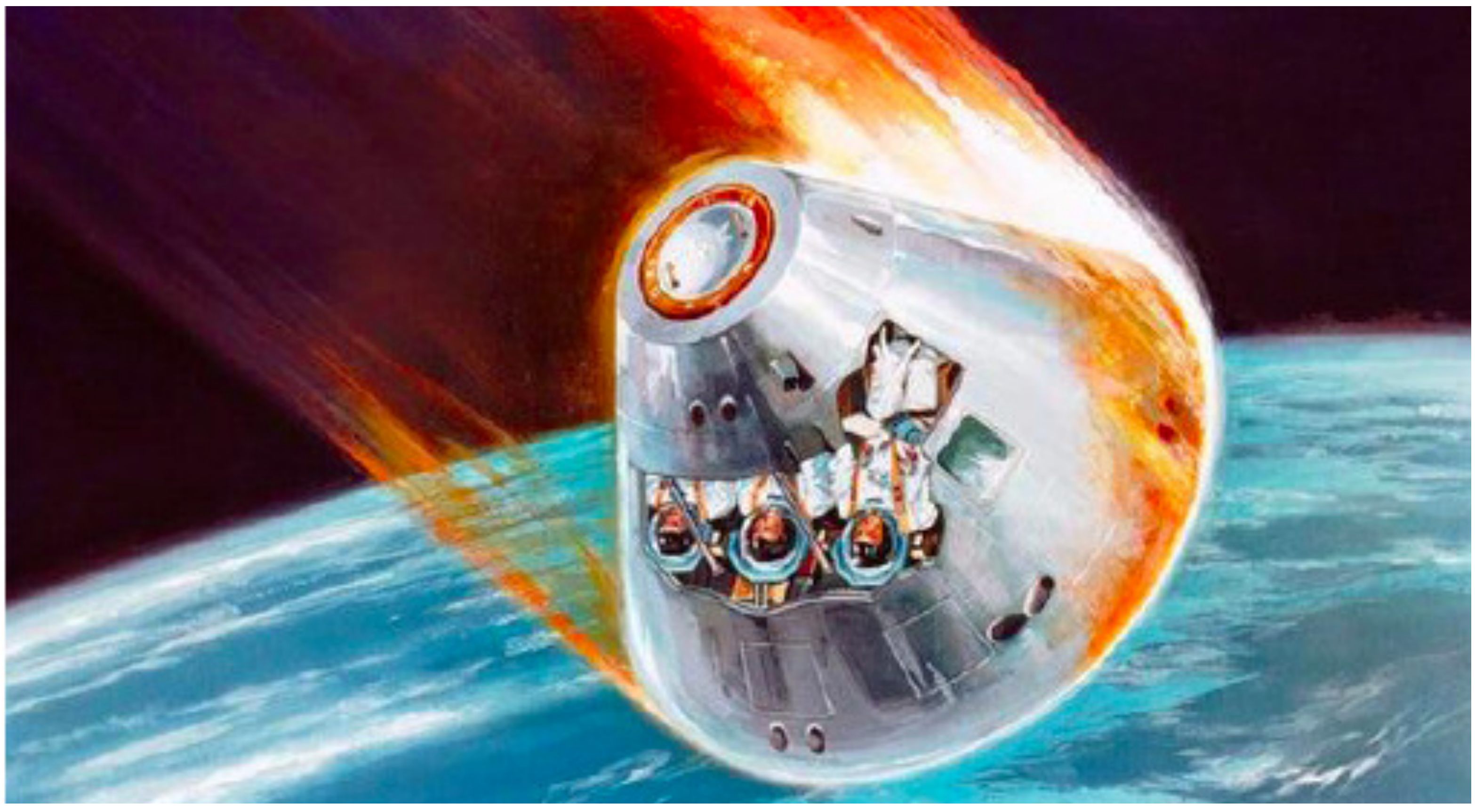
Chemical effects

The shockwaves heat the air to such high temperatures that chemical reactions, vibrational excitation, molecular ionization, molecular disassociation, plasma generation and other changes of the atmospheric particle state are induced.



One effect of ionisation is the creation around the aircraft of a plasma layer, an envelope that prevents the passage of electromagnetic signals of all wavelengths; this makes the vehicle invisible to radars and, on the other side, cuts off receiving and sending any signal

representation of the Apollo module re-entering in its plasma layer



Free molecular flow

The density of the atmosphere falls by a factor *e* = 2.72 for each 8 km increase in altitude; at 80 km altitude it is about 0.00004 times the density at surface.

At high altitudes, the physical characteristics of the atmosphere change considerably, resembling a series of discrete particles instead of continuous airflow, and the motion of individual molecules and their individual impact on the aircraft must be dealt with.

hypersonic weapons

Hypersonic military applications

Ideas that are being considered or developed for militarization in various countries include:

- **hypersonic bombers**
- **hypersonic air-launched ballistic missiles (ALBMs)**
- **hypersonic cruise missiles (HCMs)**
- **hypersonic glide vehicles (HGVs)**
- **high-speed intelligence, surveillance, and reconnaissance (ISR) aircrafts (manned or unmanned)**

the most advanced hypersonic weapons belong to two primary categories (designed for one-time use) both accelerated to hypersonic speed by boosters:

- Hypersonic glide vehicles (HGVs) deplete all their propulsion energy gliding without power to their targets

- Hypersonic cruise missiles (HCMs) rely on lift forces to reach long distances but carry engines to maintain their speed throughout flight

They can be nuclear- or conventionally armed

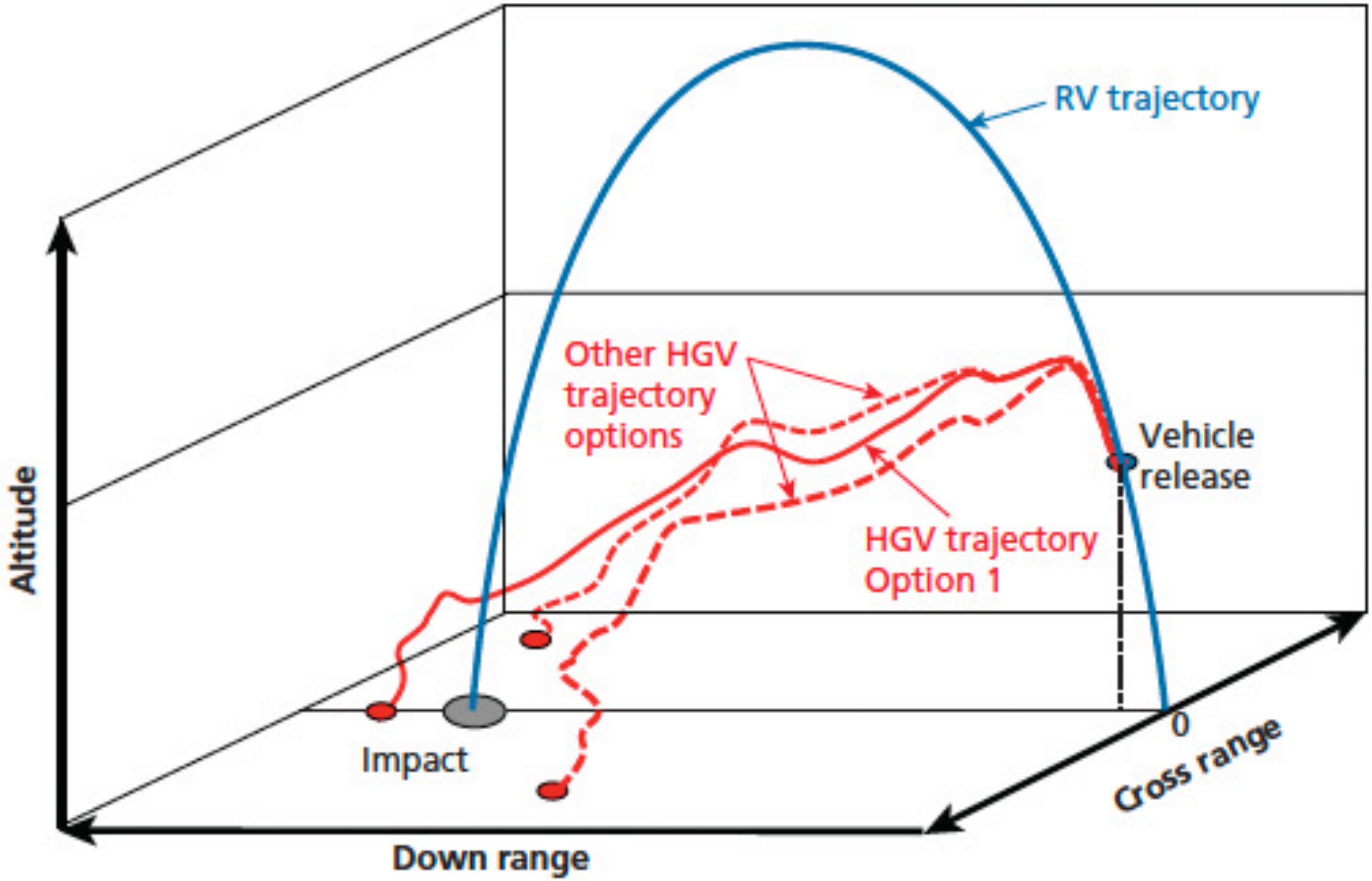
More than hypersonic velocities

What characterizes HGVs and HCMs from ballistic missiles and current cruise missiles is the creation of systems that simultaneously possess

- **hypersonic speed**
- **trajectory that is mostly endo-atmospheric and not ballistic**
- **manoeuvrability along the whole flight**
- **stealth**
- **accuracy.**

In reality, no system can simultaneously achieve optimal performance for each of these properties and compromises must be considered depending on objectives and missions

Comparison of ballistic and HGV trajectories



Common problems of hypersonic missiles

The persistent high speed and long atmospheric flight of hypersonic vehicles result in an extremely severe operating environment requiring advanced new systems, components, materials, design tools, and test facilities, including:

- **thermal management and special materials**
- **vehicle and flight control**
- **testing and modeling**
- **the necessary integration of many critical and complicated subsystems, the failure of each of them leading to the failure of the global system**

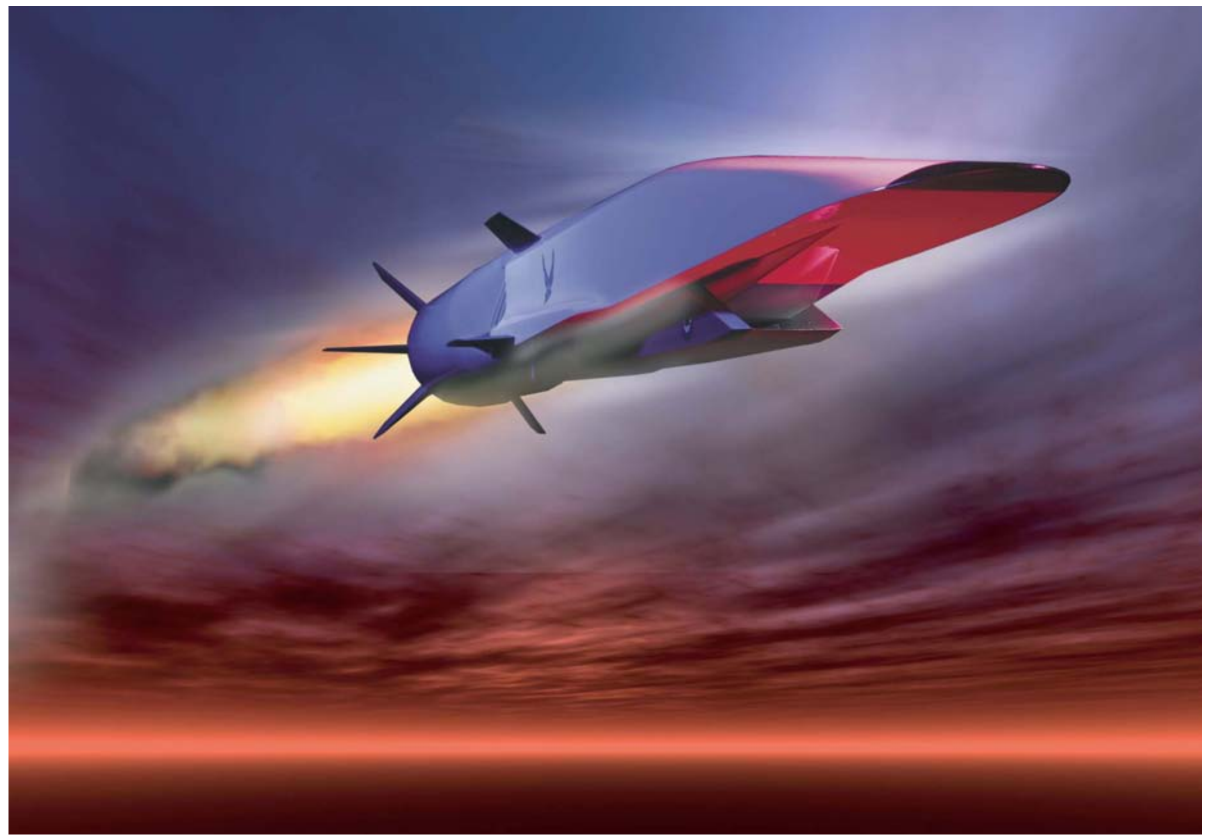
Hypersonic weapons may be disrupted by smaller impacts or perturbations to their structure or surrounding airflow

Hypersonic cruise missiles (HCMs)

HCMs are launched from a rocket or an aircraft at 20–30 km altitude; they are powered by high-speed, air-breathing scramjet engines up to Mach 8 – 10 velocity towards their target, a few thousands km away

x

X-51 wavereider



Air-breathing propulsion is a special challenge at high Mach numbers. Traditional jet engines will not work in this regime, and thus a new type of engine is required.

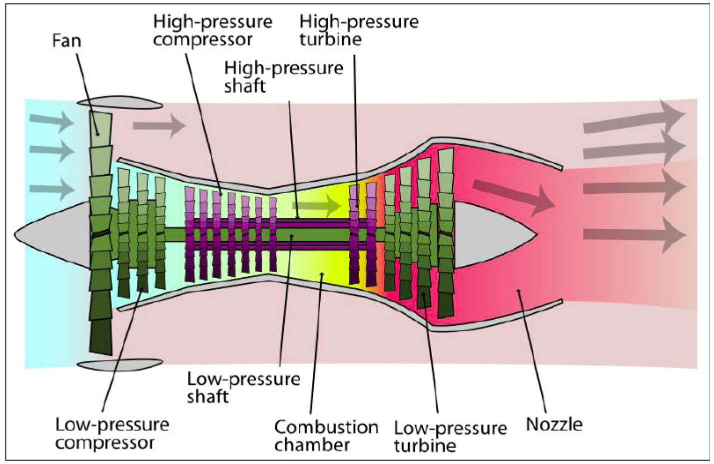
The likely hypersonic engine of choice, the scramjet, functions by allowing the air that passes through the engine to remain essentially at flight speed. This keeps temperatures inside the engine at levels where fuel can still burn.

Timescales in a scramjet become important: the engines that powered the X-51 craft had to swallow air through an inlet, inject and mix fuel into the air, burn that fuel with the air, and exhaust out the nozzle in about a thousandth of a second. This has been likened to lighting a match in a hurricane.

Engines

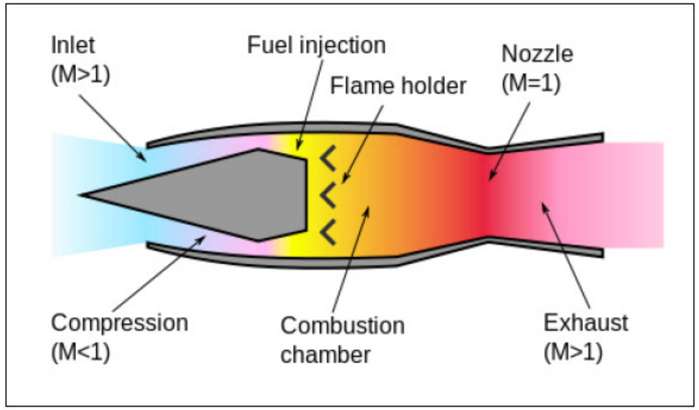
a. turbojet

the incoming flow must be compressed for combustion



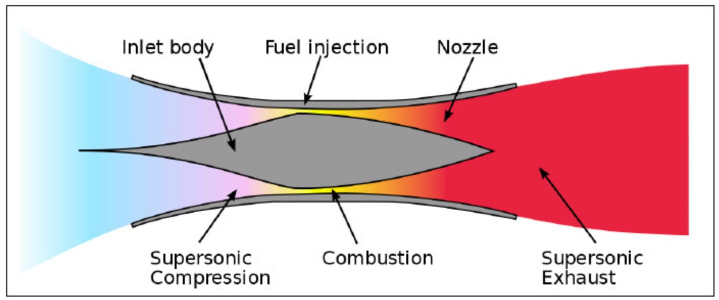
b. ramjet

the incoming supersonic flow is made subsonic for the combustion

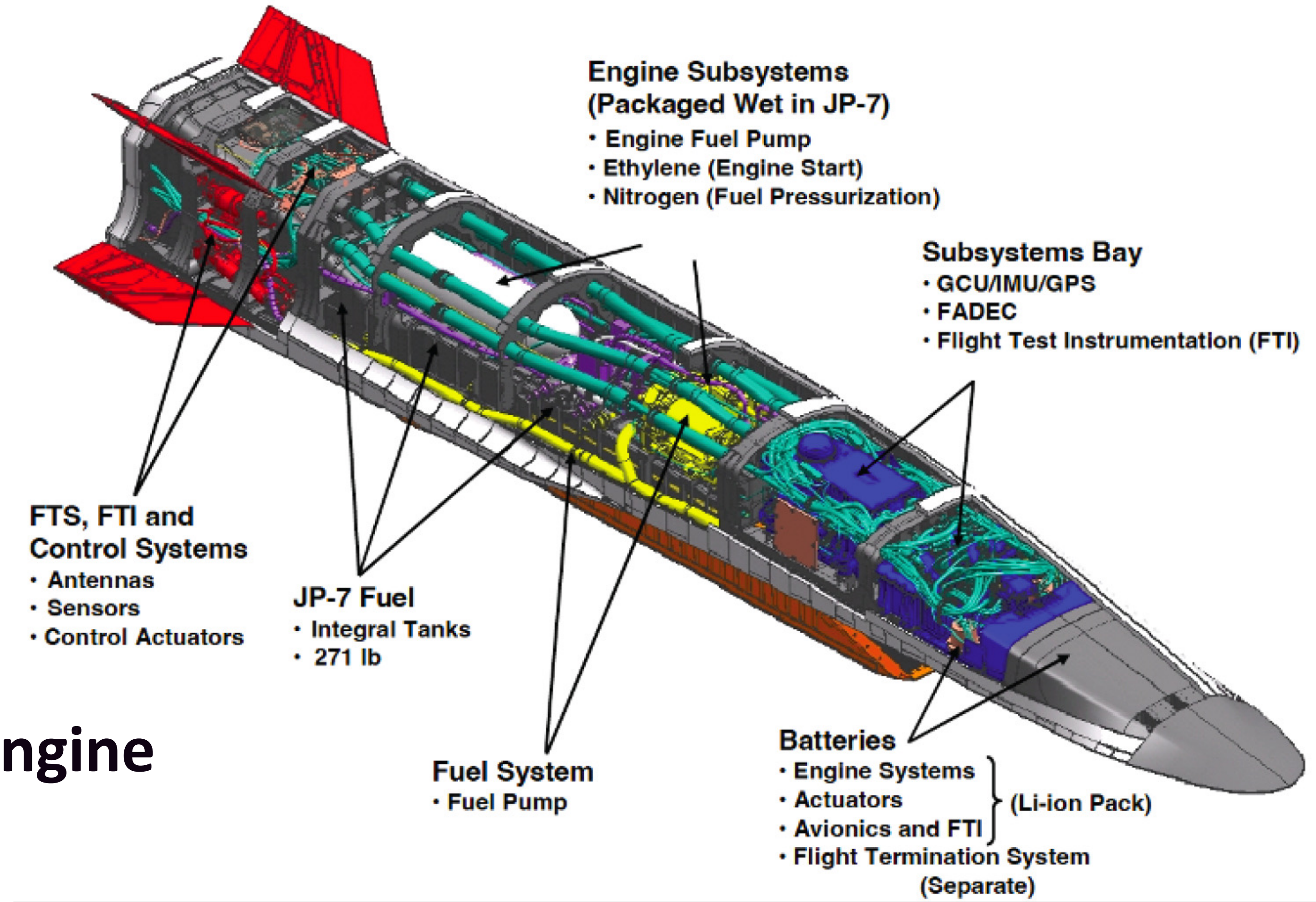


c. scramjet

ramjet with a supersonic combustion



in order to start the scramjet engine the vehicle must reach hypersonic velocities by means of a rocket or a turbine-based combine cycle (inlet-turbine-ramjet)

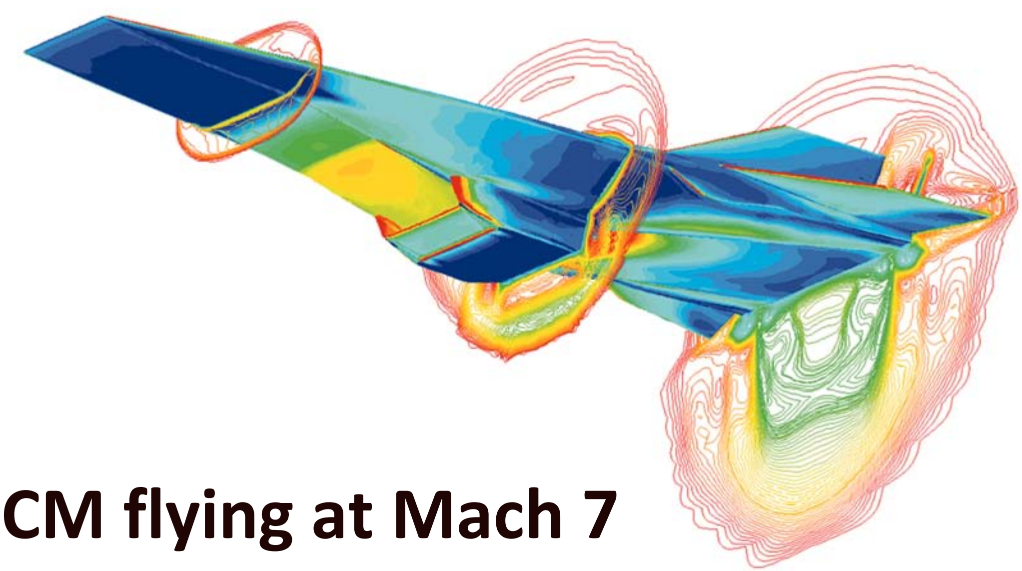


subsystems of an X-51-A scramjet engine demonstrator

Specific HCM problems

HCMs’ propulsion systems (scramjets) have to be highly sophisticated to maintain hypersonic speeds over significant durations. At Mach 6 the incoming flow temperatures can reach 1500℃ and the expelled one 2400℃.

So far, Russia only has started deploying a cruise missile using a scramjet engine, but several countries continue research, development and testing.



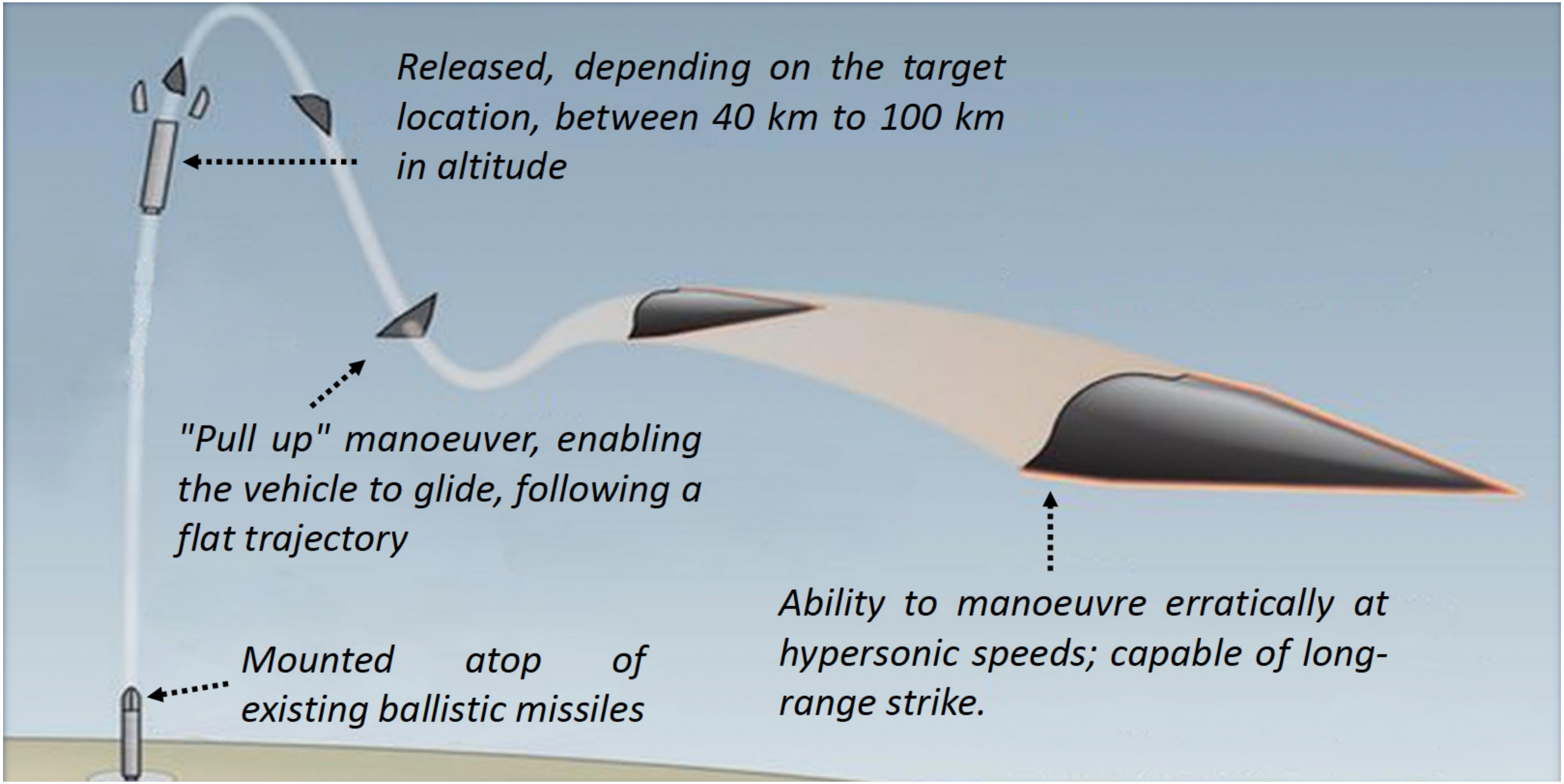
gas-dynamic simulation of a HCM flying at Mach 7

Hypersonic glide vehicles (HGVs)

HGVs are launched from a rocket into a sub-orbital trajectory before re-entering the atmosphere at high altitude (80–90 km) and glide at Mach 20–25 velocity towards a target 8–10 thousands km away

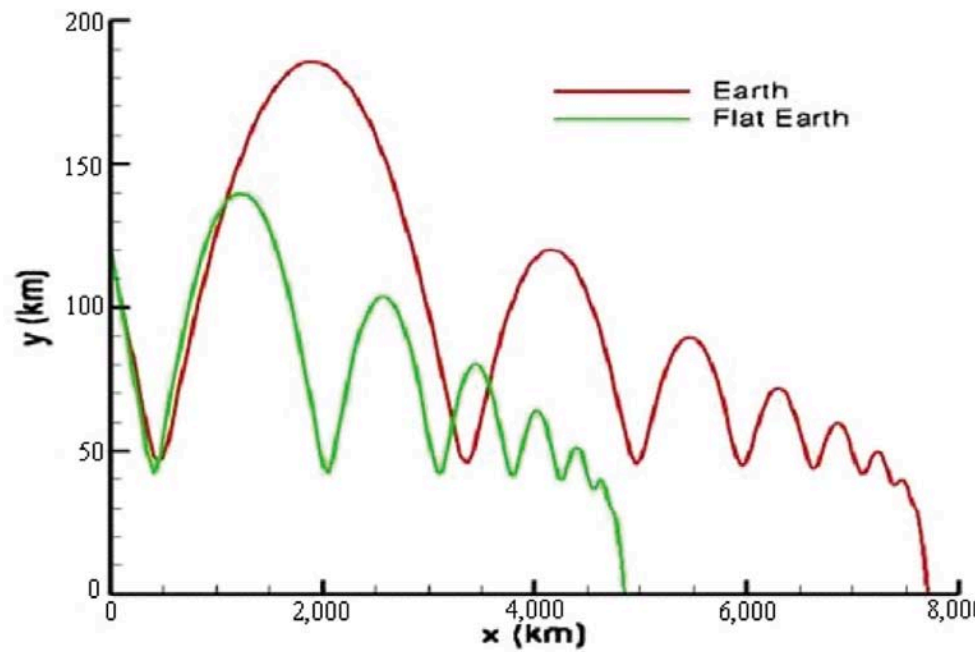
HGVs maintain near constant velocity by trading altitude for speed and deplete their energy gradually

Trajectory of a HGV



Flight phases: 1. Boost phase, 2. Exo-atmospheric phase, 3. Direct re-entry, 4. Pull-up, 5. Equilibrium gliding, 6. In the terminal phase the glider dives toward its target.

Another possibility involves a minimum-energy launch for the carrier missile, with a high apogee and the transition from ballistic reentry to gliding flight at a minimum angle, so that the HGV proceeds with a phugoid (skip-glide) trajectory, in which the aircraft bounces in and out of the atmosphere several times; since most of the flight takes place in vacuum, where drift is almost zero, the HGV can reach great distances



Range of a hypersonic glider

$$l_{GLIDE} = -\tfrac{1}{2} R \times L/D \times \ln[1 - (v_i/v_s)^2]$$

R = radius of the Earth

$v_s = (g\,R)^{1/2}$ = speed of a satellite in low Earth orbit ≈ 7.8 km/s

v_i = glider's initial speed

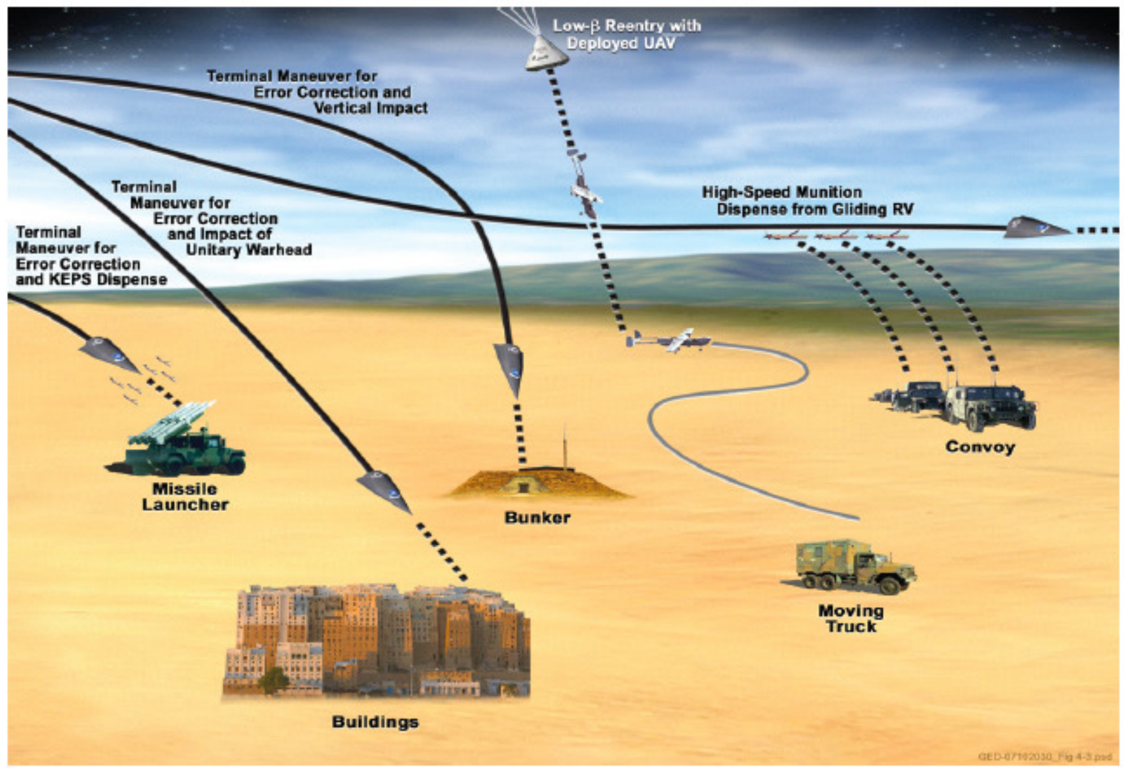
for v_i = 6.6 km/s (Mach 20) and L/D = 2.6

$l_{GLIDE} \approx$ 10 400 km

Armaments

- nuclear warhead
- conventional armaments
  - ▻ high explosive against missile silos or underground targets
  - ▻ fast ammunition to disperse over distributed targets
  - ▻ UAV against mobile systems
  - ▻ kinetic energy projectiles

✦ indicative useful load:
  - ▻ 500 kg for HGV
  - ▻ 200 kg for HCM



Kinetic energy armaments

- kinetic energy projectiles (KEP): a rose of 750 g tungsten cylinders (shock darts) with the energy of 1.5 MJ each (≈ 360 g of TNT) at impact speed 2 km/s

- kinetic energy particles: thousand particles of 75 g mass with energy 150 kJ each at impact speed 2 km/s

- a HGV could potentially rely on its own kinetic energy of impact alone (a mass of 1000 kg at impact speed 2 km/s has an energy of 4 GJ)

* a 20 kJ bullet seriously damages an airplane

HGV problems

HGVs require developing and integrating a guidance and control system, a lightweight airframe and the payload:

- the guidance and control system needs a power source, a computer, sensors, and actuators—such as aerodynamic control surfaces or small cold gas thrusters that enable performing manoeuvres
- airframe requires sufficient thermal shielding
- the actual payloads need space

As a result, HGVs are usually neither small nor light, which significantly impacts the capabilities of the overall system and the necessary trade-offs between some of its capabilities.

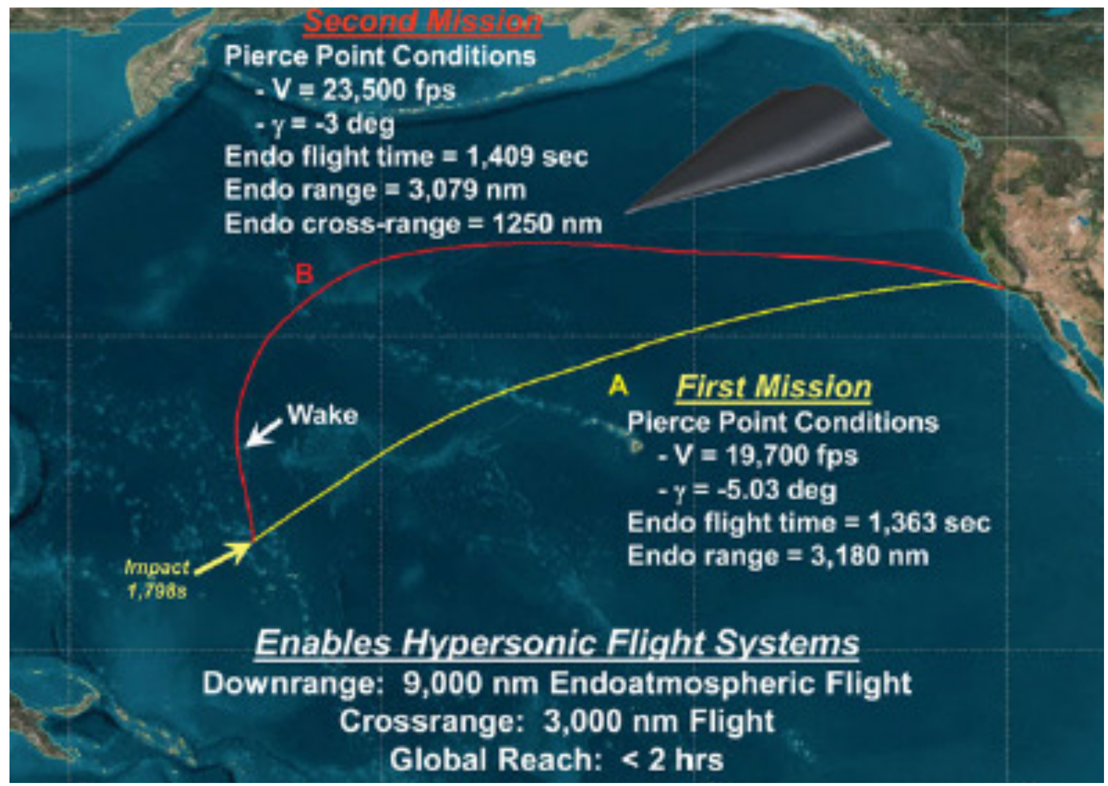
On-board sensors

the performance of all on-board sensor systems, (the Global Positioning System [or Glonass or BeiDou], telemetry, communication, command and control, radar, laser ranging, and electro-optical sensors) are adversely affected to varying degrees by the hypersonic environment, producing:

- **signal attenuation,**
- **communication blackout,**
- **signal distortion due to turbulent flow,**
- **radiation from heated optical windows,**
- **emission from hot flows.**

dispelling the myth

Some information about the (failed) tests (2010-11) of the US wedge-shaped HTV-2 was made available for independent studies of the actual performance of HTV systems.



The physics of hypersonic motion is complicated but affordable in terms of a system of coupled differential equations for the basic variables (the 3-dimensional velocity components and altitude)

David Wright and Cameron L. Tracy 2020, 2023 [nuclear experts "not disappeared"]

$$\frac{dv}{dt} = -\frac{C_d A}{2m}\rho v^2 - g\sin\gamma \tag{1}$$

$$\frac{d\gamma}{dt} = \frac{v\cos\gamma}{r_e + h} + \left({}^{L}/{}_{D}\right)\left(\frac{C_d A}{2m}\right)\rho v\cos\sigma - \frac{g}{v}\cos\gamma \tag{2}$$

$$\frac{d\kappa}{dt} = \left({}^{L}/{}_{D}\right)\left(\frac{C_d A}{2m}\right)\frac{\rho v\sin\sigma}{\cos\gamma} \tag{3}$$

$$\frac{d\Psi}{dt} = \frac{v\cos\gamma\cos\kappa}{r_e} \tag{4}$$

$$\frac{d\Omega}{dt} = \frac{v\cos\gamma\sin\kappa}{r_e} \tag{5}$$

$$\frac{dh}{dt} = v\sin\gamma \tag{6}$$

Glider's equation of motion flying over a spherical Earth

four forces govern flight trajectories: gravity, lift, drag, and an apparent centrifugal force arising from flying over a spherical Earth

$$\tfrac{1}{2}\,[(L/D)\,g\,\rho\,v^2]/\beta + v^2 / R - g = 0$$

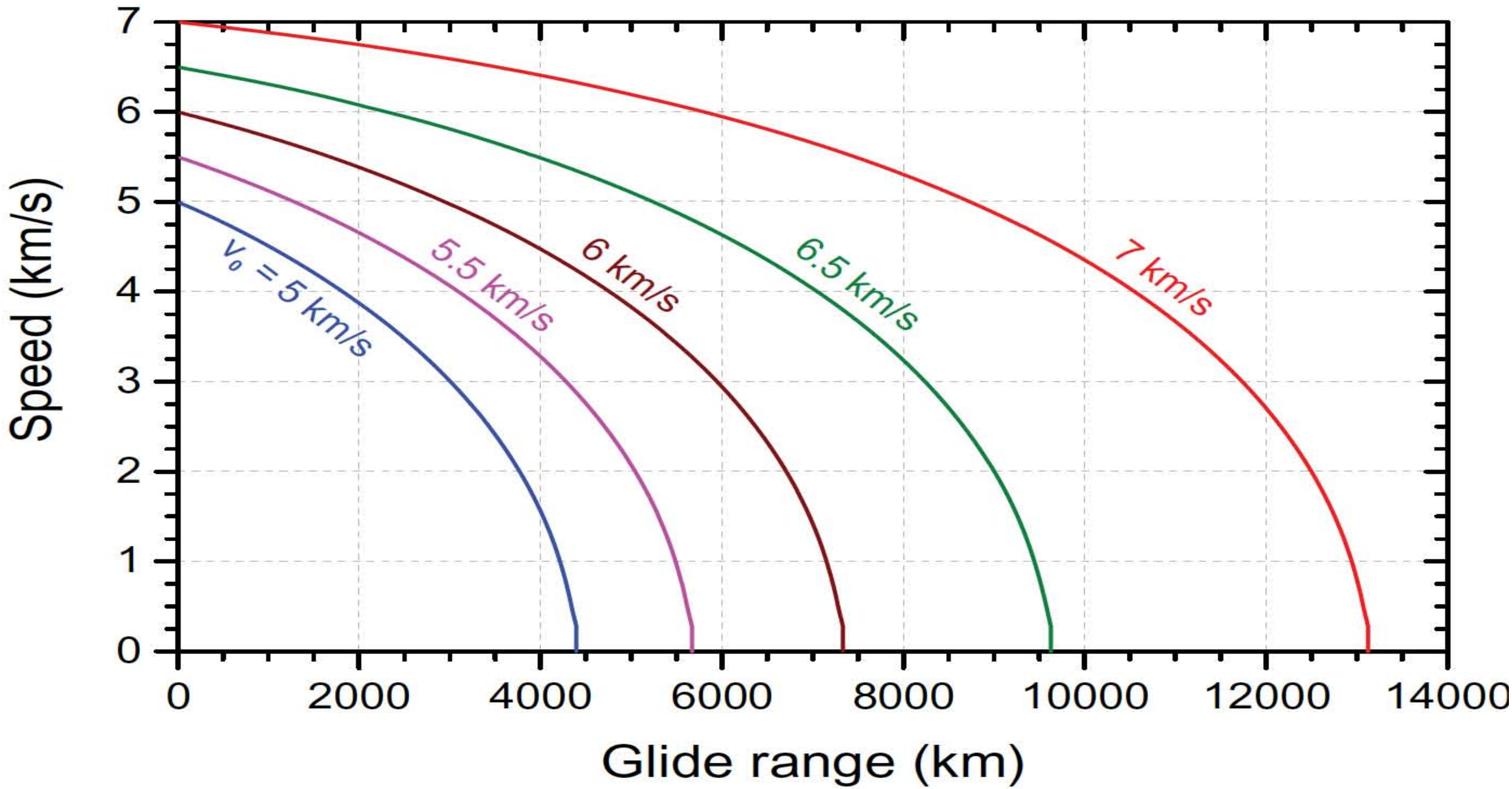
ρ = air density
R = radius of the Earth
v = glider's initial speed
β = ballistic coefficient = $m/(C_D\,A)$
- m = glider's mass
- A = glider's cross–sectional area
- C_D = drag coefficient

g = gravitational acceleration

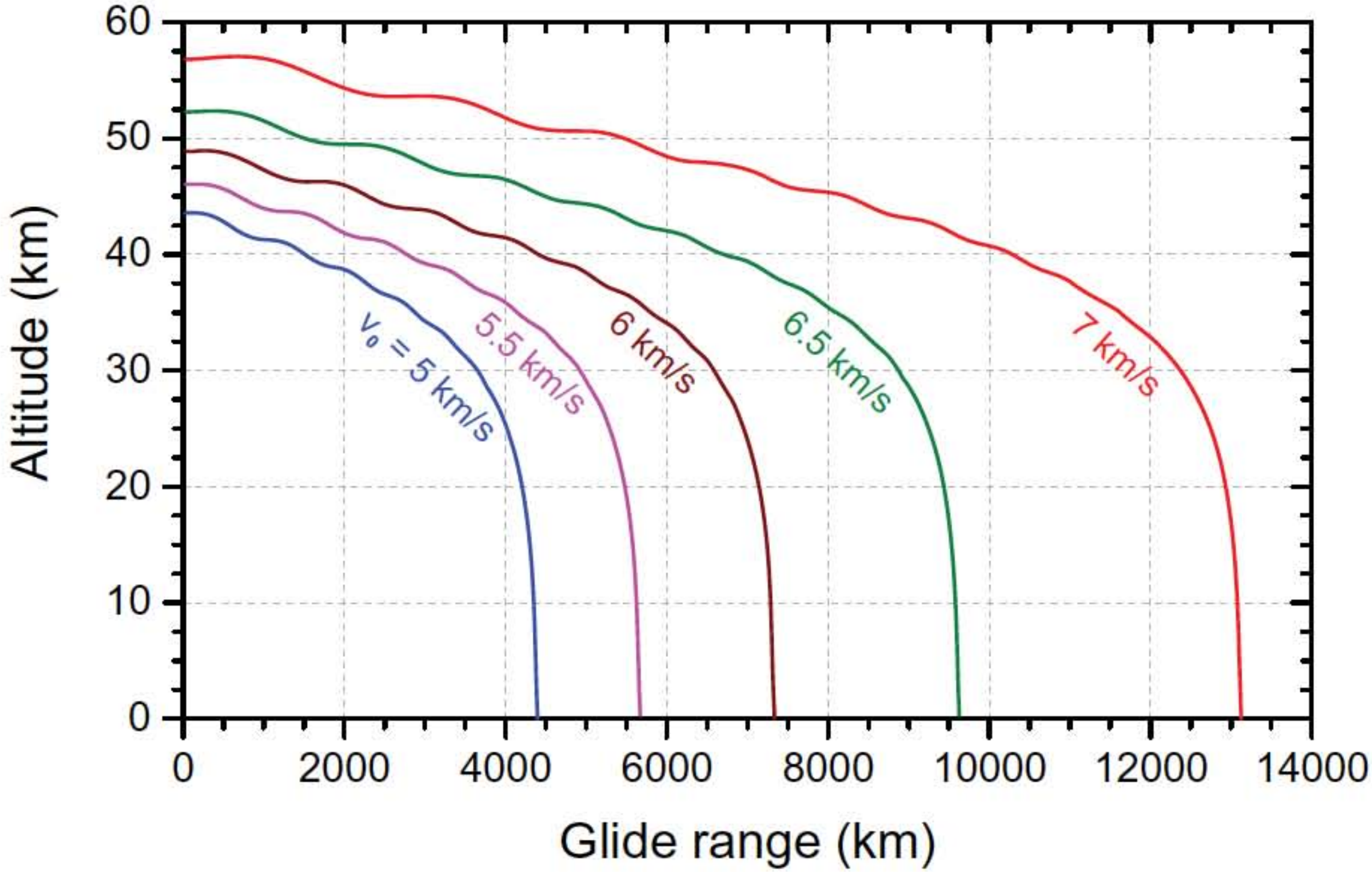
Tracy and Wright, 2020

“unmatched speed”

A glider’s velocity cannot remain constant during the complete flight: it continuously decreases due to drag



As a glider's velocity decreases due to drag, its equilibrium flight altitude also decreases. A glider must drop to lower altitudes where denser air can provide sufficient lift to keep it aloft. Continuous hypersonic flight is therefore constrained to a relatively narrow altitude-velocity corridor.

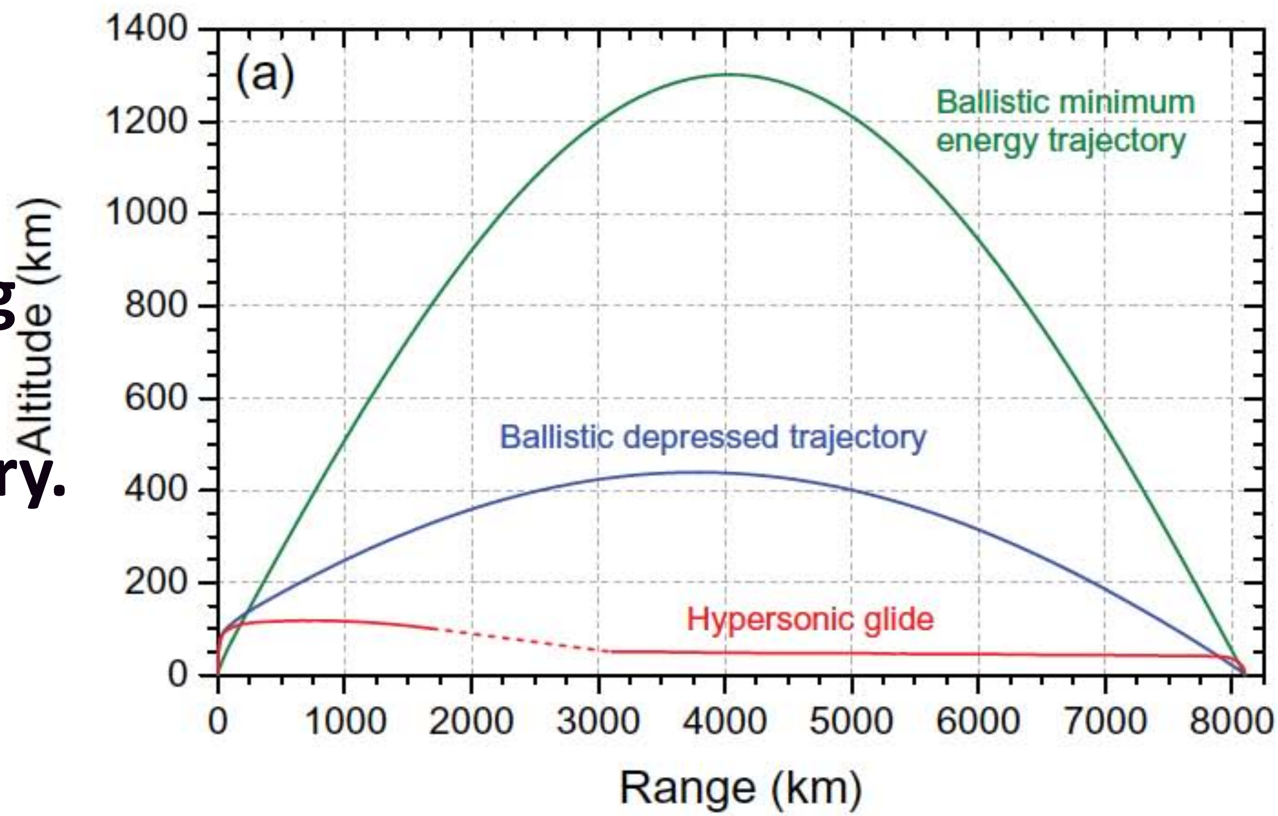


Depressed trajectory ballistic missiles

The most energy-efficient path for a ballistic missile (the minimum-energy trajectory) sends a warhead arcing high above Earth before it falls to its target.

Yet a ballistic missile can instead fly at lower altitude (the depressed trajectory), requiring higher boost power.

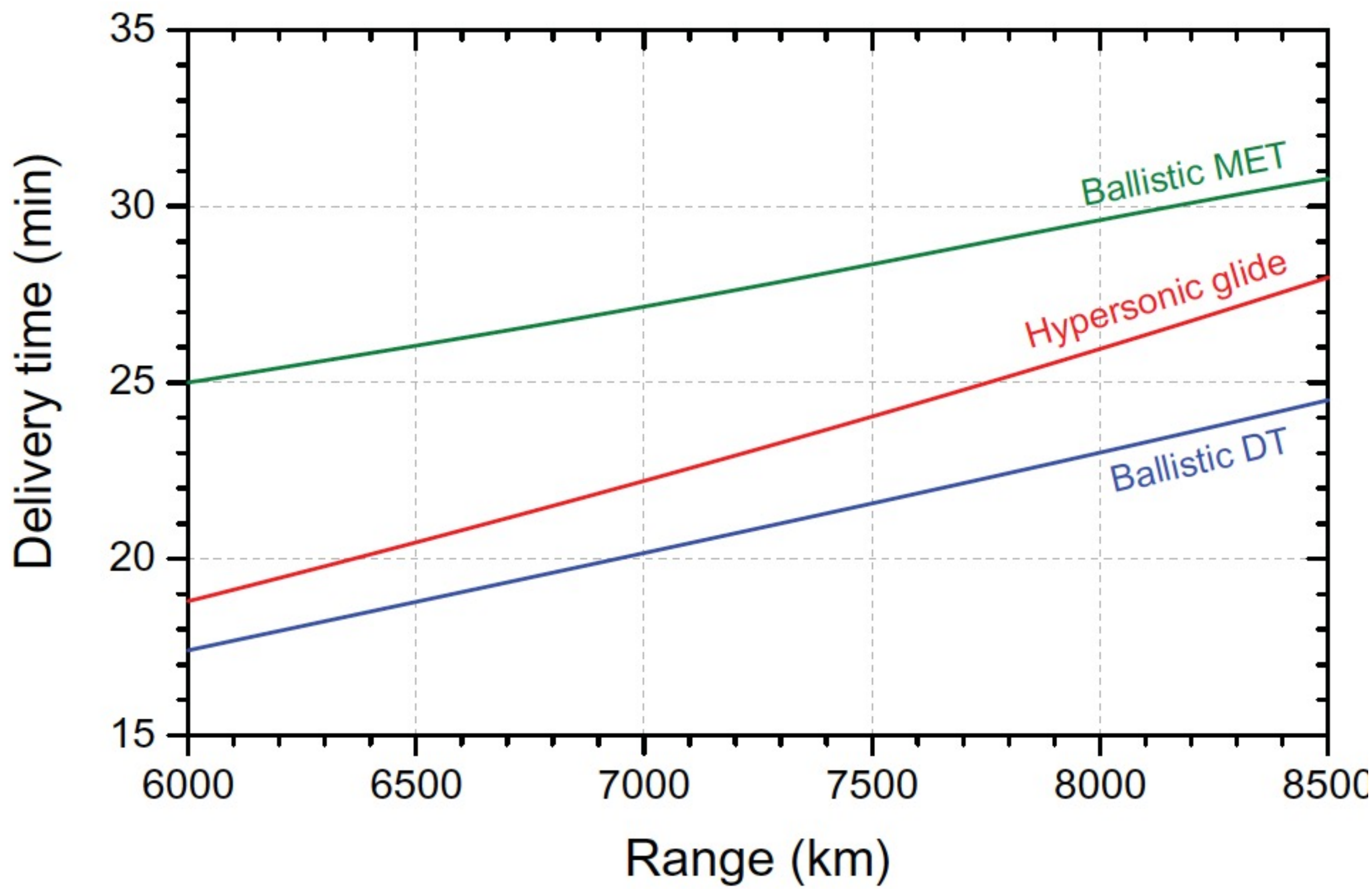
Such a path would be much shorter than a minimum-energy one, and a warhead following it would also avoid drag over most of its trajectory.



“unmatched speed”

Ballistic missiles fired on depressed trajectories reach their targets most quickly. Their delivery time advantage over hypersonic gliders increases with range.

Calculated total delivery times for a hypersonic missile and a ballistic missile flying both minimum energy and depressed



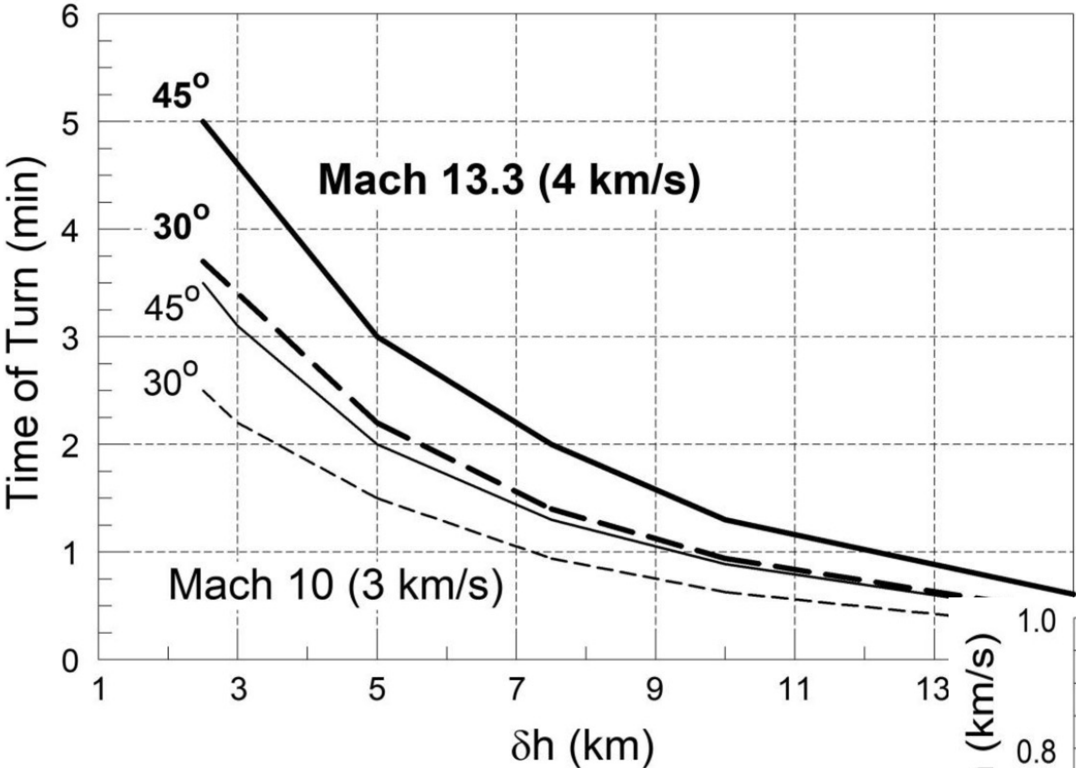
“manoeuvrability along the whole flight”

To change direction, a hypersonic glider must use lift forces to impart a horizontal velocity—which itself has to be hypersonic. At the same time, the glider must retain enough vertical lift to stay aloft. To generate the extra lift needed to change direction, the vehicle could dive to a lower altitude to use the greater push from denser air.
It would make its turn before returning to a higher altitude, with less drag, to resume its flight.
Such manoeuvres can cost significant speed and range.

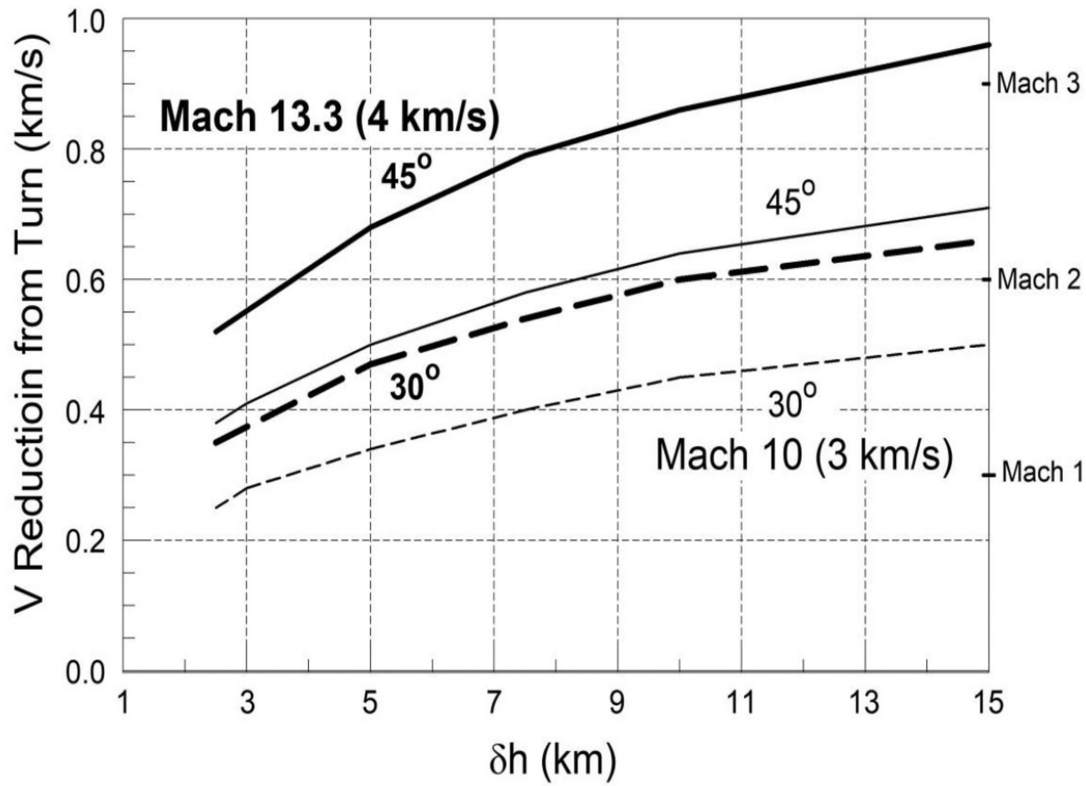
For example, to turn by 30 degrees, a glider as the HTV-2 flying at Mach 15 (4.5 km/s) at an altitude of about 40 km, must generate a horizontal velocity of Mach 7.5 (2.3 km/s).

If it drops by about 2.5 km, then turning by 30 degrees would take about seven minutes, during which it would travel along a vast arc, with a radius of some 4,000 km.

The extra drag that comes from traveling in denser air for such time would reduce the glider's speed by about Mach 1.3, causing it to lose about 450 km of range out of the 3,000 km it might otherwise have traveled.



time required for the HGV to turn through the angles of 30° and 45° by dropping in altitude *δh*

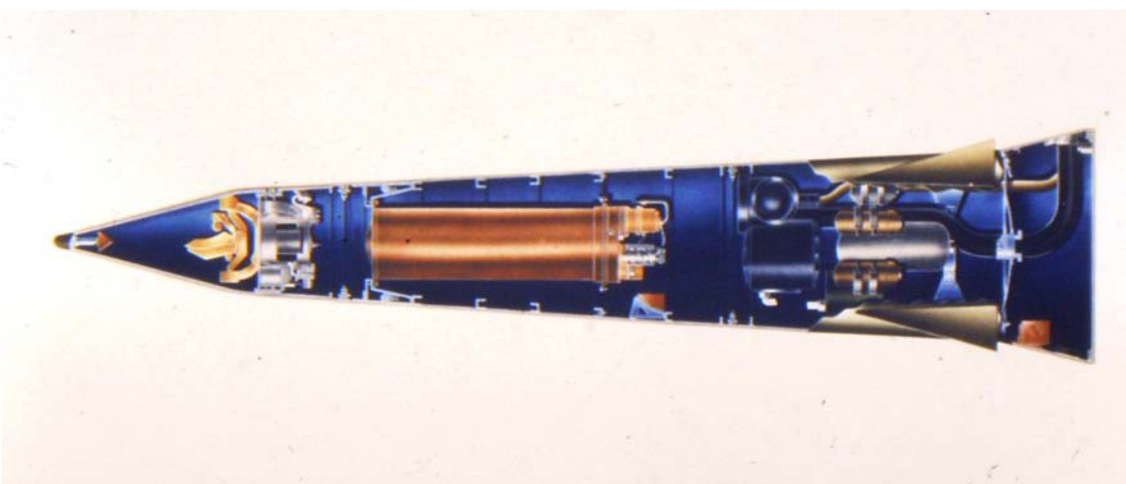


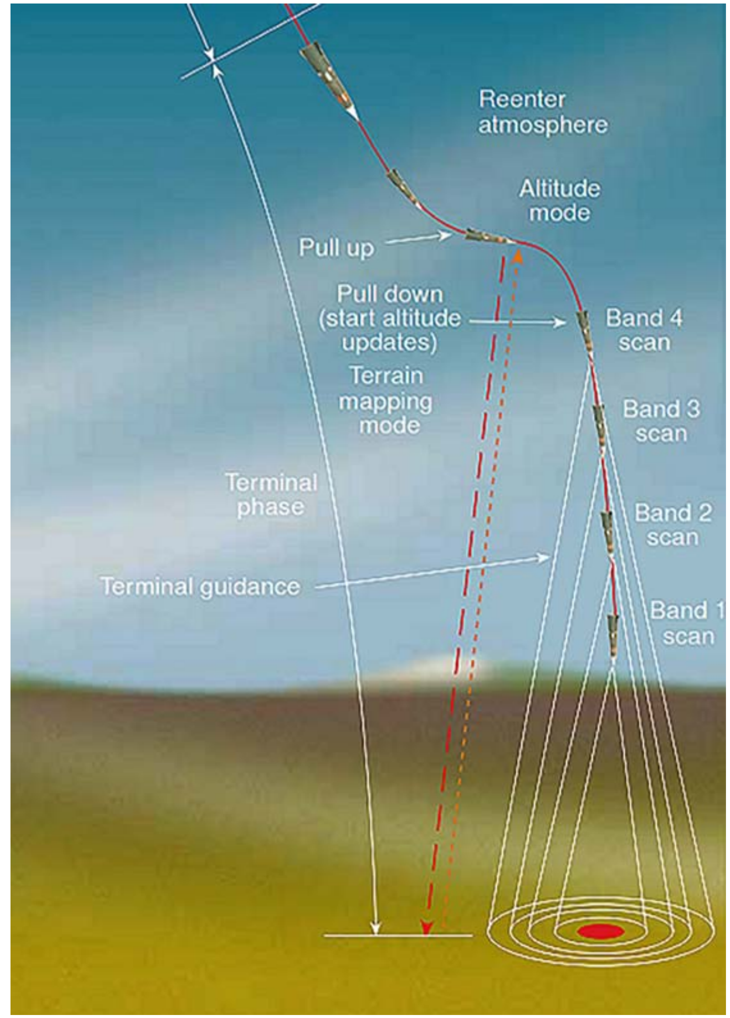
decrease in HGV speed resulting from turns, relative to the speed it would have after traveling the same distance without turning

Manoeuvring re-entry vehicle (MaRV)

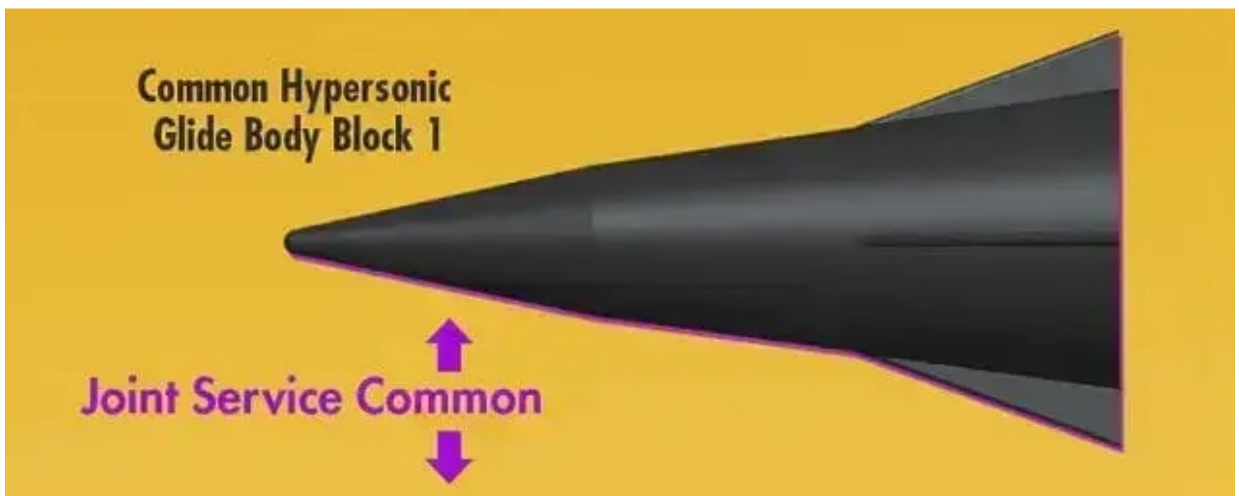
A MaRV uses atmospheric forces to manoeuvre during the terminal phase of missile flight, relying on a flap (fin) system to provide the lift necessary for manoeuvres.

This could allow it to dodge terminal defences, to use terminal guidance for high accuracy, to retarget over hundreds of km, and to dive to its target at a steep angle.



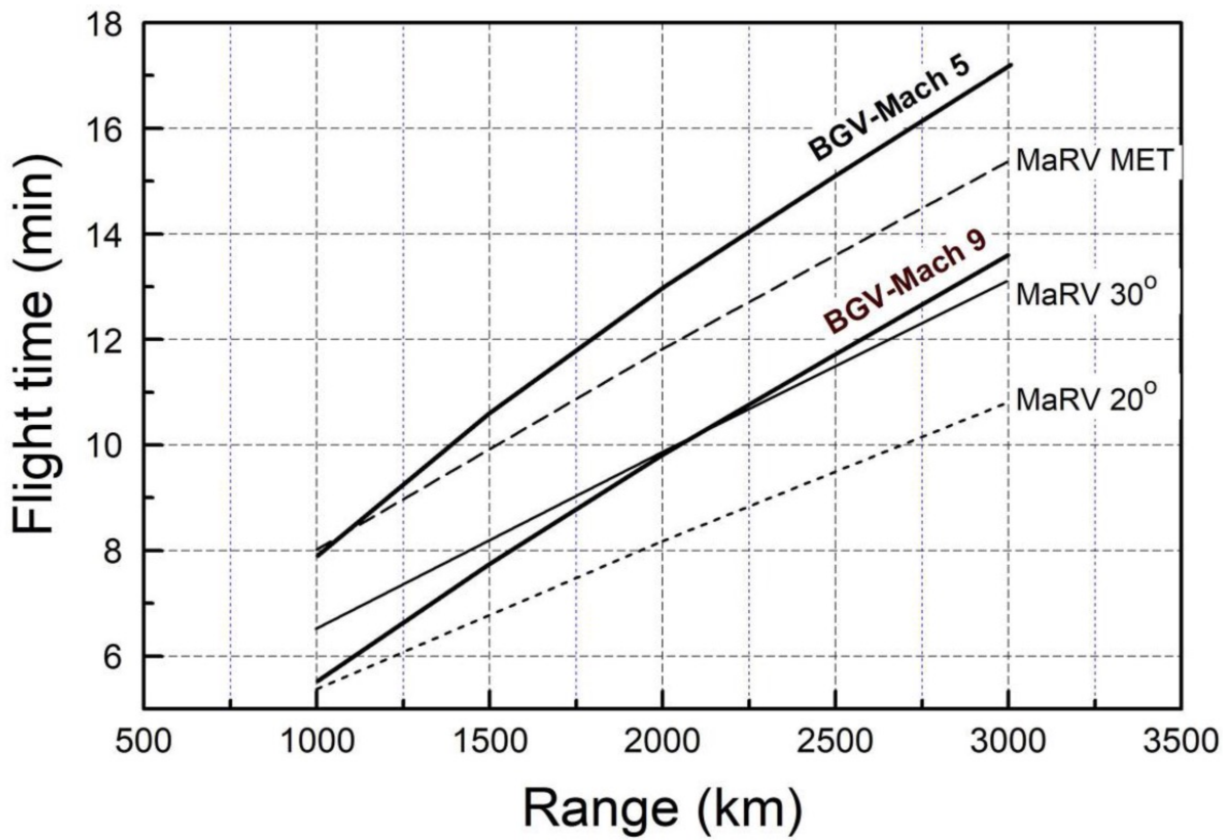


Unlike hypersonic gliders, MaRVs cannot manoeuvre significantly during midcourse flight or fly for long distances at altitudes below 50 km, and do not take advantage of glide to substantially increase their flight ranges.
In terms of capabilities, however, shorter-range hypersonic gliders are virtually indistinguishable from MaRV-tipped ballistic missiles flying on depressed trajectories.
In 2018, for a hypersonic vehicle intended for joint use by the army, navy and air force, the Pentagon chose an older conical design based on an experimental MaRV originally developed in the 1970s.



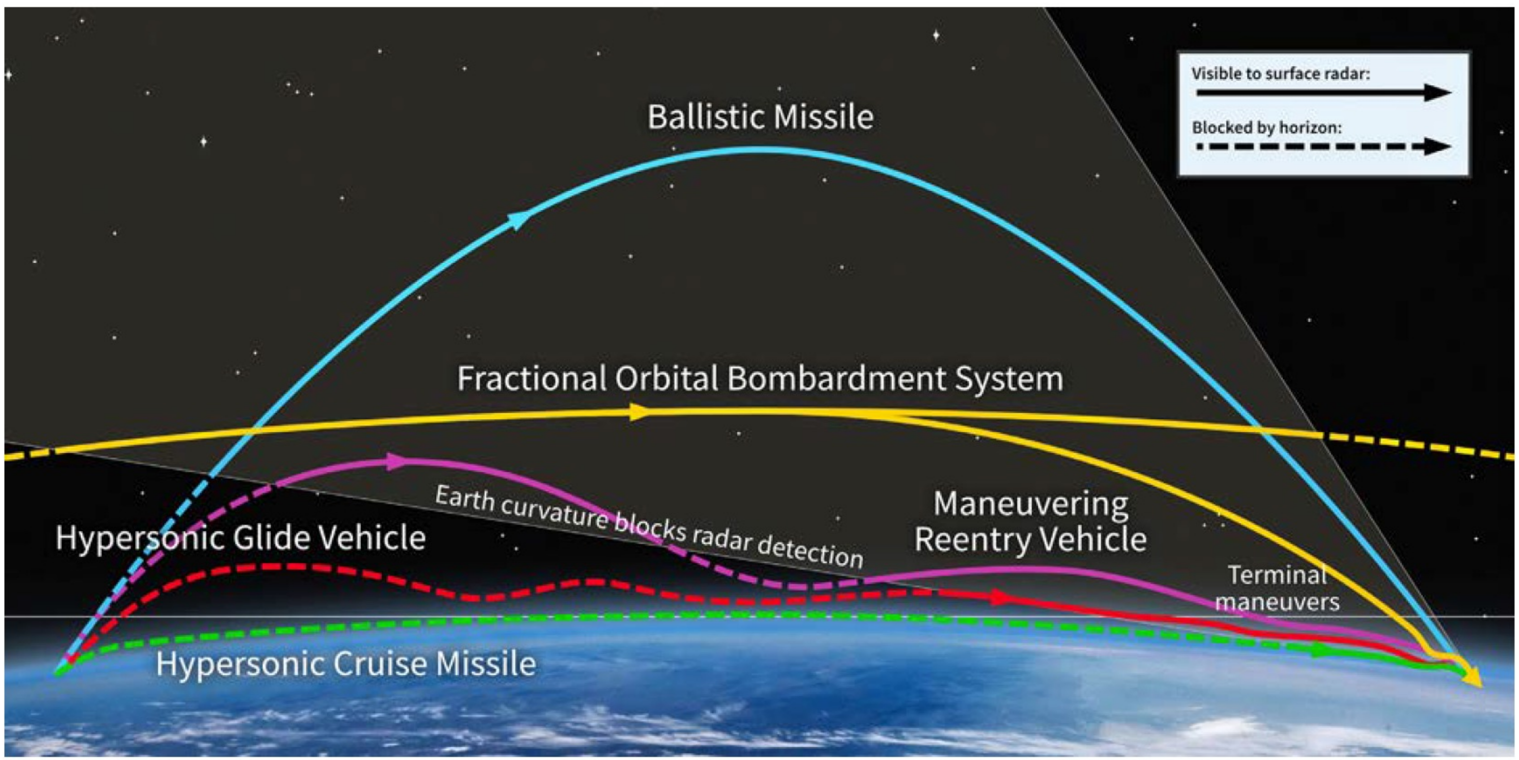
“unmatched speed”

Flight time of HGVs and MaRVs of the same mass as a funtion of range



“nearly invisible to early-warning systems”

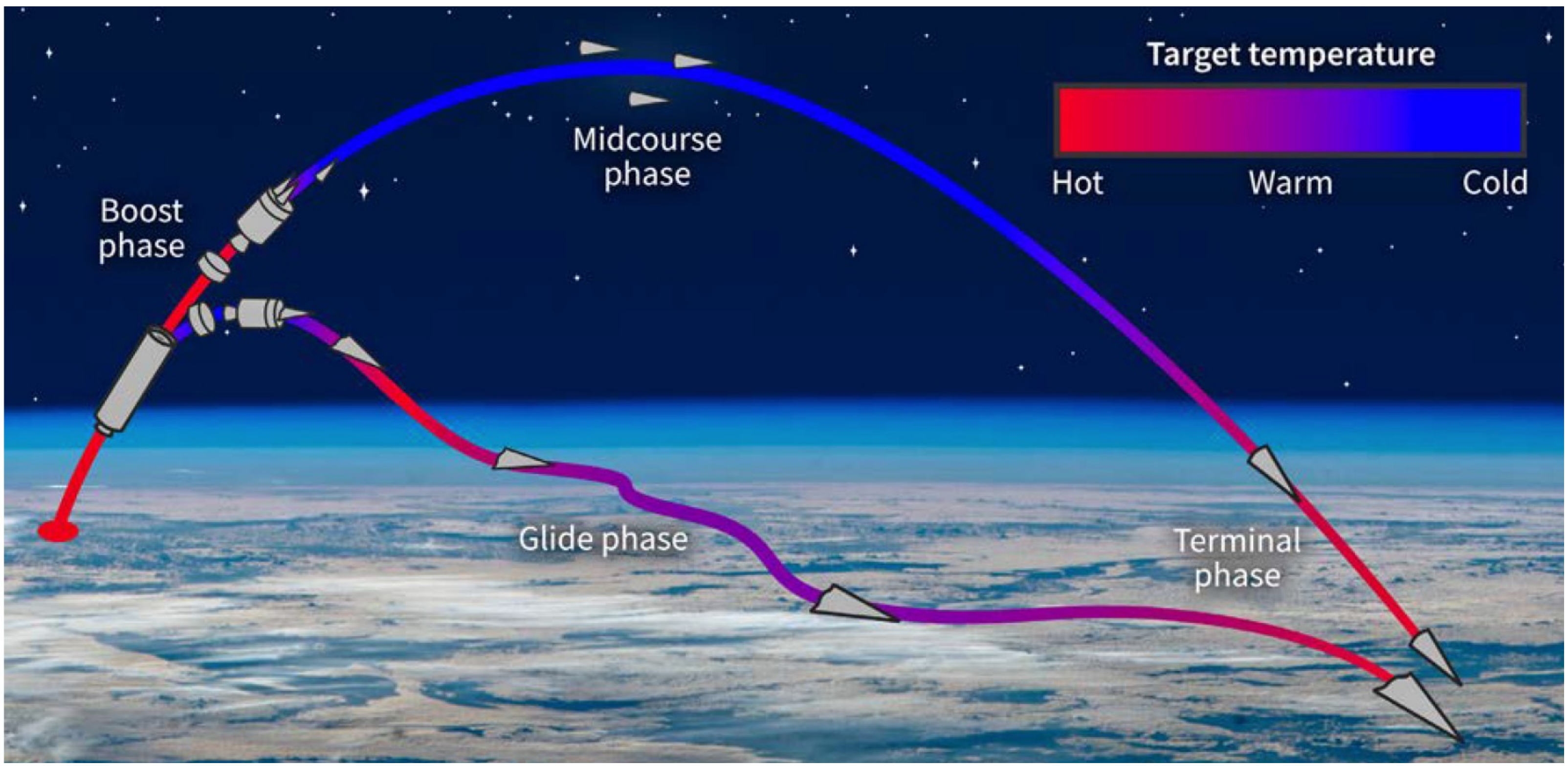
A ground-based radar system can spot a warhead at an altitude of 1,000 km from about 3,500 km away, but because of the Earth’s curvature it would not see a glider approaching at a height of 40 km until it was only about 500 kilometers away. The formation of a high-temperature plasma sheathe around a hypersonic glider might also alter its radar cross section.



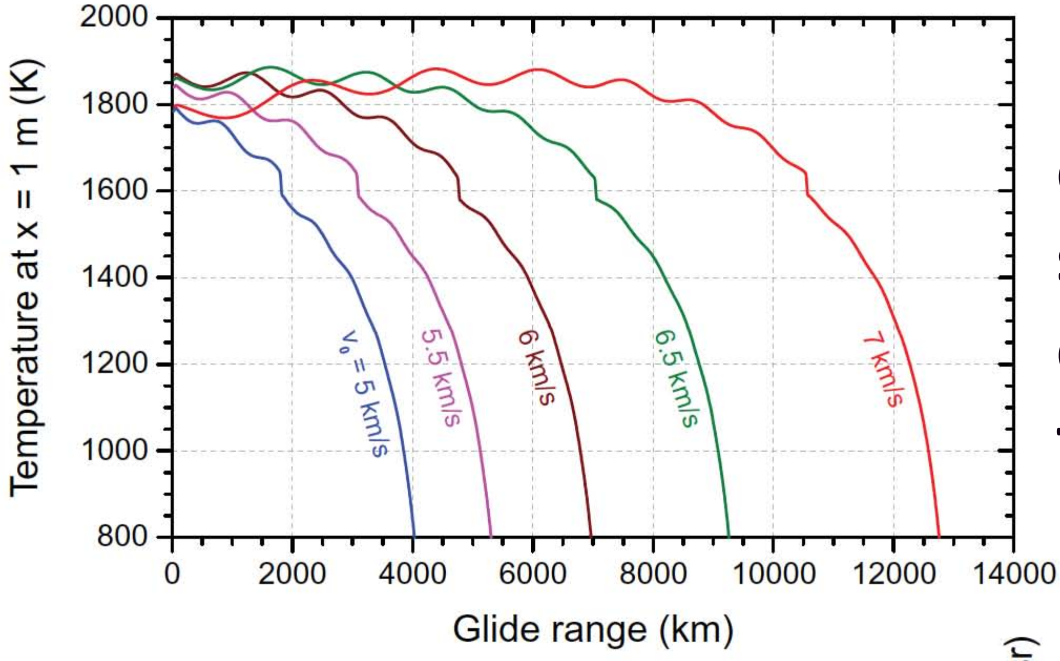
“undetectable”

The surface of a hypersonic glide vehicle reaches temperatures of thousands of Kelvin during glide, producing substantial thermal radiation across the infrared spectrum.

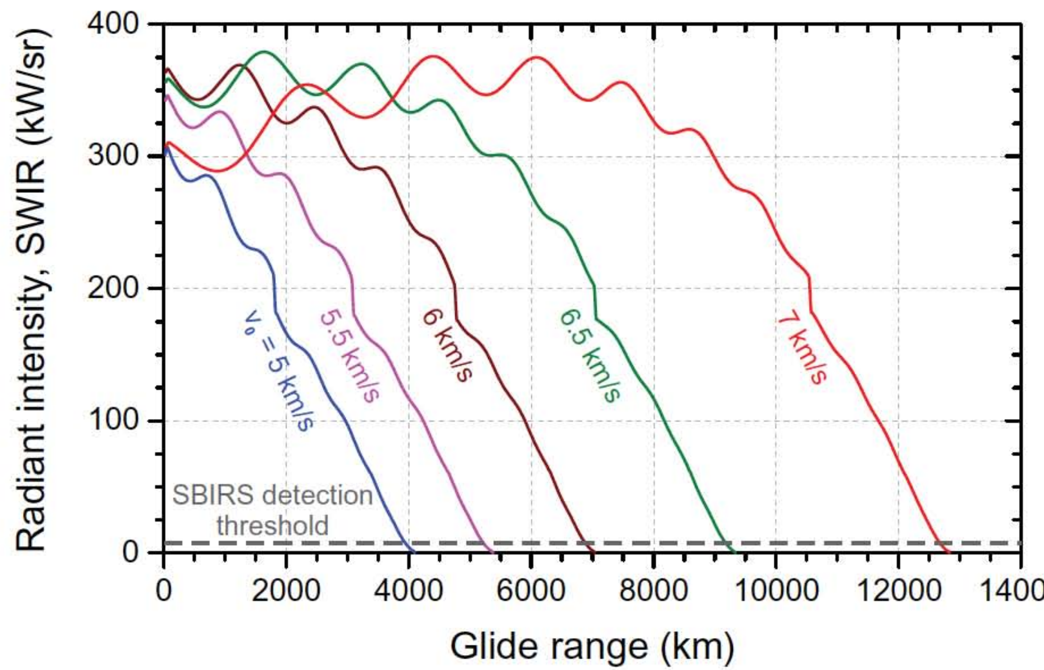
The high temperature surfaces produce a line of ionized gas that is more visible on radars and space-based sensors than the vehicle itself.



“undetectable”

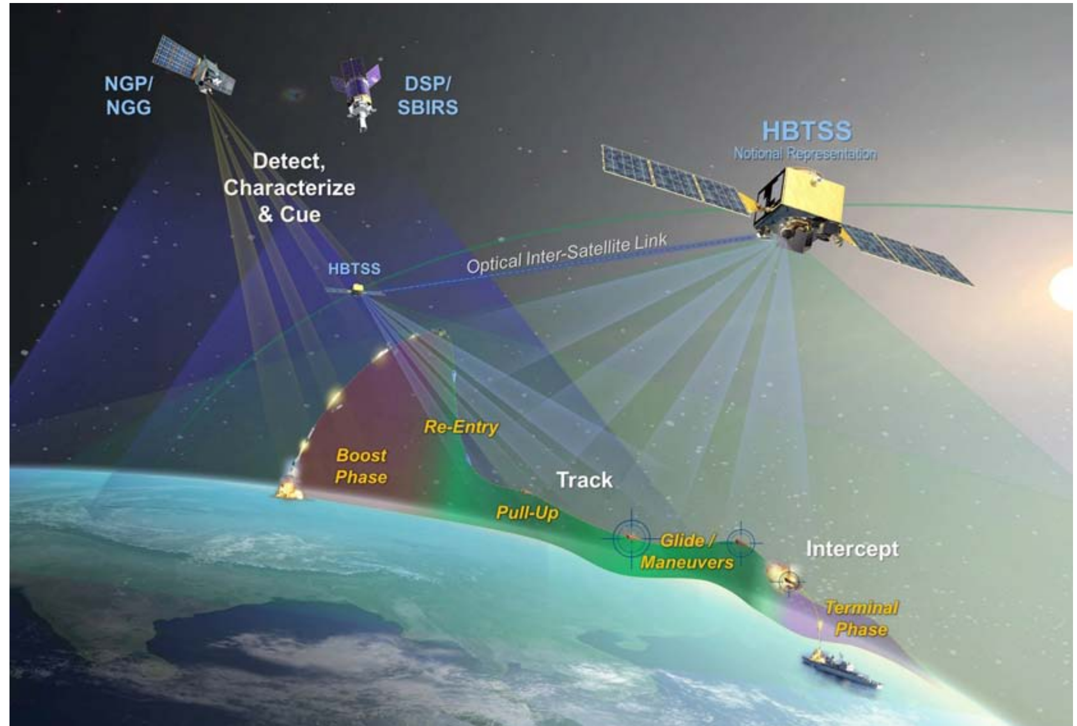


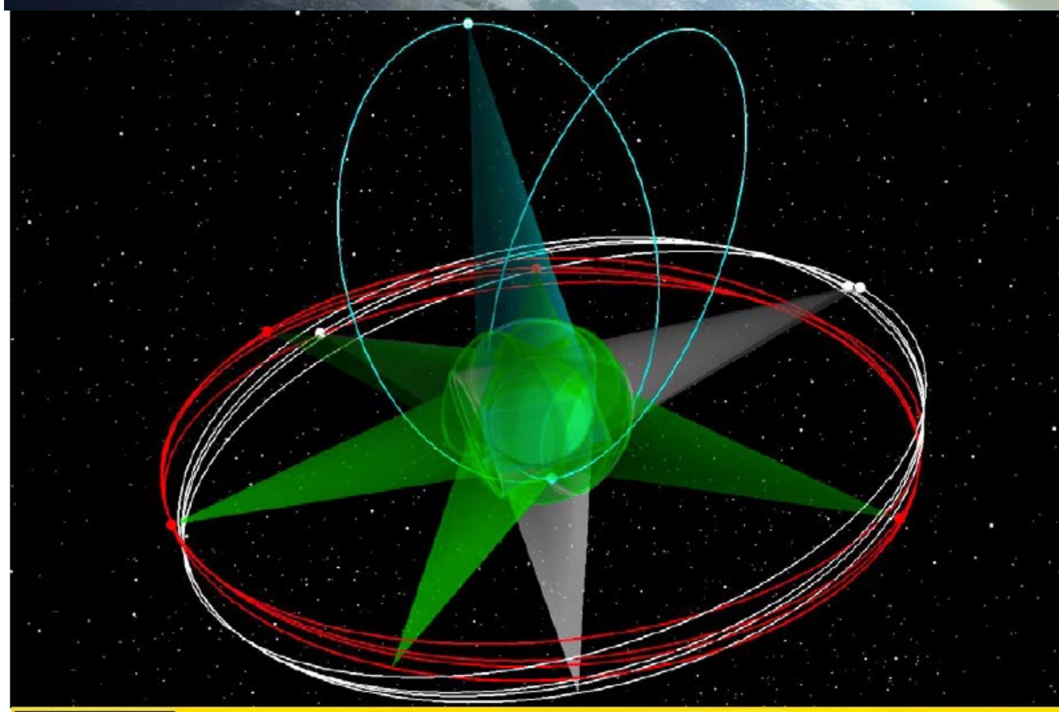
Both the US and Russia have early-warning satellites with sensitive infrared sensors that could spot the intense light that gliders emit.



US space-based early warning system is composed of two sets of satellites: the Defense Support Program (DSP), first deployed in the 1970s, and the Space-Based Infrared System (SBIRS), currently under development with the first satellite launched in 2011.

Both of them can provide tracking capability throughout much of glide phase of a HGV.

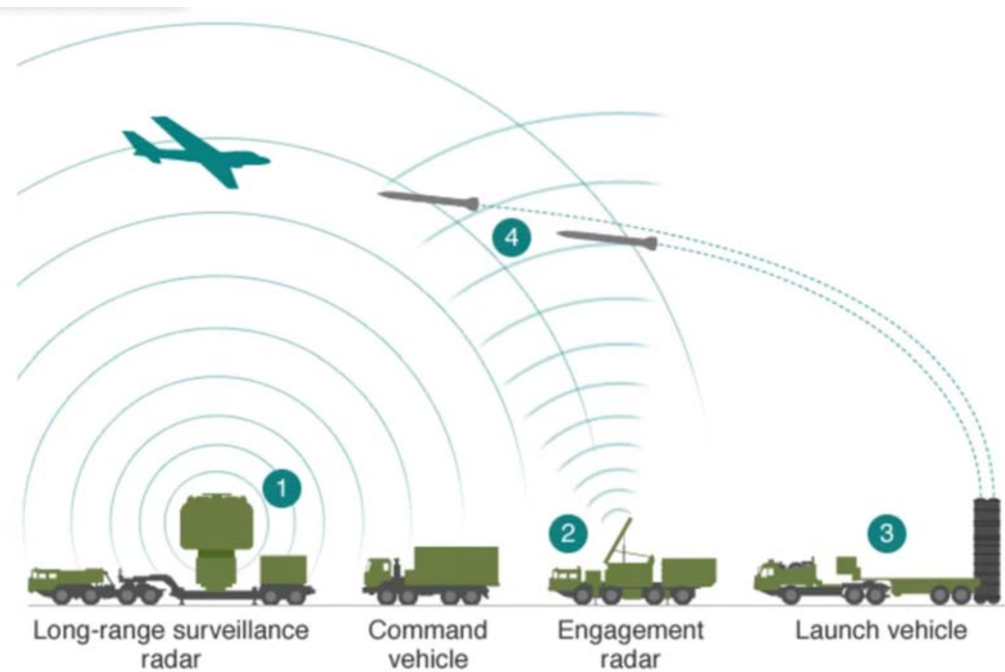




“forces that cannot be intercepted by ABMs”

Two types of missile defenses are currently deployed. Midcourse defenses, such as the US Ground-based Midcourse Defense (GMD) and Aegis Standard Missile-3 (SM-3) systems, engage weapons at long distances and high altitudes (100 km or higher) above the atmosphere and in principle can defend large ground areas.

Terminal defenses engage weapons late in flight when they are reentering the atmosphere above their target. These defenses, including the US Patriot and Aegis SM-6, and Russia’s S-400 and S-500, must operate at tens of kilometers altitude, manoeuvre aero-dynamically and engage weapons at short ranges and protect at most small ground areas.



The MIM-104 Patriot (Phased Array Tracking Radar to Intercept on Target) surface-to-air missile (SAM)

The system has four major operational functions: communications, command and control, radar surveillance (a few hundreds km), and missile guidance.

The missile interceptors PAC-3 are of two generations: MSE with speed about 1.8 km/s (Mach 6), compared to 1.4 km/s (Mach 4.7) for CRI.
The MSE intercepts in a range of 60 km at altitudes of 30+ km, compared to 20+km for CRI. The cylindrical MSE body will generate zero lift. To manoeuvre, a set of small thrusters around the body give it a non-zero angle-of-attack, which creates lift. The hit-to-kill MSE interceptor has a “lethality enhancer”: a set of rods that shoot out from the body to give it a larger lethal diameter

For endo-atmospheric engagements, both interceptor and target can manoeuvre aerodynamically, and what matters is the relative lateral acceleration that the two objects can achieve at the altitude of the engagement as each attempts to outmanoeuvre the other.

The interceptor must be able to closely match evasive movements of the target. An important principle of guidance and control theory is that interceptors must be able to achieve two to three times the lateral acceleration of a manoeuvring target to reliably intercept it

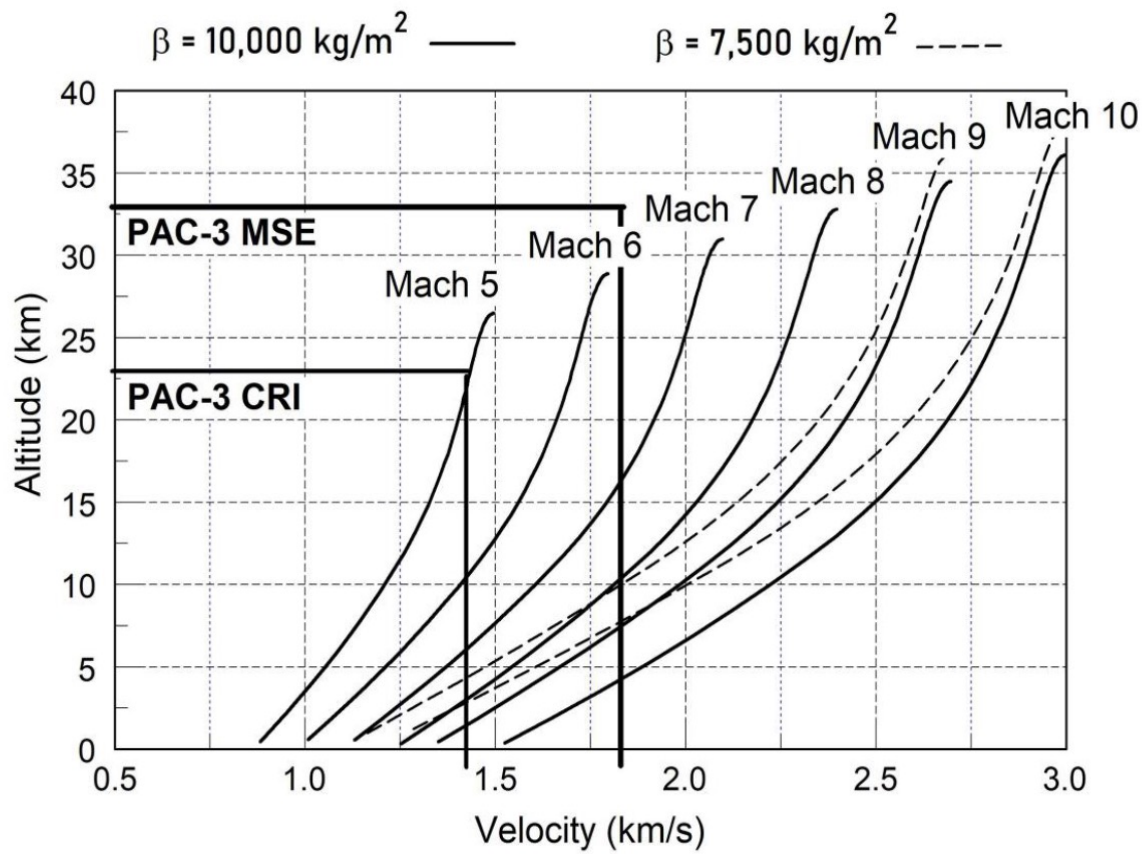
$$V_{int} \geq \left[(2 \text{ to } 3) \left(\frac{m_{Int}}{m_{target}} \right) \left(\frac{(C_L A)_{target}}{(C_L A)_{Int}} \right) \right]^{\frac{1}{2}} V_{target} \equiv \gamma \; V_{target}$$

computations in case of a wedged HGM and a PAC-3 interceptor give for γ values from 0.85 to 1

“forces that cannot be intercepted by ABMs”

Computation of final speed of a wedged HGV with high *L/D (*2.6) during its dive from its glide altitude. The boxes show the regions where the PAC-3 CRI and MSE would likely be able to intercept such a vehicle during its dive.

Curves are labeled by the vehicle’s speed at the start of its dive (i.e., at the end of glide).



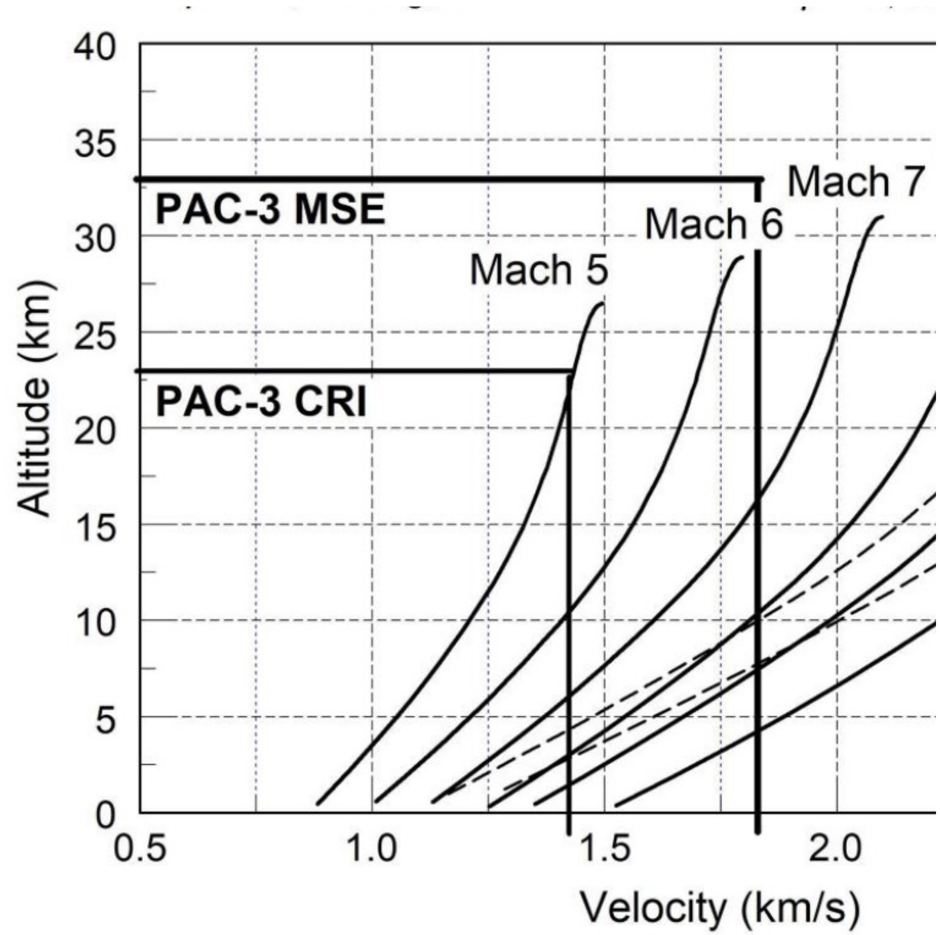
Kinzhal employments in Ukraine

- 18 March 2022 against western Ukraine
- 6 May 2023 against Kyiv
- 11 August 2023 four missiles against Kyiv and the region of Ivano-Frankivsk, lanched by Mig-31K from Tula and Lipetsk
- 14 December 2023 against central Ukraine
- 29 December 2023 five Kinzhal
- 1 January 2024 five Kinzhal
- 2 January 2024 10 Kinzhal (all shot down)
- 7/8 January 2024 4 Kinzhal

In 2023 Ukraine has received two Patriot batteries from US and two from Germany (the second on 13 December) and several PAC-3 missiles from The Netherlands

“Could this be possible?”

The Kinzhals employed in Ukraine are ballistic missiles launched at altitudes of about 18 km from Mikoyan MiG-31K about 700-1000 km away from their targets. In order to manoeuvre they have to glide for a while (low L/D) and start their dive at velocities of Mach 6 or below.



The Patriot battery installed near Kyiv can possibly intercept a Kinzhal approaching the capital.

The May 2023 shootdowns have been verified by US government sources. Unnamed US officials claimed that the Ukrainians fired multiple Patriot missiles at different angles to intercept the Kinzhal missile

strike options against distant threats
- **minimum energy trajectory BM**
- **HGV**

strike options against defended threats
- **maneuvering reentry vehicles (MaRVs)**
- **ballistic missiles with penetration aids**
- **cruise missiles**
- **HGV and HCM**

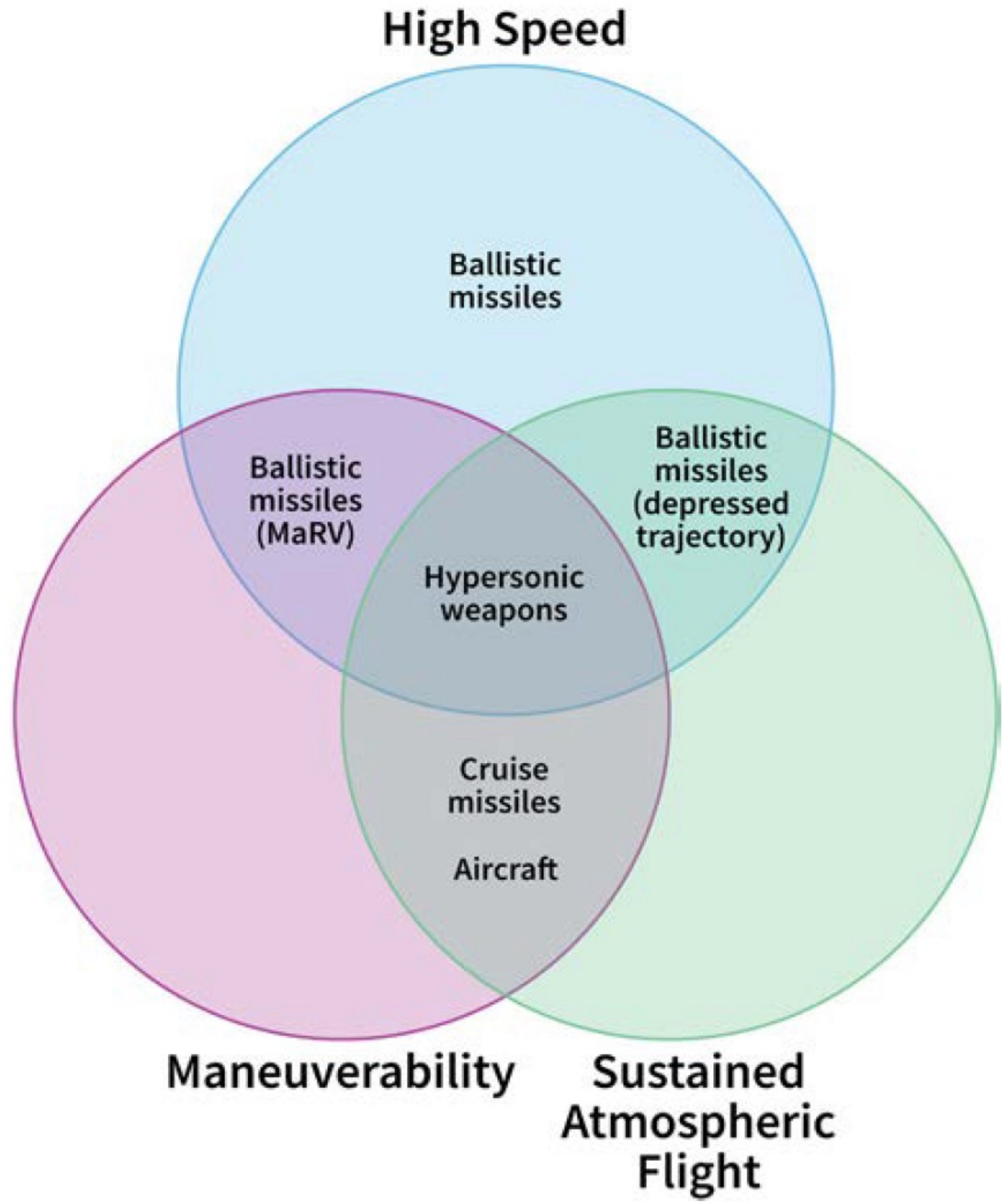
strike options against distant time-critical
- **depressed trajectory ballistic missiles**
- **HGV**

strike options against time-critical threats
- **depressed trajectory ballistic missiles**
- **HCM**

high precision strikes
- **aircraft**
- **cruise missiles**
- **MarVs**
- **HGV and HCM**

strike options against distant, defended, and time-critical threats (if any...)
- **HGV and MaRV**

Figure 4: Relation of Weapon Categories



Source: CSIS Missile Defense Project.

“game changer”

There are important missions in which MaRVs have a combination of mass and delivery time that make them preferable to HGVs. A general advantage of MaRVs is that they use existing technologies and are not subject to the prolonged, intense heating or aerodynamic instabilities of a HGV’s glide phase. MaRVs may therefore be available sooner, be less expensive, and have higher reliability than HGVs.

“MaRVs and HGVs would have similar capabilities in a conflict, but HGVs could cost one-third more to procure and field than ballistic missiles of the same range with maneuverable warheads.”

[Congressional Budget Office (CBO), *U.S. Hypersonic Weapons and Alternatives*, January 2023, Washington DC]

hypersonic weapon programs

- advanced
  - Russia
  - China
  - USA
- in development
  - Australia
  - France
  - India
  - Germany
  - Japan
  - South and Nord Korea

Russia

- long experience with space re-entry vehicles
- activity resumed after the US withdrawal from the ABM treaty

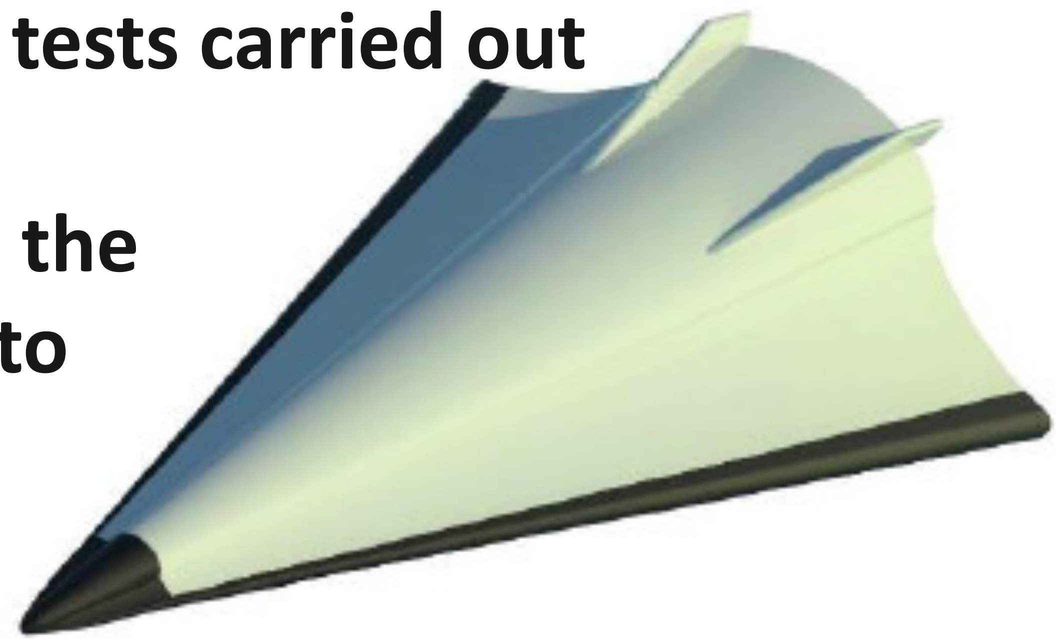
The US is permitting constant, uncontrolled growth of the number of anti-ballistic missiles, improving their quality, and creating new missile launching areas. If we do not do something, eventually this will result in the complete devaluation of Russia's nuclear potential. Meaning that all of our missiles could simply be intercepted.
President Putin (March 1, 2018)

- development program includes
  - ▻ nuclear armed HGVs
  - ▻ hypersonic ship-launched cruise missiles
  - ▻ nuclear-capable manoeuvring air-launched ballistic missiles

Avangard (Project 4202 o Yu-74)

nuclear armed manoeuvring HGV: released at its apogee (about 100 km height) from a ballistic missile like the SS-19 (UR-100NUTTH, RS-18), and in the future from the R-28 “Sarmat”, then it should glide for over 6,000 km at speeds up to Mach 20

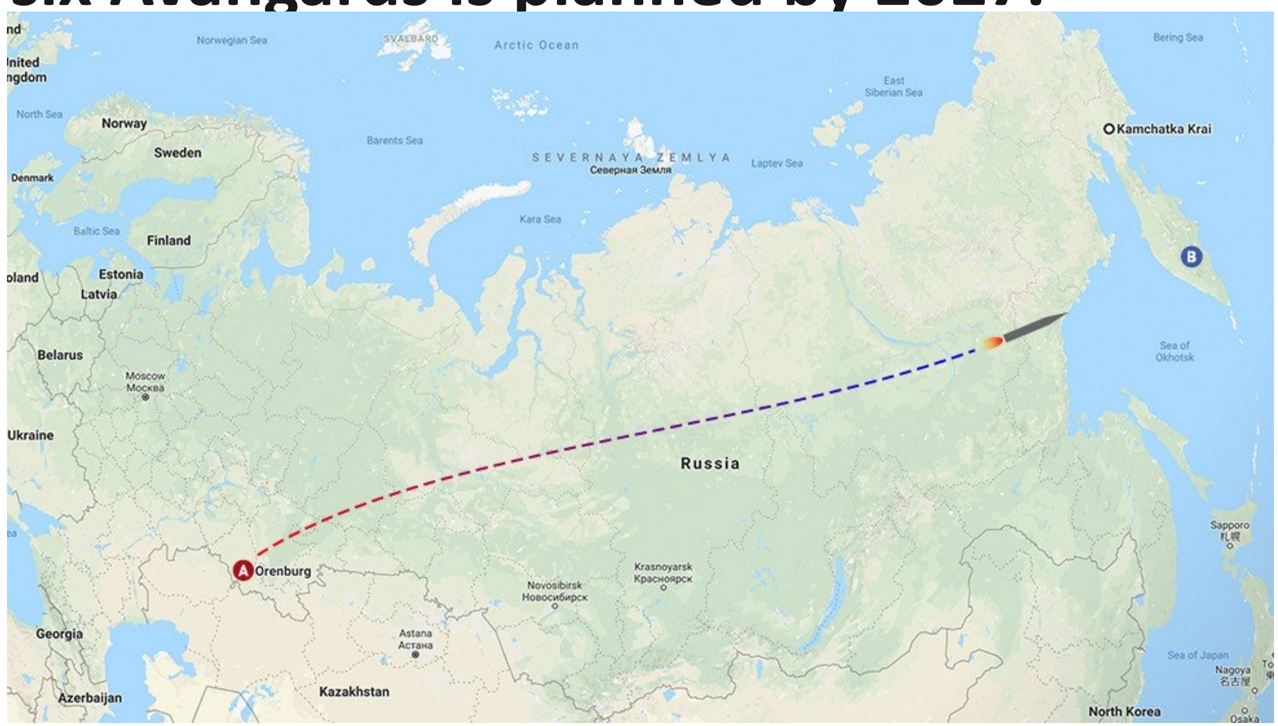
- more than a dozen flight tests carried out
- President Putin declared (27 December 2019) that the first Avangard entered into combact duty.



Avangard

The first Avangard regiment (6 missiles) is operational at the Dombarovsky base. Each Avangard constitutes the payload of its RS-18 ballistic missile, replacing six 400 kton warheads (MIRV); as per New START, the replacement has been communicated to the US.
A second deployment of six Avangards is planned by 2027.

Final successful public test-launch of Avangard before its entry into service in 2019.



3M22 Tsirkon (NATO SS-N-33)

manoeuvring, winged hypersonic ship-launched cruise missile with a lift-generating centre body, capable of striking both ground and naval targets. A booster stage with solid-fuel engines accelerates it to supersonic speeds, after which a scramjet motor with liquid-fuel accelerates it to hypersonic speeds. The missile's maximum range is estimated to be 1000 km at a speed of Mach 6-Mach 8. In January 2023 it was first deployed on a Project 22350 frigate and is scheduled for Project 885 Yasen-class submarines

In July 2022 in a positive test from the frigate *The Admiral Gorshkov* a Tsirkon hit a surface target in the White Sea

Kh-47M2 Kinzhal ("dagger")(NATO AS-24 Killjoy)

The Kinzhal is a nuclear-capable air-launched ballistic missile, with a payload of up to 480 kg and a thermonuclear option with a 10–50 kt warhead. It has a claimed range up to 2,000 km, Mach 10 maximun speed, and an ability to perform evasive manoeuvres (using fins) at every stage of its flight. It can be launched at altitudes of about 18 km from Tu-22M3 bombers or Mikoyan MiG-31K interceptors.

The Kinzhal is derived from the ground-launched 9K720 Iskander-M short-range ballistic missile

China

China is strongly committed to HM development, with significant investments in accelerated programmes

- **to avoid technological surprises from potential adversaries**
- **to keep pace with the progress of Russia and the US**
- **to counter specific security threats from increasingly sophisticated US military technologies, *in primis* missile defence deployments (most important reason)**

China maintains a policy of deliberate opacity on its military forces and policies, and even information on hypersonic weapons is inferred by researchers from indirect sources

Chinese programs

Chinese conventionally armed HGVs mated with the DF-17 and DF-41 ballistic missiles are considered anti-ship force, to control the Chinese seas, and as a system to strengthen her A2/AD (anti-access/denial area) capabilities in the Asia-Pacific area, i.e. to prevent operations of the opponent in an exclusive area adjacent to her own territory by means of a combination of sensors and long-range vectors in anti-aircraft, anti-ship and land-based anti-missile function.

Possible HGV with nuclear weapons on intercontinental vectors can contribute to deterrence vis-a-vis the US with their penetrability of anti-missile systems.

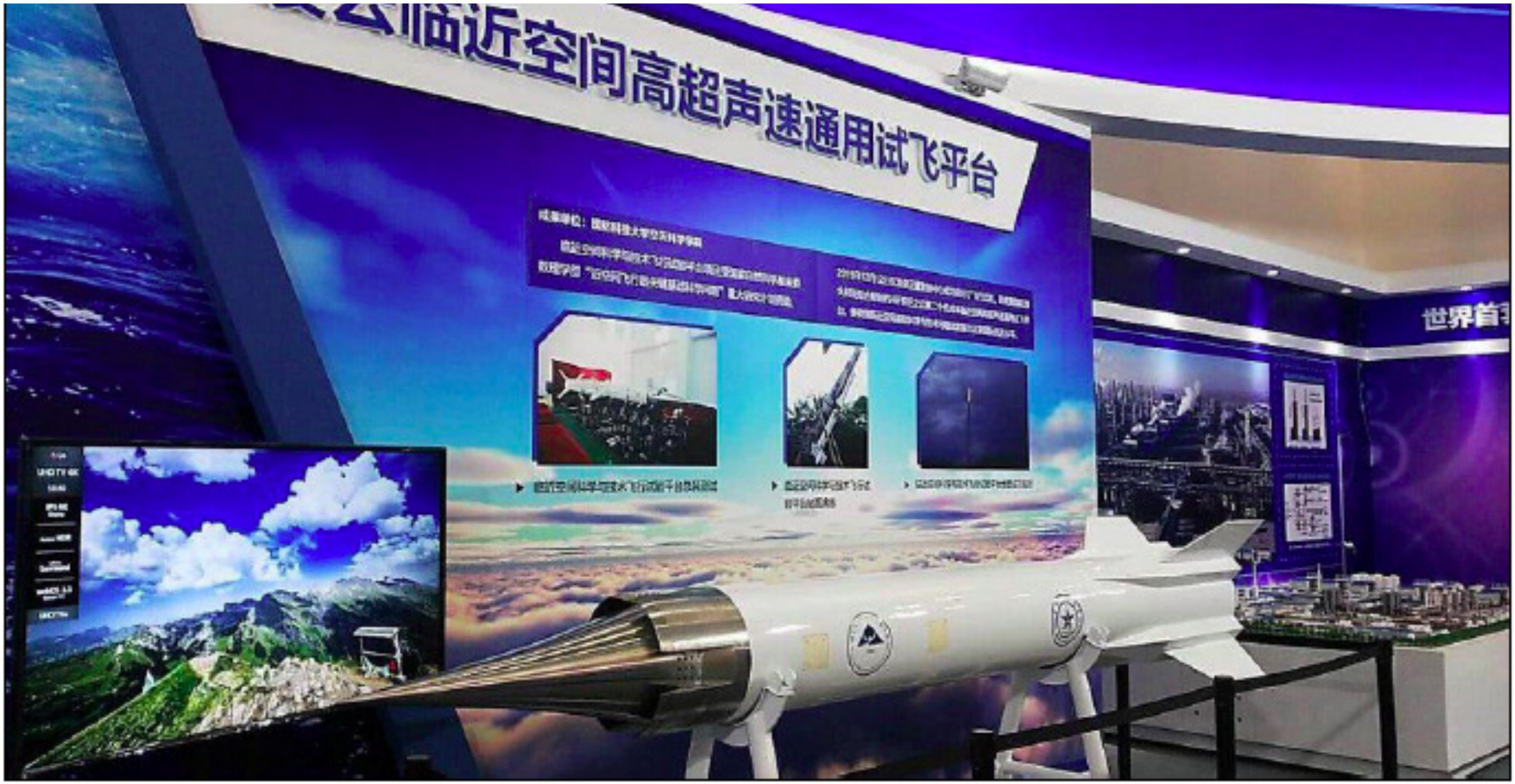
Chinese programs

- **advanced HGV: Dong Feng DZ-DF vehicle (previously WU-14) speeds exceeding Mach 10 and a range up to 2000 km**
  - ▻ **several tests launched by short and medium-range missiles**
  - ▻ **China reportedly fielded the Dong Feng in 2020**

- **Xing Kong-2 or Starry Sky-2 is a nuclear-capable HGV prototype with wedge-shaped fuselage and advanced thermal protection systems.**
  - ▻ **in August 2018 China claims the vehicle reached top speeds of Mach 6 and executed a series of in-flight manoeuvres before landing**
  - ▻ **could be operational by 2025**

HGV Dong Feng (East wind) or DF-DZ or WU-14

The 18th National Science and Technology Week in Beijing in 2018 saw the unveiling of the prototype of the Mach 6 HCM Lingyun-1 ("reach-clouds") employing one of the scramjet engines that China has been developing since 2015.



China’s JF-12 hypersonic wind tunnel for speeds of Mach 5–9.

China is reportedly completing construction of the JF-22 wind tunnel, capable of reaching speeds of Mach 30

US Conventional Prompt Global Strike (CPGS) mission

In 2003, the Department of Defense (DOD) identified a new mission—prompt global strike—that sought to provide the United States with the ability to strike targets anywhere on Earth with conventional weapons in an hour, without relying on forward-based forces.

In light of the appropriately extreme reluctance to use nuclear weapons, conventional prompt global strike could be of particular value in some important scenarios in that it would eliminate the dilemma of having to choose between responding to a sudden threat either by using nuclear weapons or by not responding at all.

Committee on Conventional Prompt Global Strike Capability, 2008

US hypersonic weapons “more realistic” rationale

hypersonic weapons could enable responsive, long-range, strike options against distant, defended, and/or time-critical threats [such as road-mobile missiles] when other forces are unavailable, denied access, or not preferred.

General John Hyten, former Commander of U.S. Strategic Command, 2019

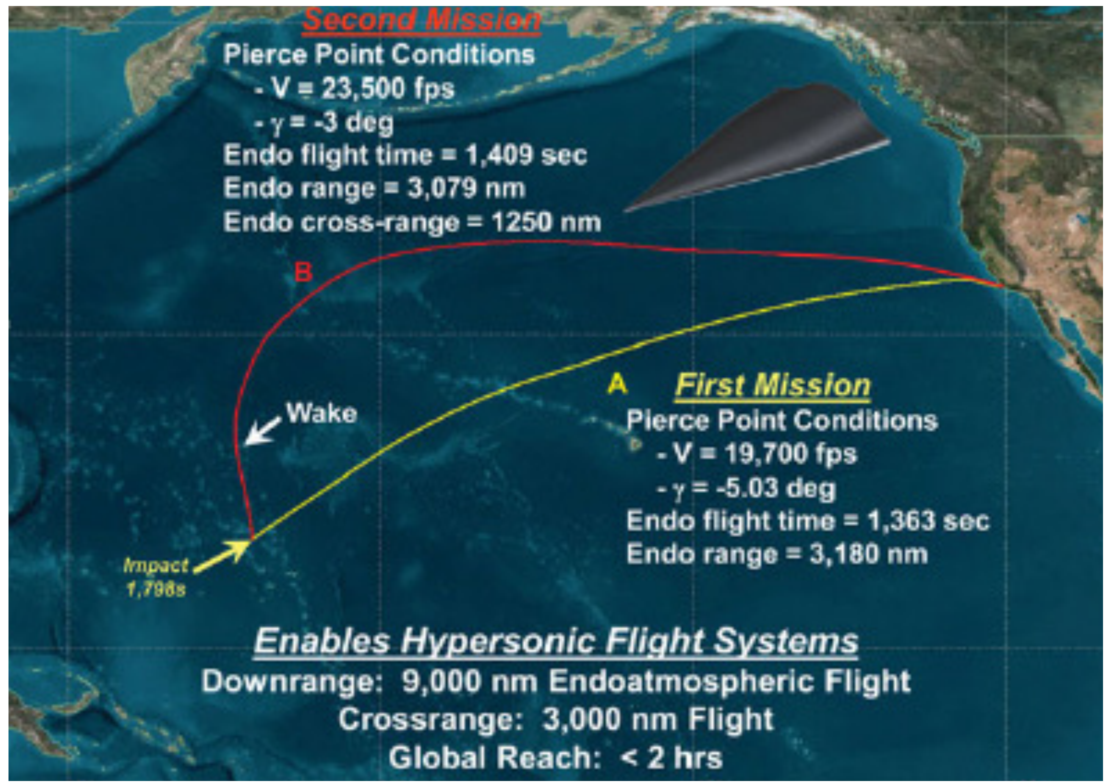
conventional weapon strikes replacement of nuclear weapons requires extreme precision systems

US policy

At present, the Department of Defense (DOD) has not established any programs of record for hypersonic weapons, suggesting that it may not have approved either mission requirements for the systems or long-term funding plans.
DOD has not yet made a decision to acquire hypersonic weapons and is instead developing prototypes to assist in the evaluation of potential weapon system concepts and mission sets.
The Pentagon’s FY2023 budget for hypersonic research is $4.7 billion—up from $3.8 billion in the FY2022 request.
The Missile Defense Agency additionally requested $225.5 million for hypersonic defence.

The wedge-shaped Hypersonic Technology Vehicle-2 (HTV-2) developed by the Air Force and DARPA, planned for a range of 7,600 km at Mach 20, was tested in April 2010 and August 2011; both tests failed and the program was cancelled.

Present US programs are based on older conical designs, with lower range and less manoeuvrability, but less risky.

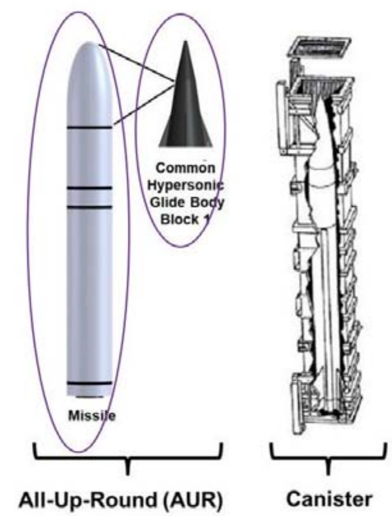


The United States has a number of major offensive hypersonic weapons and hypersonic technology programs in development:

- **US Navy—Conventional Prompt Strike (CPS)**
- **US Navy—Offensive Anti-Surface Warfare Increment 2 or Hypersonic Air-Launched OASuW (HALO)**
- **US Army—Long Range Hypersonic Weapon (LRHW)**
- **US Air Force—Hypersonic Attack Cruise Missile (HACM)**
- **DARPA—Tactical Boost Glide (TBG)**
- **DARPA—Operational Fires (OpFires)**
- **DARPA—More opportunities with Hypersonic Air-breathing Weapon Concept (MoHAWC, pronounced "mohawk")**

These programs are intended to produce operational prototypes, as there are currently no programs of record for hypersonic weapons

USS *Zumwalt* (DDG-1000) arrived in Pascagoula, Miss., *on Aug.19, 2023* to enter a modernization period and receive technology upgrades including the integration of the Conventional Prompt Strike weapon system



US Army—Long Range Hypersonic Weapon (LRHW) with Common Hypersonic Glide Body (C-HGB)

The AGM-183 was an air-launched hypersonic glide vehicle prototype capable of travelling at average speeds of between Mach 6.5 and Mach 8 at a range of approximately 1,000 miles. The first test of the full prototype ARRW was on 9 December 2022. The program was cancelled on March 2023


DARPA, in partnership with the Air Force, continues to test Tactical Boost Glide, a wedge-shaped hypersonic glide vehicle capable of Mach 7+ flight both for air-launched, tactical-range systems, and for integration with the Navy Vertical Launch System.

Operational Fires seeks to develop a ground-launched system that will “precisely engage critical time sensitive targets.” OpFires completed its first flight test in July 2022.

Hypersonic Air-breathing Weapon Concept (HAWC), with Air Force support, aims “to an effective and affordable air-launched hypersonic cruise missile.” HAWC was successfully tested in March and July 2022.

US Hypersonic Missile Defences

Since September 2018, the Missile Defense Agency (MDA) is exploring hypersonic missile defence options, including interceptor missiles, hypervelocity projectiles, laser guns, and electronic attack systems. MDA issued a draft request for prototype proposals for a regional, sea-based Glide Phase Intercept (GPI) for the in the late 2020s.
In addition, MDA is developing the Hypersonic and Ballistic Tracking Space Sensor (HBTSS) in an effort to improve the agency's ability to detect and track incoming missiles.
DARPA is working on a program called Glide Breaker, which "will develop critical component technology to support a lightweight vehicle designed for precise engagement of hypersonic threats at very long range."

Potential questions about the rationale for hypersonic weapons:

- **What mission(s) will hypersonic weapons be used for? Are hypersonic weapons the most cost-effective means of executing these potential missions? How will they be incorporated into joint operational doctrine and concepts?**
- **Given the lack of defined mission requirements for hypersonic weapons, how should Congress evaluate funding requests for hypersonic weapons programs or the balance of funding requests for hypersonic weapons programs, enabling technologies, and supporting test infrastructure? Is an acceleration of research on hypersonic weapons, enabling technologies, or hypersonic missile defense options both necessary and technologically feasible?**
- **How, if at all, will the fielding of hypersonic weapons affect strategic stability?**
- **Is there a need for risk-mitigation measures, such as expanding New START, negotiating new multilateral arms control agreements, or undertaking transparency and confidence--building activities?**

Kelley M. Sayler, 2023

Australia

Since 2007, the United States has collaborated with Australia on the Hypersonic International Flight Research Experimentation (HIFiRE) program to develop hypersonic technologies.
The most recent HIFiRE test, successfully conducted in July 2017, explored the flight dynamics of a Mach 8 hypersonic glide vehicle, while previous tests explored scramjet engine technologies.
HIFiRE's successor, the Southern Cross Integrated Flight Research Experiment (SCIFiRE) program, is to further develop hypersonic air-breathing technologies. SCIFiRE demonstration tests are expected by the mid-2020s.
In addition to the Woomera Test Range facilities—one of the largest weapons test facilities in the world—Australia reportedly operates seven hypersonic wind tunnels and is capable of testing speeds of up to Mach 30.

Australia

Australian–U.S. HIFIRE Scramjet

SOURCE: Australian Hypersonics Initiative at the University of Queensland, Australian Defence Science and Technology Group, and U.S. Air Force Research Laboratory.

India

India’s Defense Research and Development Organization (DRDO) has collaborated with Russia on the development of BrahMos II, a Mach 7 hypersonic cruise missile. BrahMos II program faces significant delays and is now scheduled to achieve initial operational capability between 2025 and 2028.

Reportedly, India is also developing an indigenous, dual-capable hypersonic scramjet cruise missile as part of its Hypersonic Technology Demonstrator Vehicle (HSTDV) program and successfully tested a Mach 6 scramjet in June 2019 and September 2020.

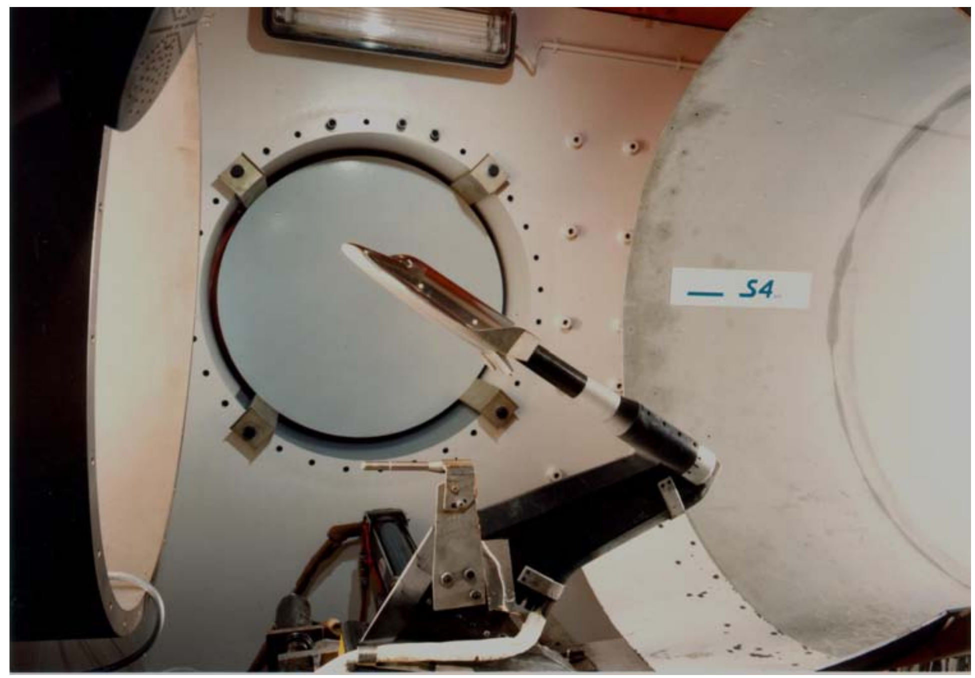
India operates approximately 12 hypersonic wind tunnels and is capable of testing speeds of up to Mach 13.

HSTDV integrated hypercarbon fuel scramjet engine vehicle on show at Berlin

France

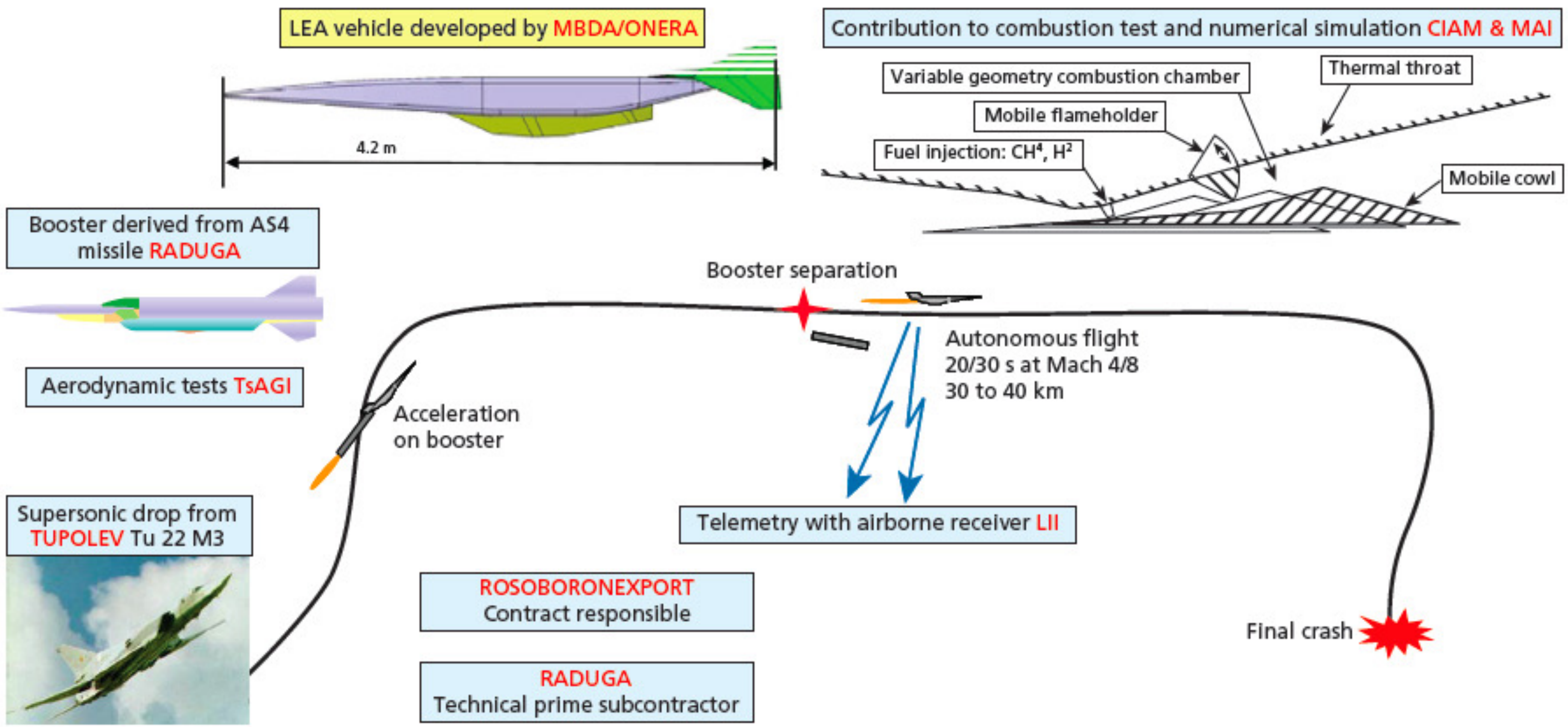
France has collaborated and contracted with Russia on the development of hypersonic technology. Although France has been investing in hypersonic technology research since the 1990s, it has only recently announced its intent to weaponize the technology. Under the V-max (Experimental Manoeuvring Vehicle) program, France plans to modify its air-to-surface ASN4G supersonic missile for hypersonic flight by 2023. The V-max program is intended to provide France with a strategic nuclear weapon. France operates five hypersonic wind tunnels and is capable of testing speeds of up to Mach 21.

For its hypersonic glide vehicle demonstrator, France is utilizing Onera's S4 wind tunnel, previously used to study atmospheric re-entry of space vehicles and missile flight.



French programs for HCM

Figure 3.1
French LEA



SOURCE: Francois Falempin and Laurent Serre, "French Flight Testing Program LEA Status," Washington, D.C.: NATO Research and Technology Organisation, RTO-EN-AVT-185, undated, p. 17-5, Figure 5.

RAND *RR2137-3.1*

Germany

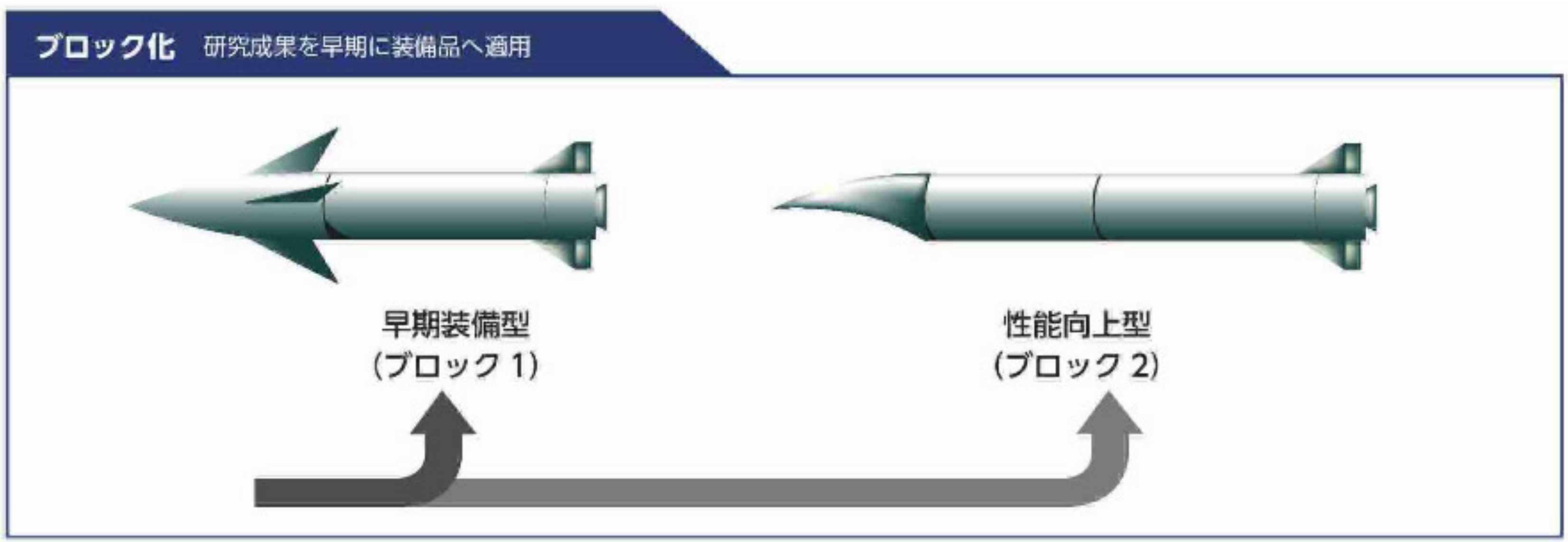
Germany successfully tested an experimental hypersonic glide vehicle sharp Edge Flight Experiment (SHEFEX II) in 2012. German defence contractor DLR continues to research and test hypersonic vehicles as part of the European Union’s ATLLAS II (Aero-Thermodynamic Loads on Lightweight Advanced Structures II project), which seeks to design a Mach 5-6 vehicle.

Germany operates three hypersonic wind tunnels and is capable of testing speeds of up to Mach 11.

Japan

Japan is developing the Hypersonic Cruise Missile (HCM) and the Hyper Velocity Gliding Projectile (HVGP). It reportedly plans to field HVGPs for area suppression and neutralizing aircraft carriers. HVGP is expected to enter service in 2026, with a more advanced version available by 2030, while HCM is expected to enter service in 2030.

The Japan Aerospace Exploration Agency operates three hypersonic wind tunnels, with two additional facilities at Mitsubishi and the University of Tokyo. Japan and the United States have agreed to conduct "a joint analysis focused on future cooperation in counter-hypersonic technology."



North Korea

Although North Korea tested the Hwasong-8—which it identifies as a hypersonic glide vehicle—in September 2021, reports indicate that the vehicle may have reached speeds of only Mach 3.

On 5 and 11 January, North Korea performed test flights of what it claims is a "hypersonic missile": a rotational symmetric glide vehicle atop a rocket booster that performed pull-up and cross-range manoeuvres during its flights. However, experts believe that that weapon may instead be a manoeuvring re-entry vehicle.

South Korea

South Korea is developing the missile in response to growing concern about North Korea military modernization and plans to eventually develop sea- and air-launched variants.

South Korea reportedly has been developing a ground-launched Mach 6+ hypersonic cruise missile, Hycore, since 2018 and plans to test the missile in 2023.

Civilian programs

Hypersonic technology has a dual-use character.
Non-military purposes include: space launch, orbital cargo-retrieval systems, orbital-, suborbital- (and lunar-) space tourism, and civilian transport of passengers and cargo.
The current situation sees hypersonic research openly disseminated and widely spread among governments, industries, and universities.

Several countries are active in the field in Europe, Australia, Brazil, Canada, South Corea, Iran, Israel, Japan, Pakistan, United Kingdom, Singapore, Taiwan ...

Japan has developed a conceptual model for a hypersonic aircraft capable of cruising at Mach 4.5 and traveling trans-Pacific routes in just a few hours, using dual precooled liquid hydrogen-fueled turbojets.

The European Union

The EU has primarily invested in two R&D programs using hypersonic technology, involving several countries.
The LAPCAT II project is intended to develop a civilian Mach 5 transport airplane, using a hybrid turbo-scramjet engine.

IXV is an experimental suborbital RV designed to test atmospheric reentry conditions from (hypersonic) orbital speeds and trajectories. It is intended to be a reusable satellite launch vehicle that is able to reenter the Earth's from a maximum altitude of 412 km.

arms control

Nuclear hypersonic weapons and arms control

The nuclear hypersonic weapons fall generically under the dictates of the article VI of the Non-proliferation treaty, in particular if they are triggering a new arms race.

Non-nuclear weapon states may regard hypersonic missiles with nuclear payloads as defying the spirit of the NPT's disarmament obligations and this could lower the confidence of non-nuclear weapon states parties in the NPT.

The nuclear hypersonic weapons of Russia and US would count under the limits in New START, as it was the case with the Avangard deployment.

Conventional arms control

At the moment there are no treaties or conventions limiting the development of HGV or HCM with conventional armament.

During the New START negotiations, Russia raised the issue of high precision conventional weapons, which she still considers a threat to strategic stability.
Hence, land-based ballistic missiles armed with conventional warheads would count under the limits in New START if the missile "has a ballistic trajectory over most of its flight path" and a range greater than 5,500 kilometers (par. 6 of Part One of the Treaty Protocol).
So conventional HGV or HCM systems remain excluded.

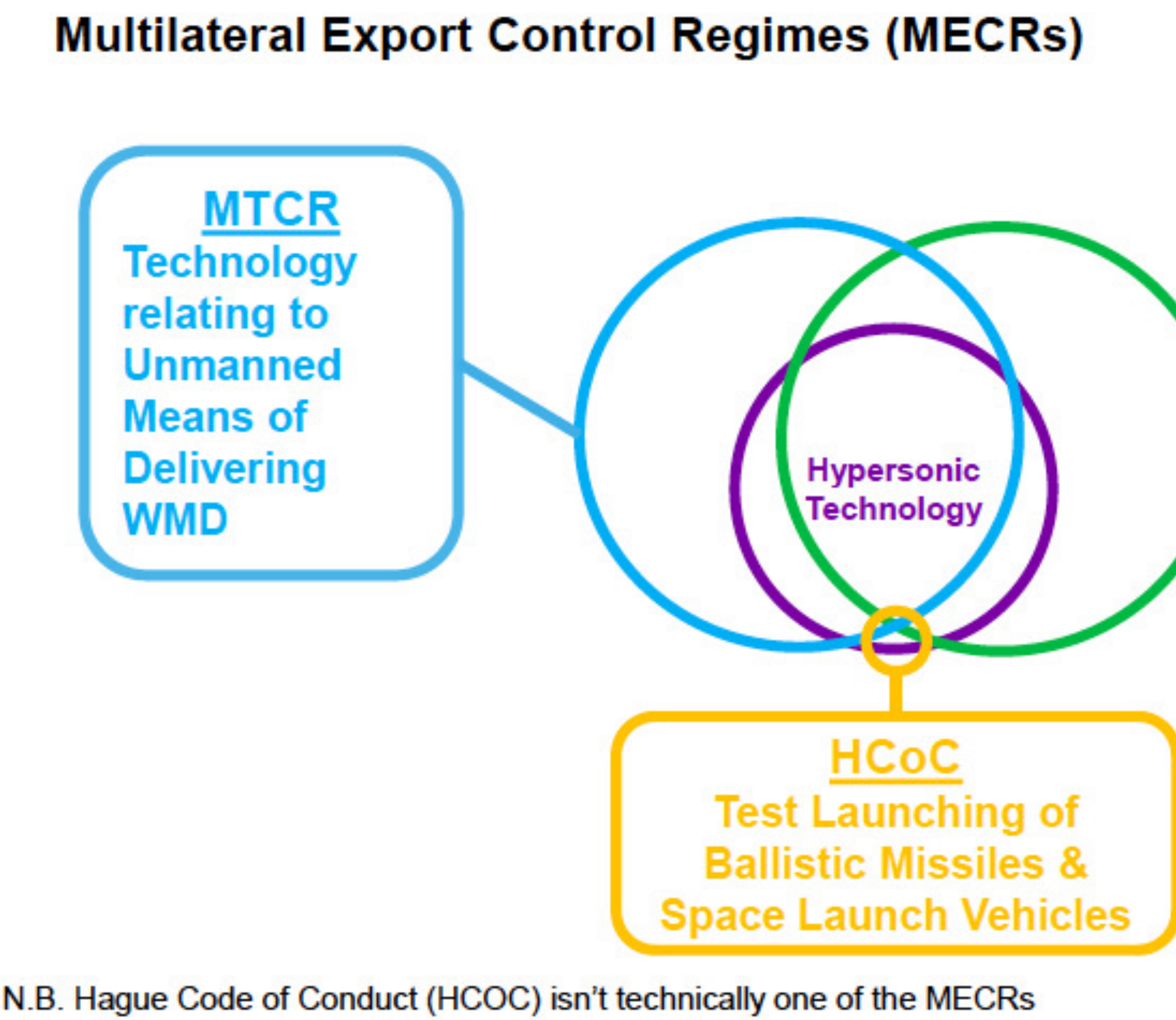
Under the definitions in New START, the boost-glide systems would qualify as "new kinds of strategic offensive arms". Article V of the treaty indicates that, "when a Party believes that a new kind of strategic offensive arm is emerging, that Party shall have the right to raise the question of such a strategic offensive arm for consideration in the Bilateral Consultative Commission."

As a result, a party would have the opportunity to question the other party on whether the boost-glide systems should count under the treaty. But the second party would not have to delay the development, testing, and deployment of these systems while the discussions proceeded.

Non proliferation

The technology can be imported or exported, short-circuiting the slow route of indigenous development.

Multilateral export control regimes are relevant



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

Wassenaar Arrangement

Founded in 1996 by a voluntary group of countries, the Arrangement's purpose is to promote transparency in transfers of conventional arms, and military and dual-use technologies. 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: rockets and missiles (ML4), propellants (ML8b), aircraft, Unmanned Aerial Vehicles and aero-engines (ML10), electronic equipment (ML11),
software and other technologies designed for development, production, operation, maintenance, repair, overhaul of items in the Munitions List (ML21 and ML22)

Wassenaar Arrangement

At least four provisions of the Dual-use List may apply to HGVs and HCMs:

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

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

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

Missile Technology Control Regime (MTCR)

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''. Category II items (maximum range equal to or greater than 300km) allow partners a greater flexibility in the 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.
Questions of classification remain about HGV (UAV or re-entry vehicle?).

Missile Technology Control Regime (MTCR)

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''.
Category II items (maximum range equal to or greater than 300km) allow partners a greater flexibility in the 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.
Questions of classification remain about HGV (UAV or re-entry vehicle?).

Hypersonic Technology and MTCR: System Overview

MTCR Category-II
Stage/Separation Mechanisms
(3.A.4.)

Booster MTCR Category-I
Ballistic System
(Boost Phase)

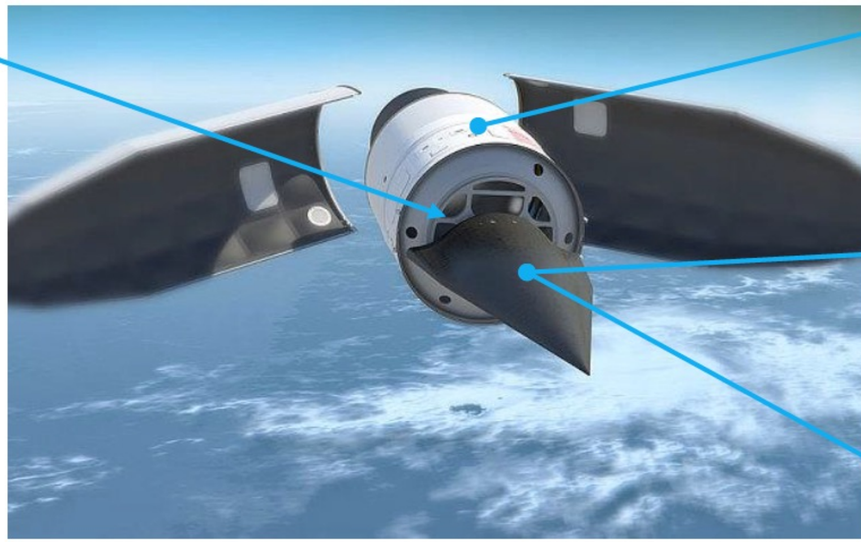


Image: Defense Advanced Research Projects Agency DARPA

HGV MTCR Category-I
Re-entry Vehicle Sub System?

HGV MTCR Category-I
UAV System?

HGV MTCR Category-II
UAV System? (<500kg)

note on non-proliferation

- the limitations and restrictions foreseen by both the Wassenaar Arrangement and the Missile Technology Control Regime are not legally binding and can be applied selectively
- several countries with the technological basis for the development of hypersonic weapons are already active in field
- existing international collaborations are facilitating the diffusion of the technology
- private companies are developing commercial programs

Impact on arms control

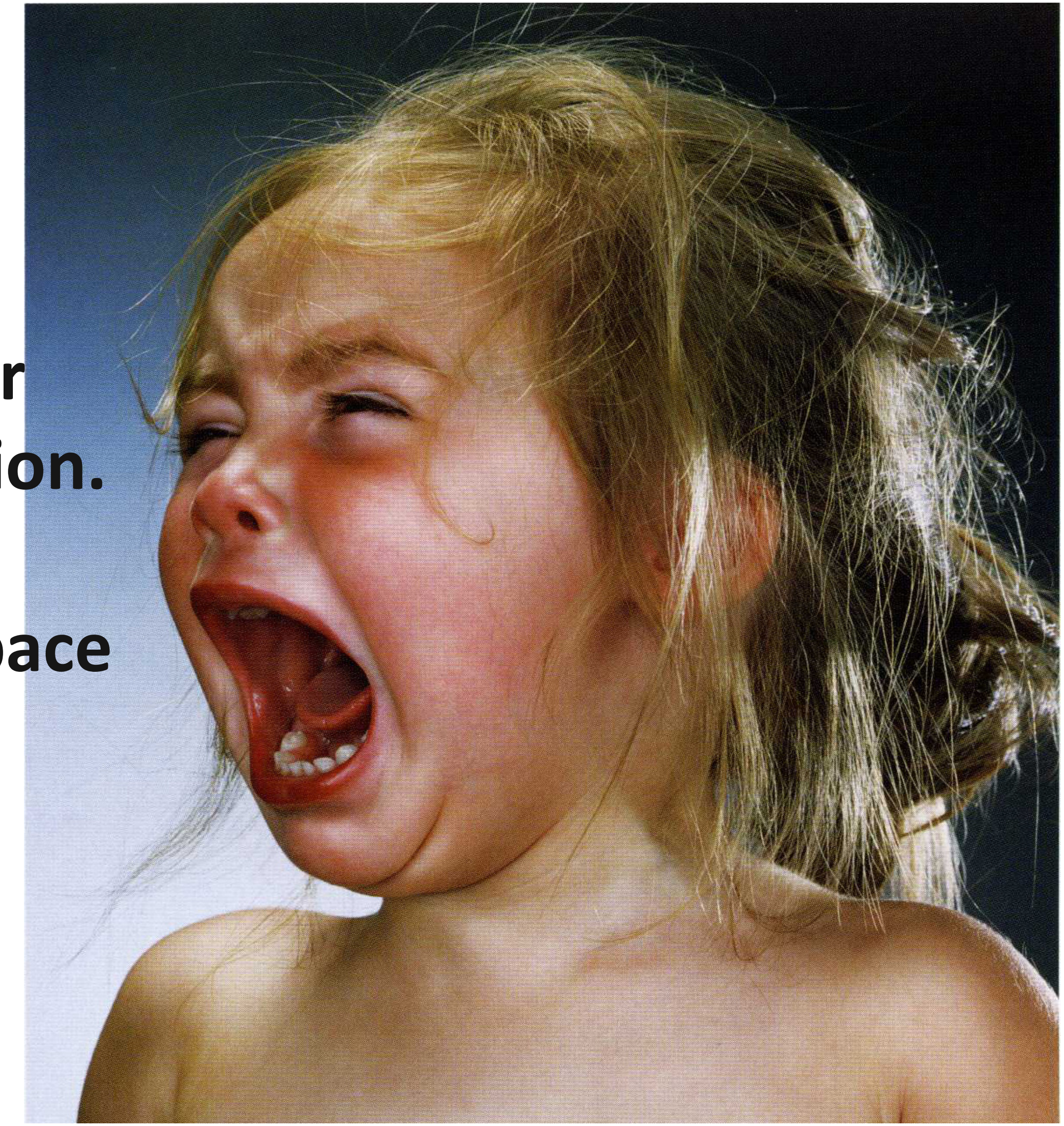
The ongoing hypersonic arms race is fuelling distrust between states, reducing states' willingness to participate in arms control, and complicating the negotiation of future treaties.

Hypersonics are likely to make verification and monitoring more challenging, given that they are hosted on various platforms and can be fitted with both nuclear and conventional warheads.

Arms control and hypersonic weapons

The present military posture increasingly requires weapons that can travel faster, farther and with greater precision.

This leaves not much space and hope for either arms control or confidence-building measures



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Alessandro Pascolini

pascolini@pd.infn.it
https://ilbolive.unipd.it/it/ricerca?search=pascolini
@pascolin