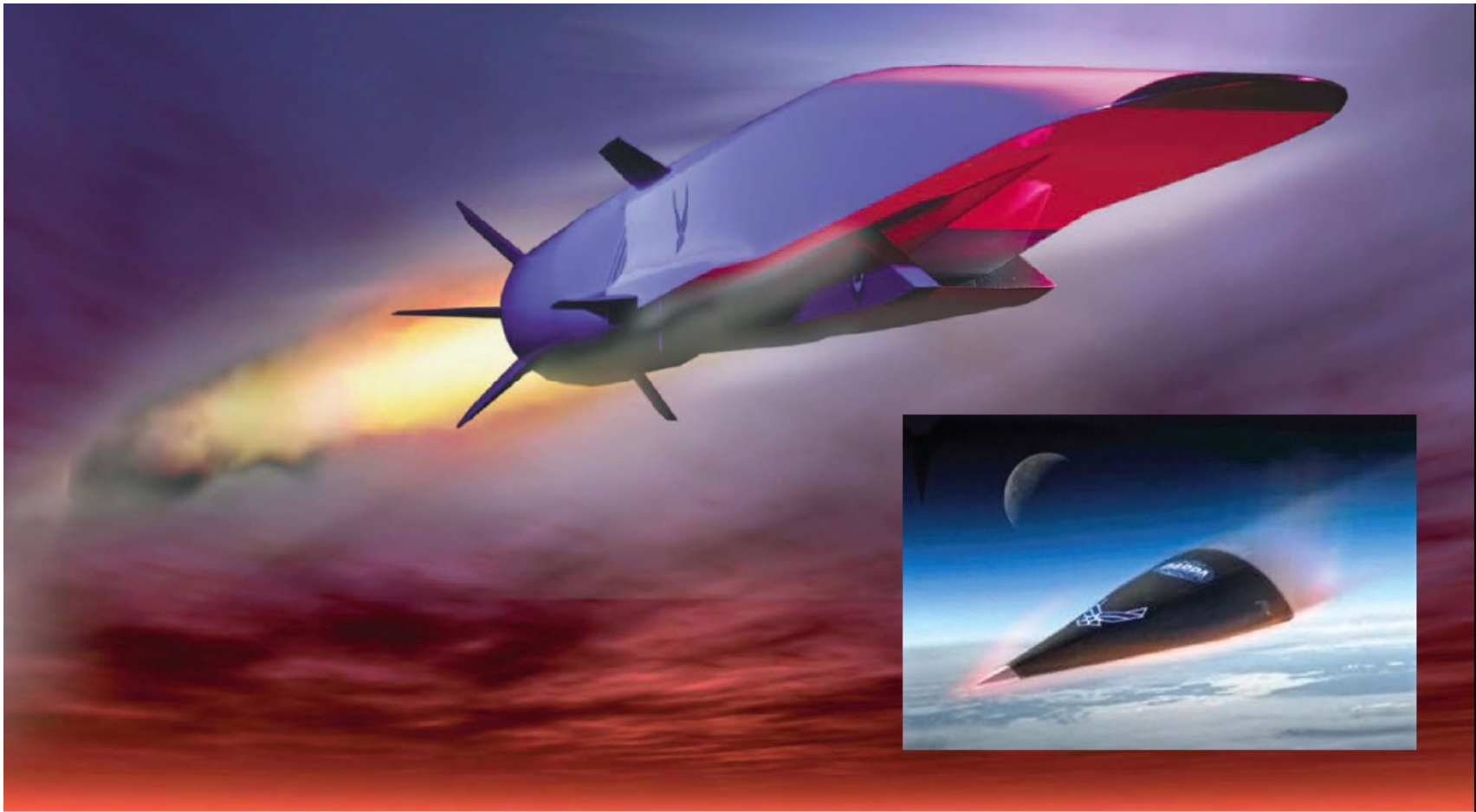




Hypersonic weapons (a re-emerging technology)

January 2025 Alessandro Pascolini

to-day offer

hypersonic flight

hypersonic weapons

limits and competitors

hypersonic weapon programs

arms control

strategic implications

hypersonic flight

Speed regimes

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

every device aiming to (or coming from) space missions crosses the atmosphere at hypersonic velocity

- **reentering vehicles from orbital stations reach Mach 28**
- **reentering vehicles from Moon flights exceed Mach 32**

ballistic missiles with range over 300 km exceed Mach 5

ICBMs exceed Mach 20

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**

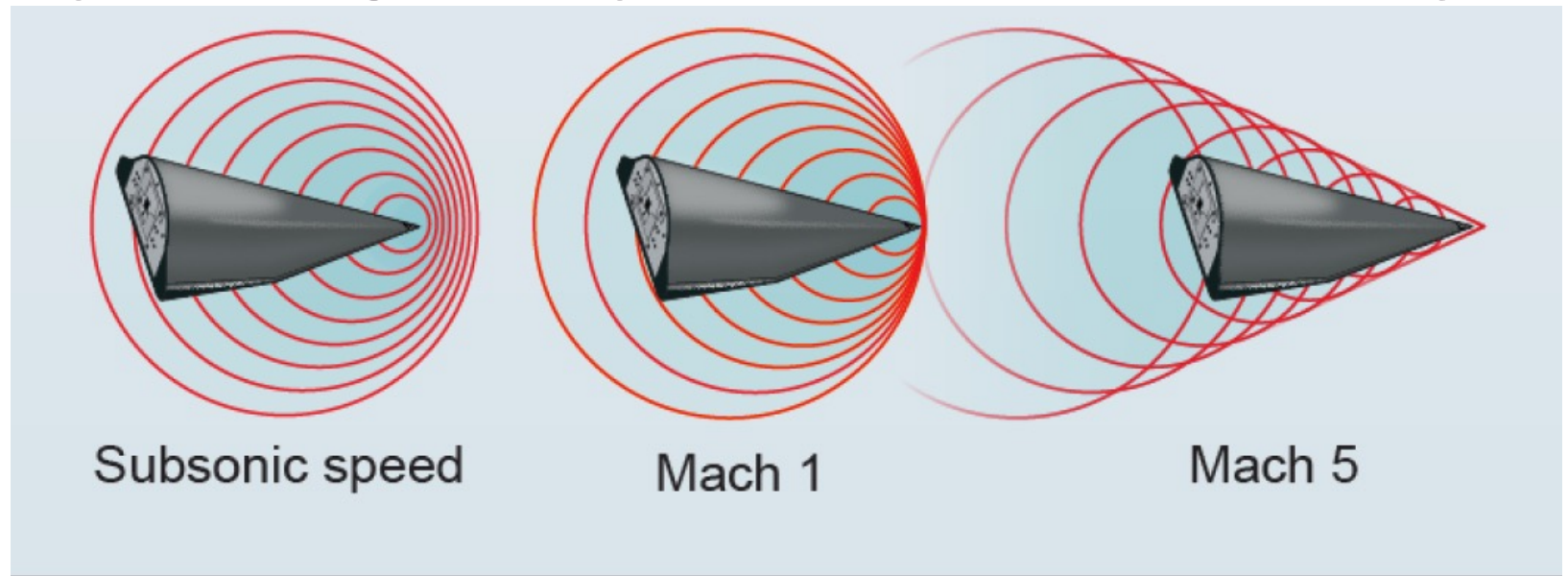
All these phenomena are sharpened with the square of the Mach number

Shock waves

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

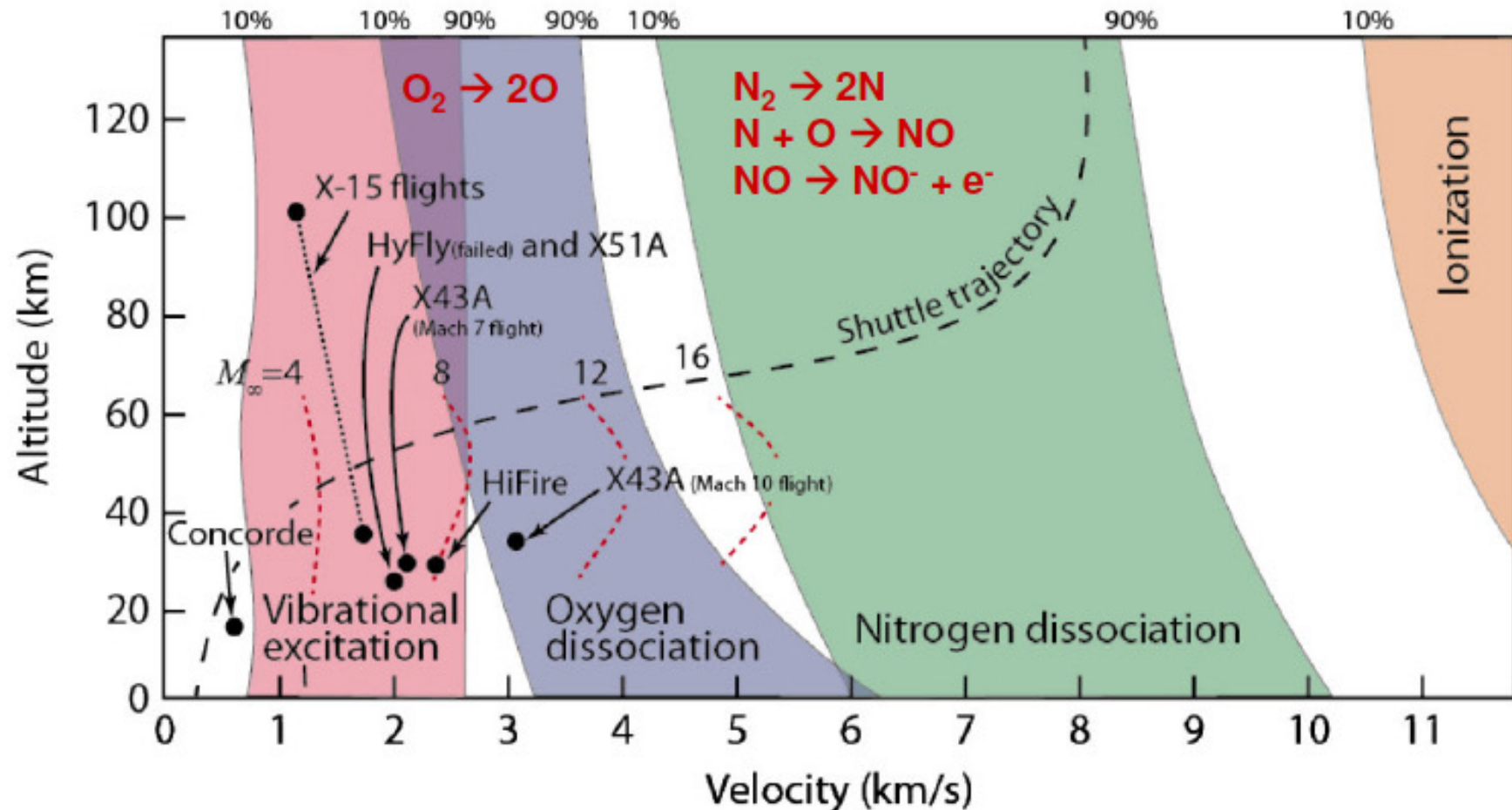
At hypersonic speeds, the angle the shock wave makes with the direction of motion is very narrow and hugs the aircraft's body.

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



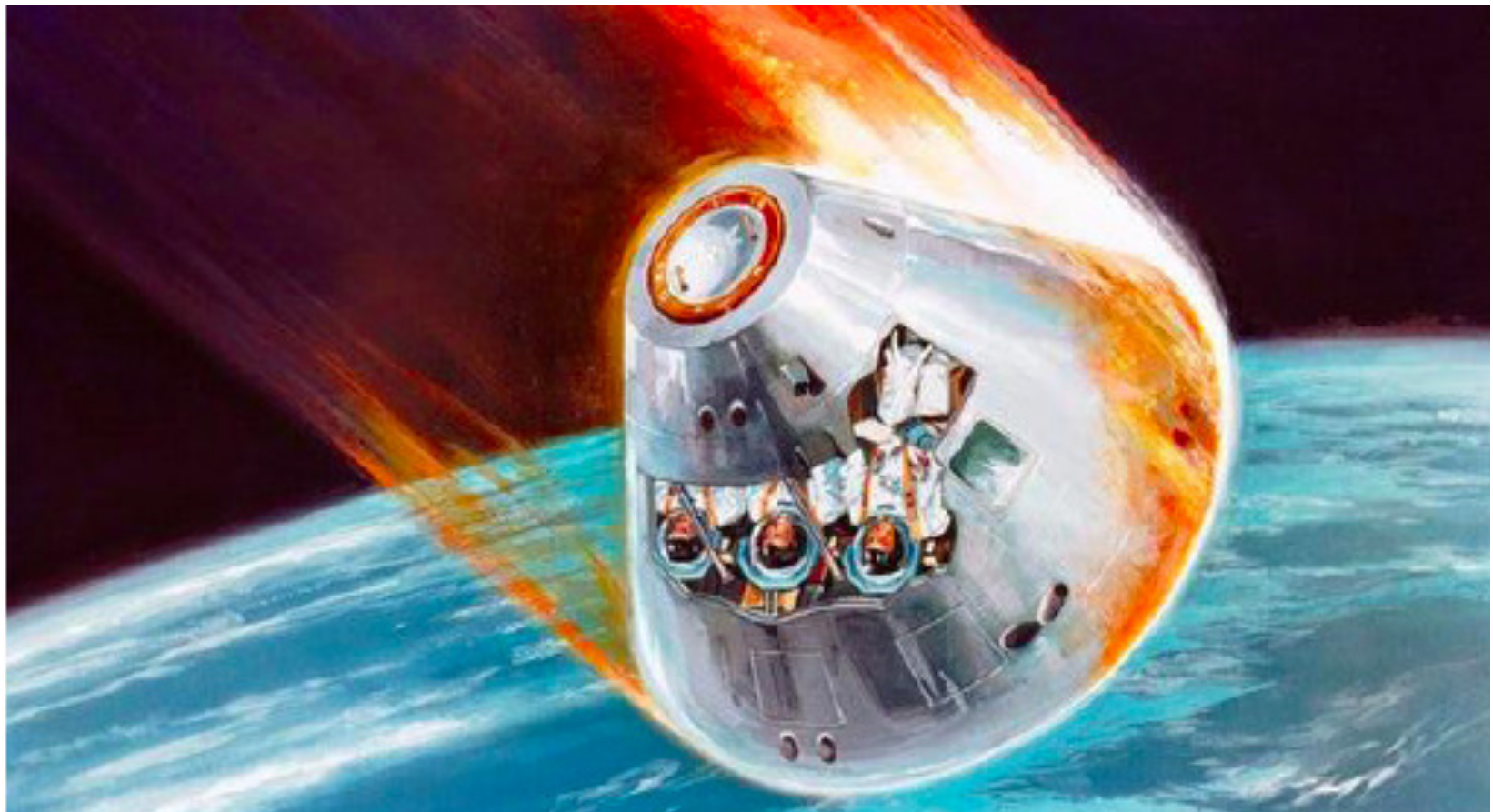
Chemical effects

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



One effect of ionisation is the creation around the vehicle 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**



Physical effects are different on the various parts of the vehicle

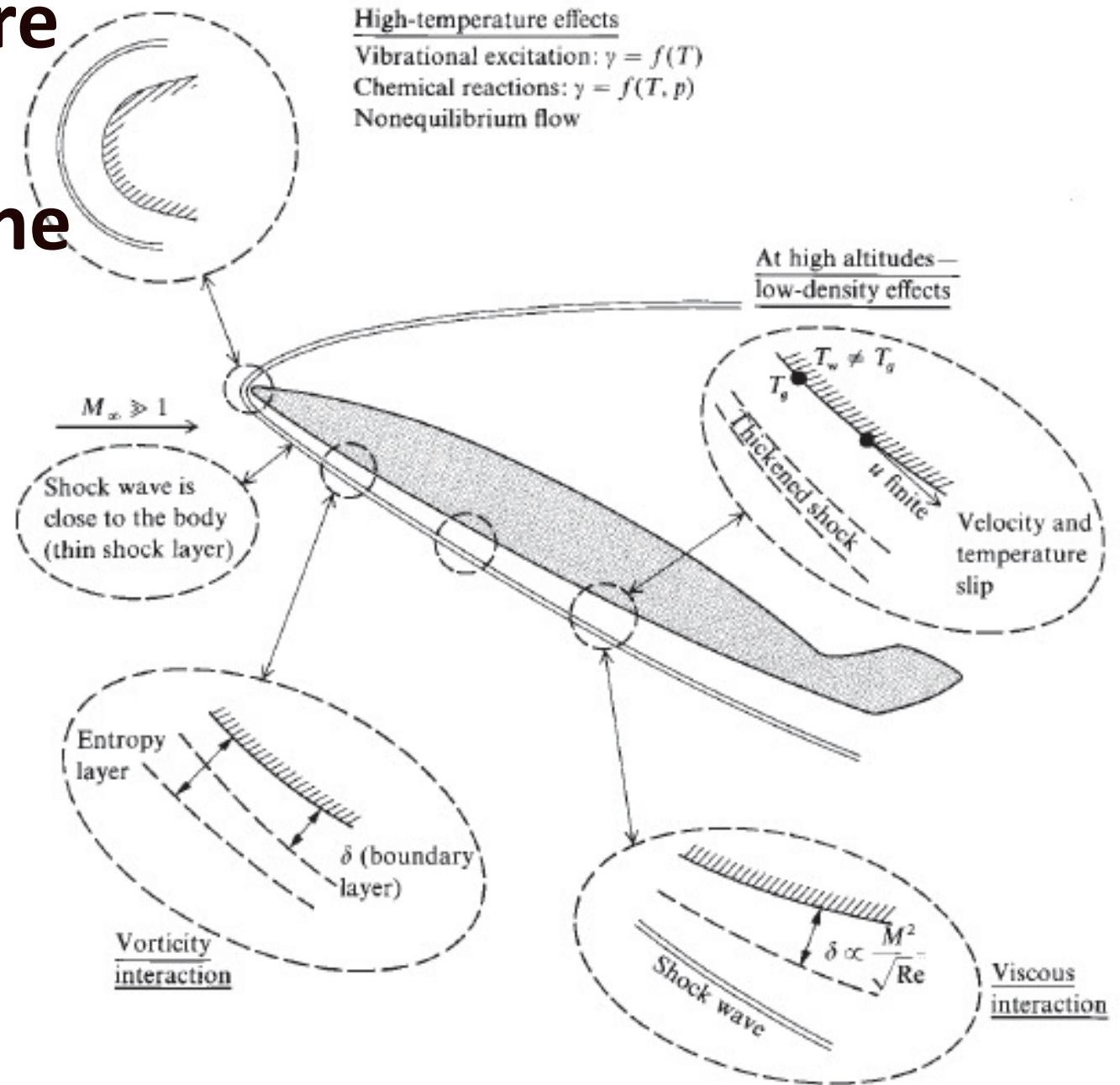
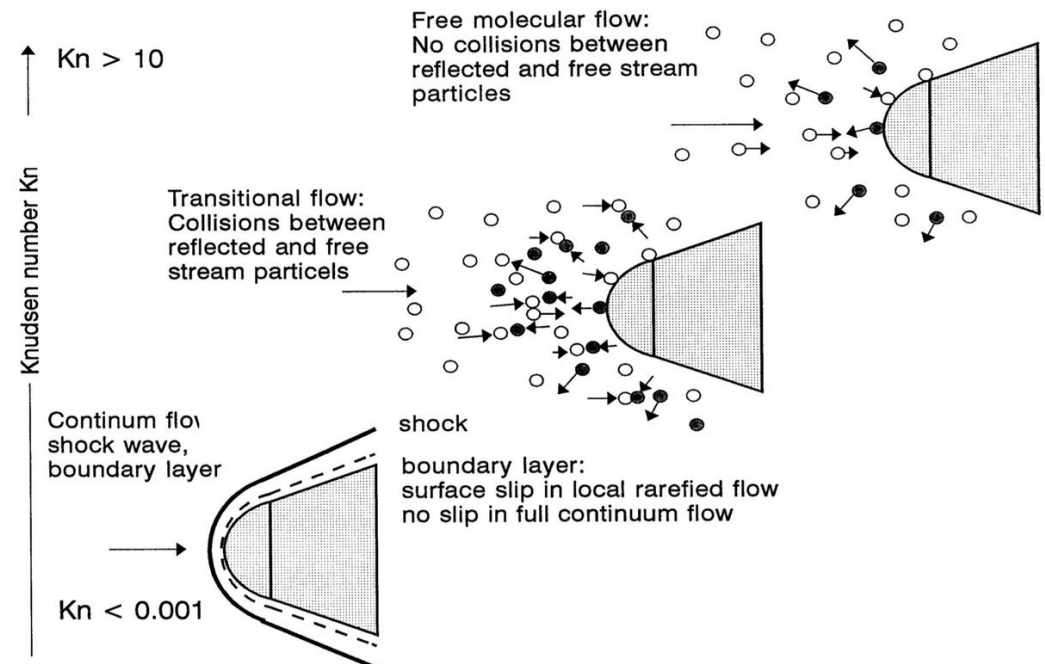


Fig. 1.20 Physical effects characteristic of hypersonic flow.

Free molecular flow

The density of the atmosphere falls by a factor $e \approx 2.72$ 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.



Aerodynamic heating of hypersonic vehicles

The high aerodynamic heating experienced by HVs creates difficulties in maintaining the temperature of structure, leading edges, control surfaces, and internal components below the allowable temperature limit. These high temperatures (over 2000 °C) create high thermal gradients that can cause bending or warping of the HV.

Surface ablation, erosion, and oxidation of the leading edges can also change the shape of the HV.

The development of advanced materials is necessary for hypersonic flight applications.

hypersonic weapons

The evolution of hypersonic weapons is the present chapter of the secular defense/offense competition; the technology aims to defeating anti-ballistic missile defences ensuring penetrability and accuracy of attacking missiles



**Defense/offense strategic competition in the 60's:
air defences made bombers dominance hard to keep
and pushed the development of ICBMs**



Intercontinental ballistic missiles (ICBM)

- high penetrability because of
 - ▷ hypersonic velocities (over Mach 19)
 - ▷ small dimensions of warheads (of the order of few meters)
- problems
 - ▷ deterministic trajectory and targeting
 - ▷ limited accuracy

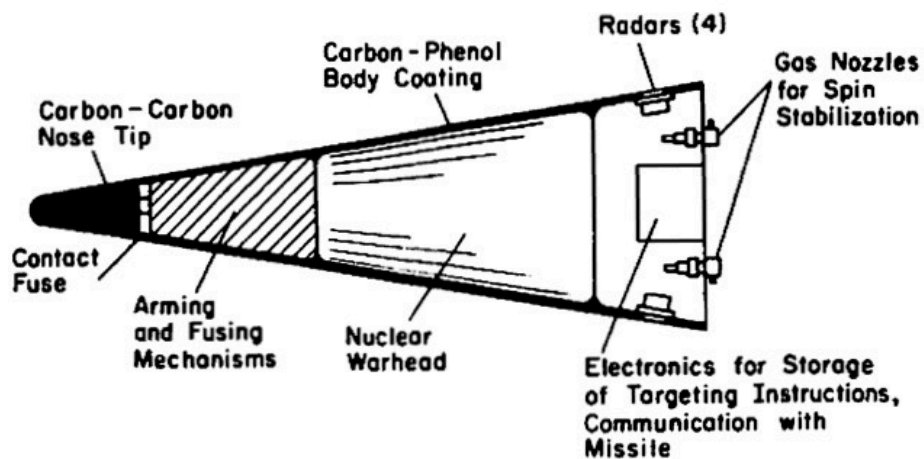
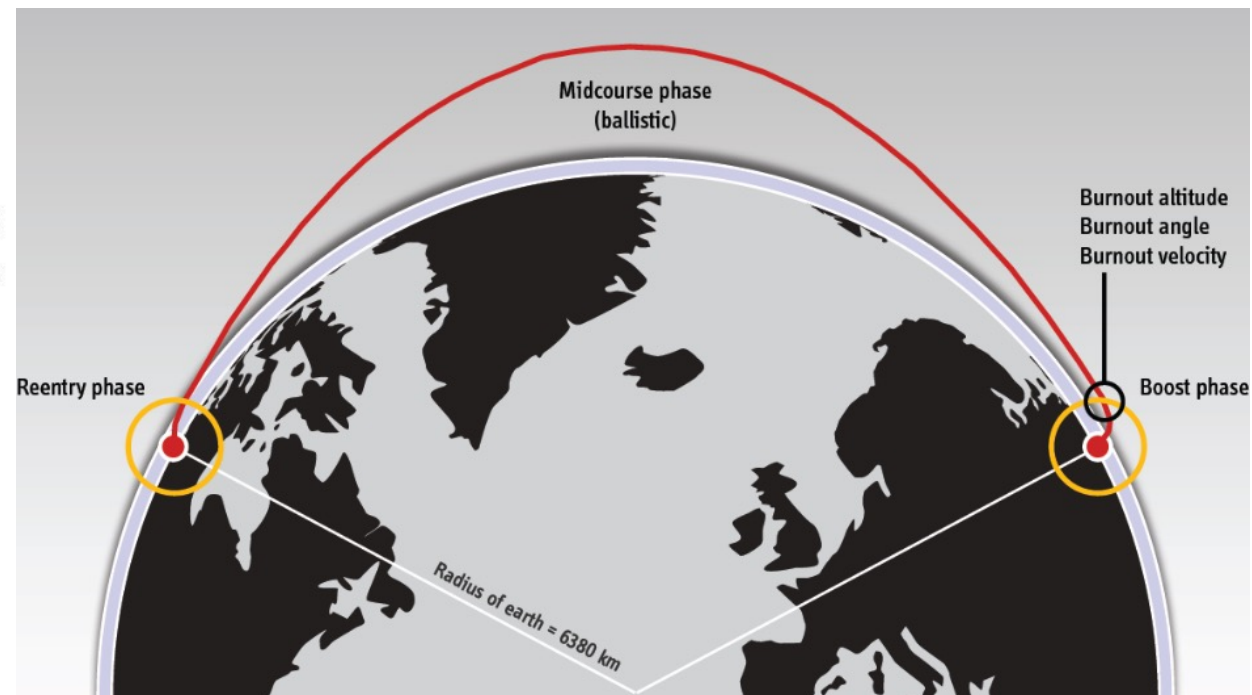


FIGURE 6.1. Typical Ballistic RV

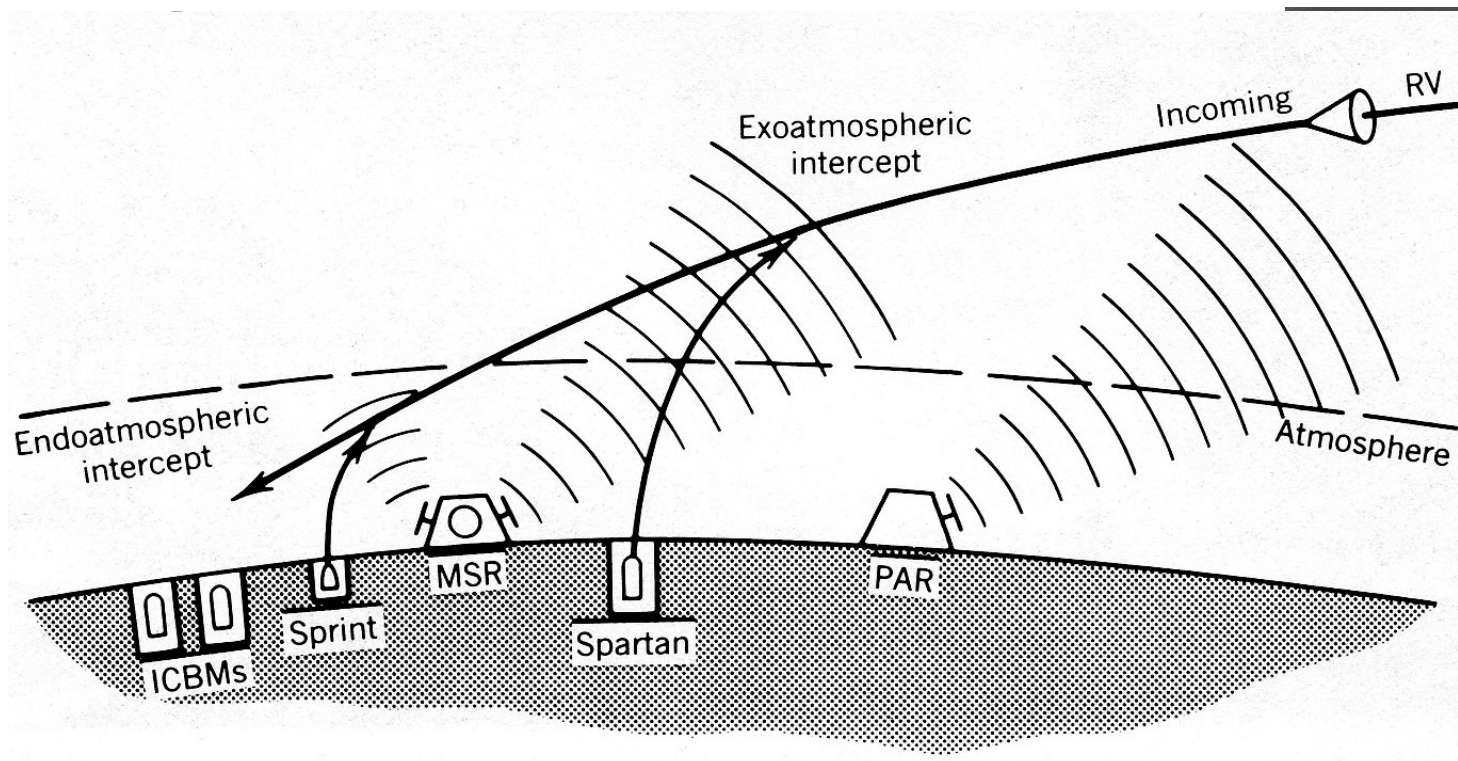


Limits of ballistic missile penetrability

- their trajectory is fully determined by gravity and initial conditions (position and velocity at the release after the boost phase)
- the velocity of the warhead in the final endo-atmospheric phase substantially decreases below Mach 8, because of the air draft
- radar detection during mid-course and final phase makes conceivable terminal anti-missile defences
 - ▷ US Safeguard nuclear ABM system (since mid-1960s)
 - ▷ Soviet A-35 nuclear ABM system (since mid-1960s)

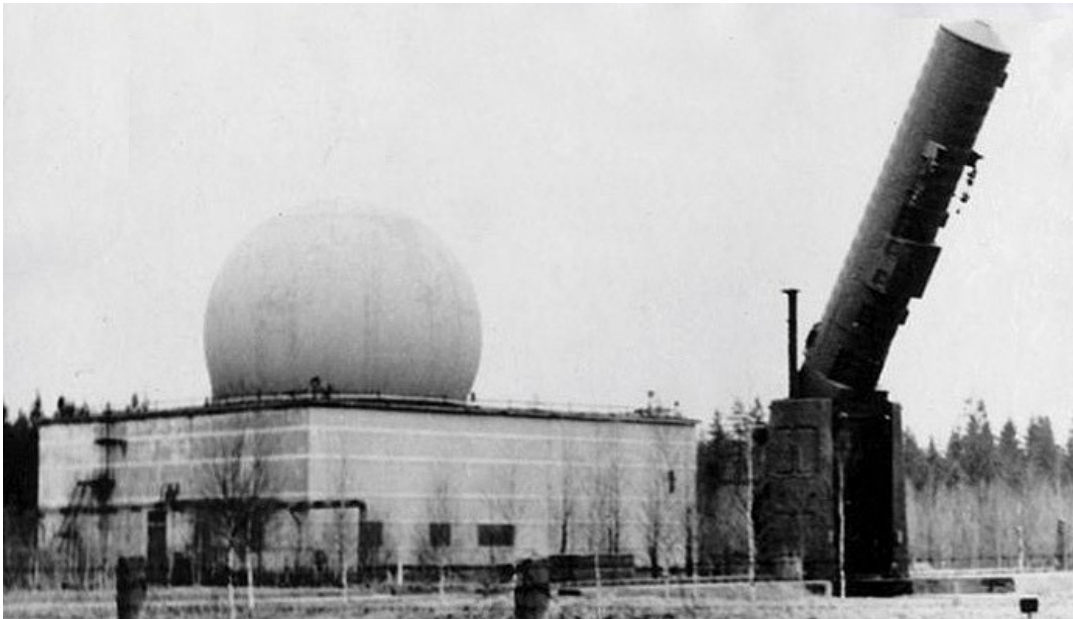
Safeguard ABM system (since mid-1960s)

- two-layer point-defence system for US missile basis
- long-range exo-atmospheric (Spartan) nuclear interceptors
- short-range endo-atmospheric (Sprint) nuclear interceptors
- guided by long-range perimeter acquisition radar and short-range missile site radar



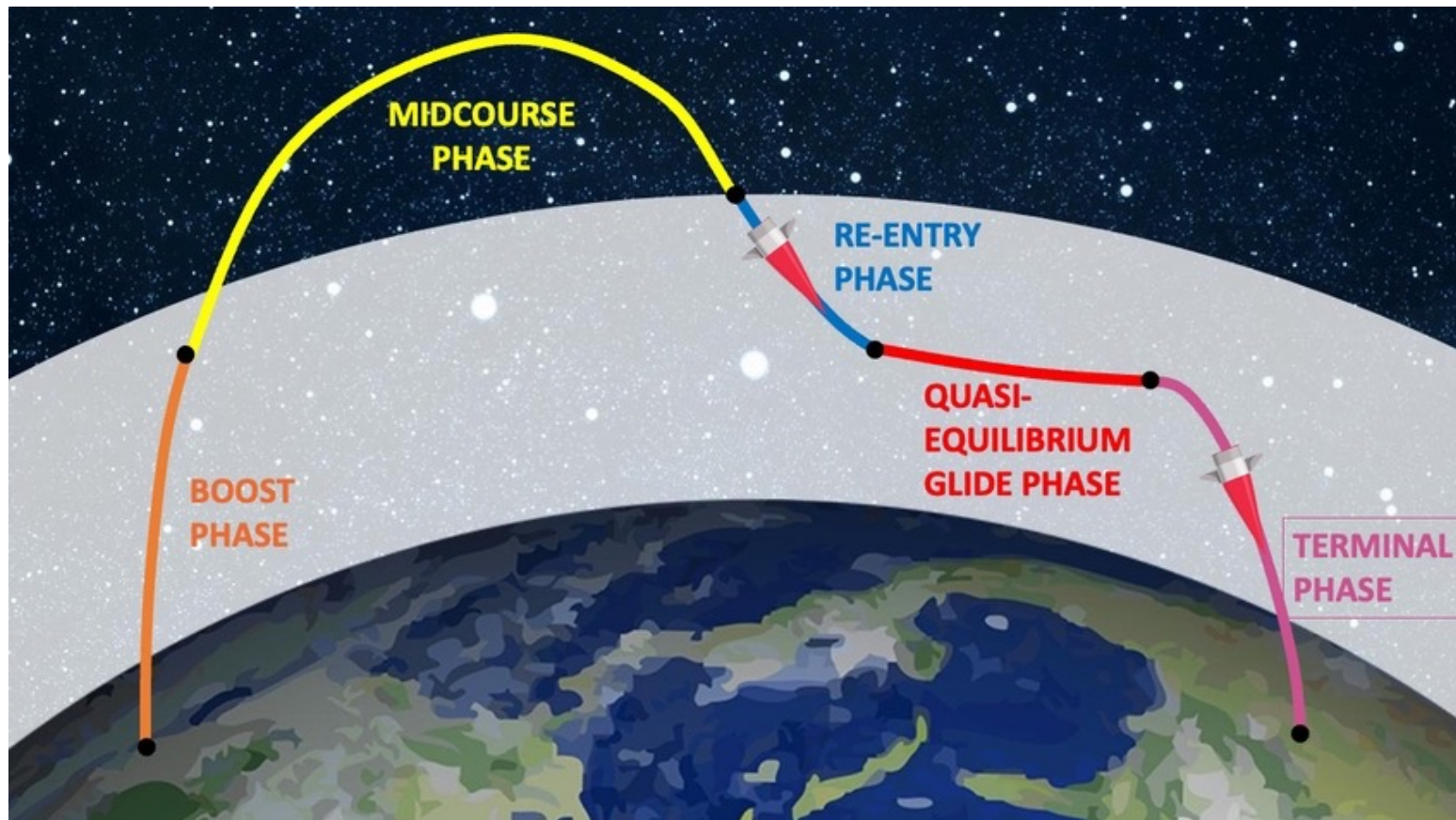
A-35 Sovier ABM system

- point-defence system for Moscow
- supported by two Dunay radars and the early warning system
- composed by a main command centre, eight early warning radars with overlapping sectors, and 32 battle stations
- each battle station had two tracking radars, two battle management radars and sixteen nuclear-armed A350 exo-atmospheric interceptor missiles



In order to penetrate the terminal ABM point-defences: manoeuvring re-entry vehicles (MaRVs)

A MaRV during the terminal (endo-atmospheric) phase of flight assumes a gliding attitude, relying on a flap (fin) system to provide the lift necessary for manoeuvres



MaRVs

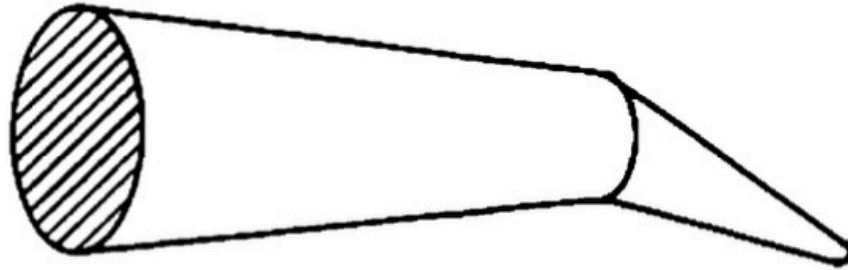


FIGURE 6.9. The Mk 500 "Evader"

The US Mark 500 Evader.

The simplest method to provide the lift necessary for manoeuvres is to bend the vehicle, with the forward portion pointing in a slightly different direction than the rear.

MaRV-tipped missiles have been developed in China, India, Iran, North Korea, Pakistan, South Korea in addition to USA and Soviet Union/Russia

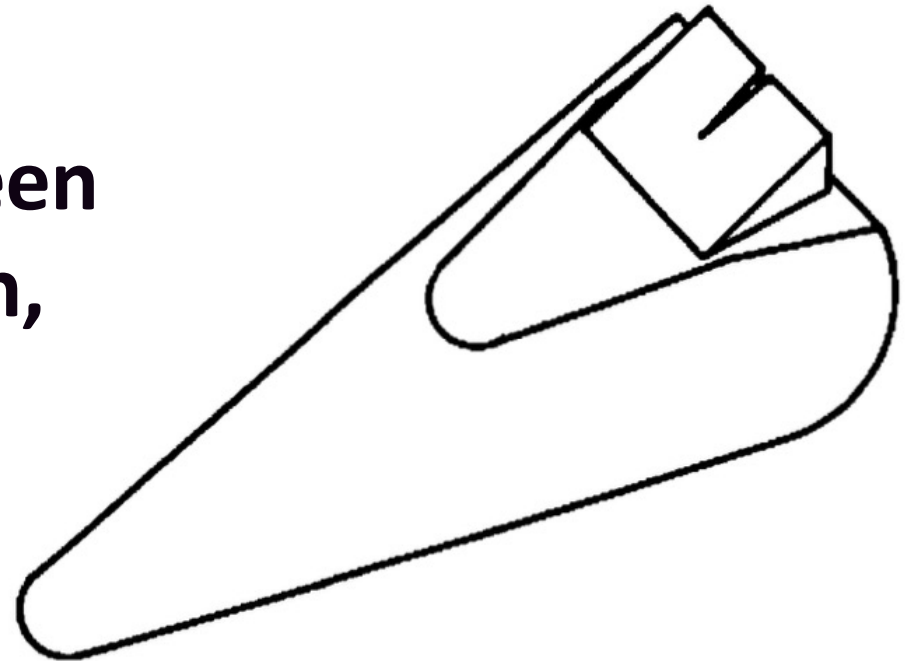
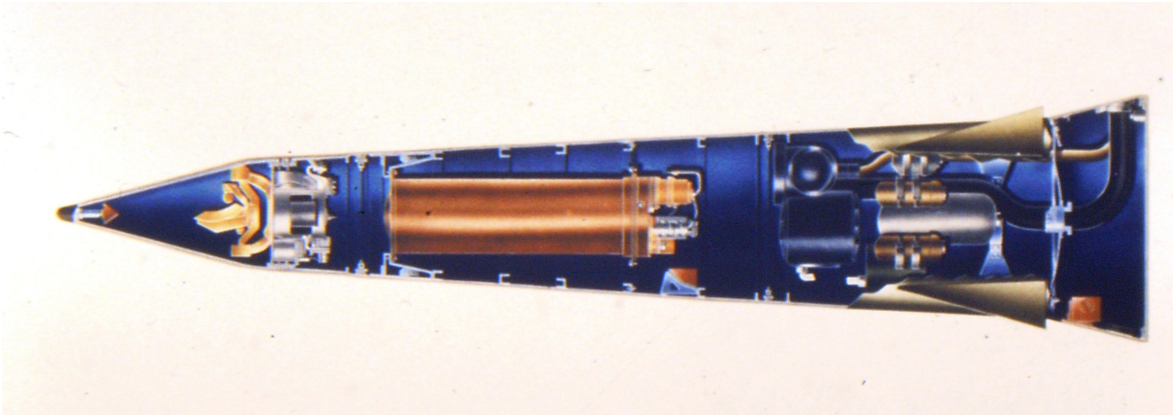


FIGURE 6.10. The Advanced Maneuvering Reentry Vehicle

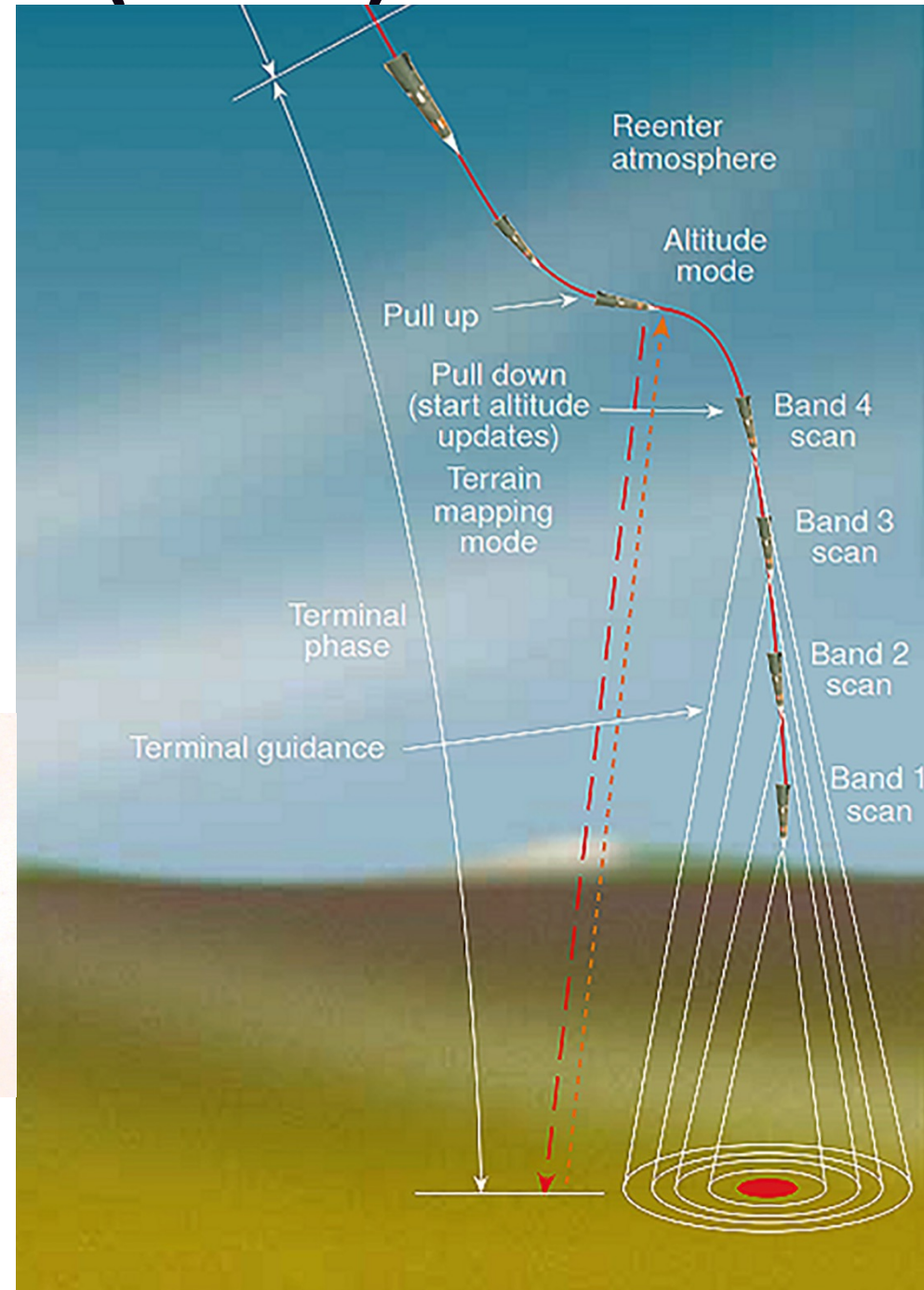
the US AMaRV used small flaps for manoeuvres

Manoeuvring re-entry vehicle (MaRV)

In addition to dodge terminal defences, MaRVs use terminal guidance for high accuracy, to retarget over hundreds of km, and to dive to its target at various angles



Pershing II also used laser final guidance for high accuracy



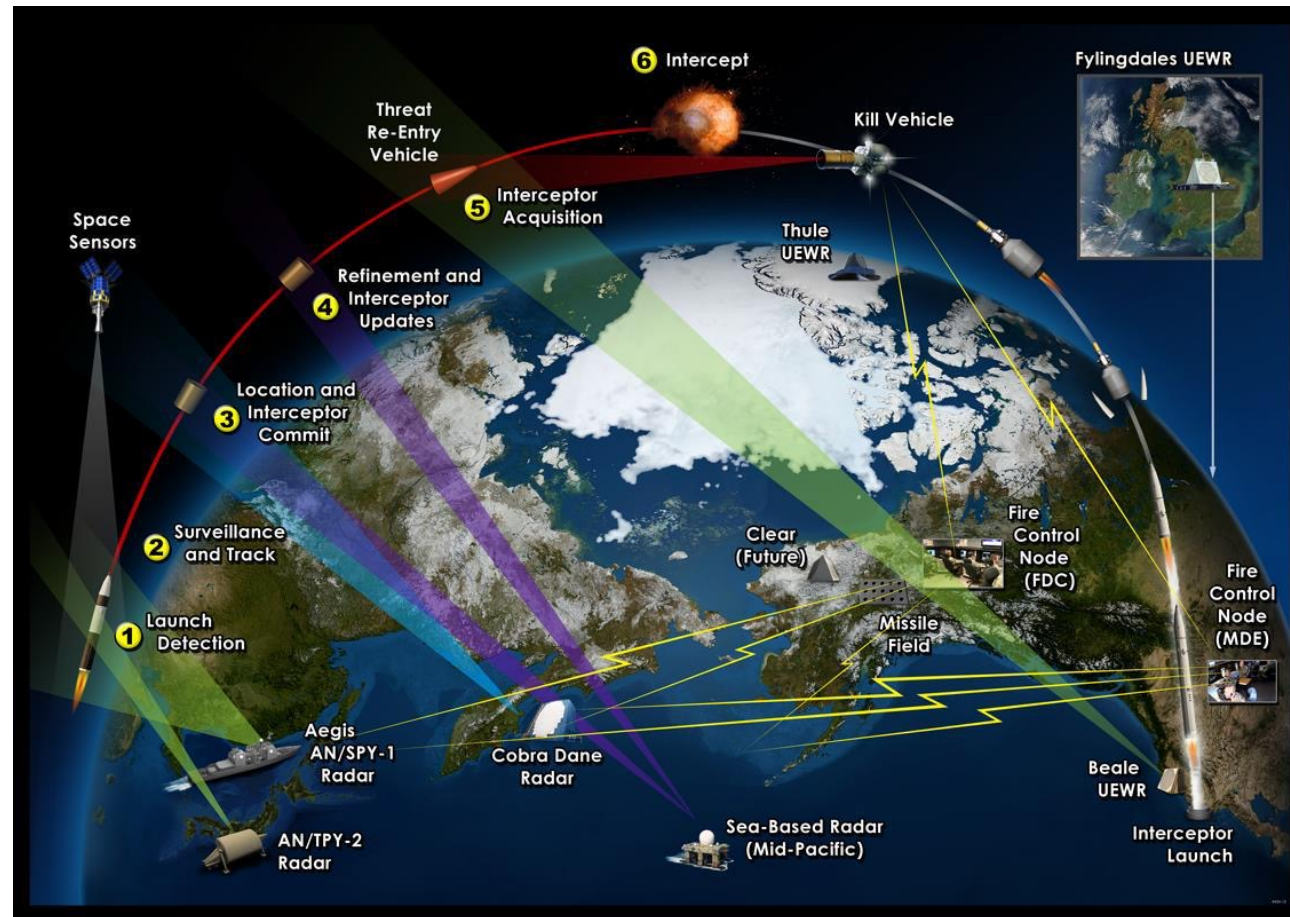
The development of MaRV technology was stopped both in Soviet Union/Russia and United States because of

- the limited efficiency of point-ABM systems in front of cheaper penetration aids of ballistic missiles**
- the failure of ABM systems aiming to area defence**
- the constrains to both defence and offense capabilities imposed by arms control agreements**

the technology was put aside, but not forgotten ...

Development of mid-course ABM systems and the demise of the ABM treaty (2001) brought in the need for new ICBM's penetration means.

Mid-course manoeuvring was suggested and therefore the development of the present hypersonic weapons



Hypersonic weapons – more than hypersonic velocities

Hypersonic weapons are systems that simultaneously possess:

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

No system can simultaneously achieve optimal performance for each of these properties and compromises must be considered

The most advanced hypersonic weapons belong to two primary categories both accelerated to hypersonic speed by boosters:

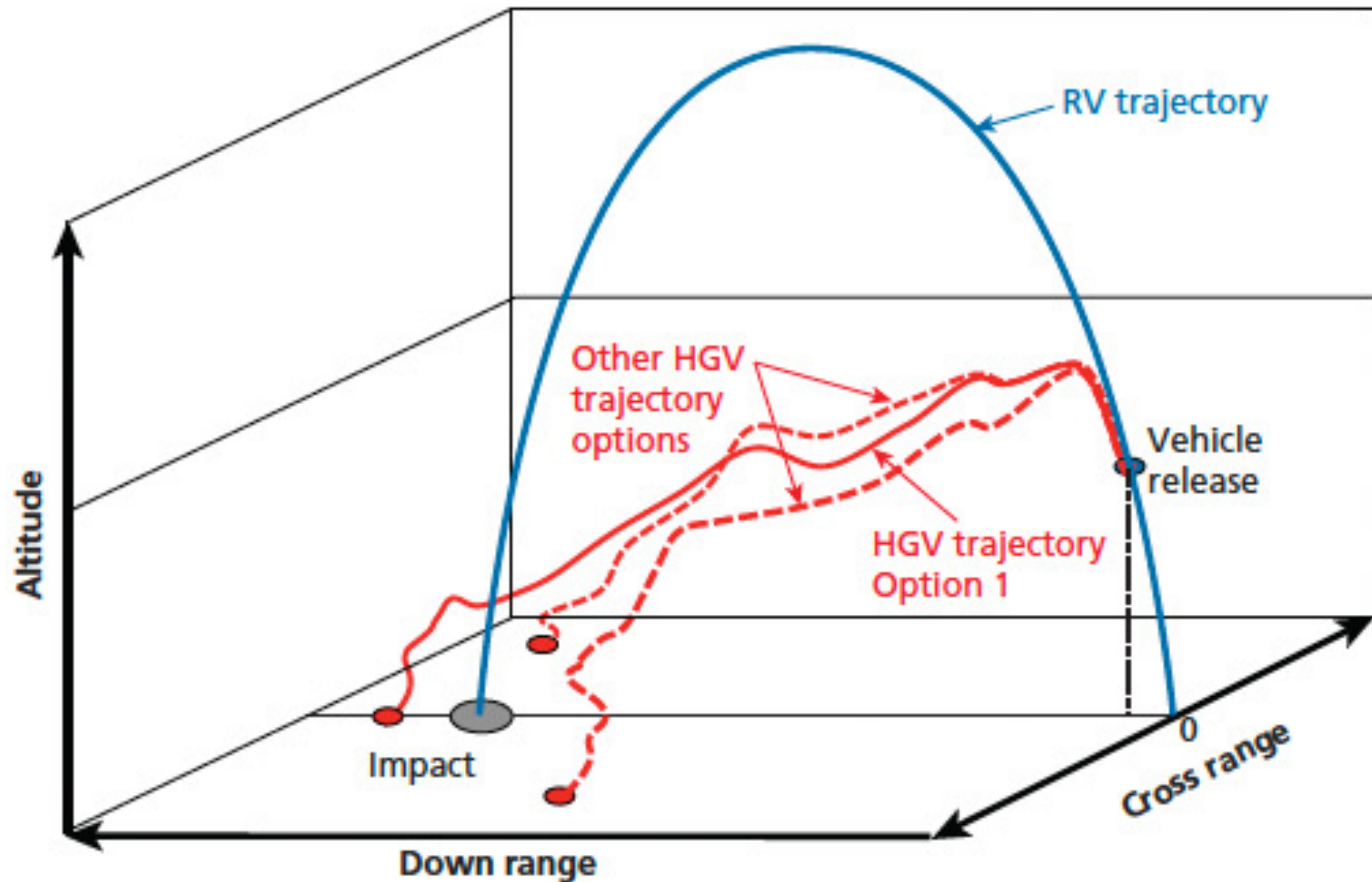
- **hypersonic glide vehicles (HGVs) [or boost-glide vehicles (BGVs)] launched from a rocket into a sub-orbital trajectory deplete their initial energy gliding towards their target**
 - **hypersonic cruise missiles (HCMs) rely on lift forces to reach long distances but carry engines to maintain their speed throughout flight**
-
- ▷ **both can be nuclear- or conventionally armed**
 - ▷ **both are designed for one-time use**

Hypersonic glide vehicles (HGV or BGV)

After a short ballistic phase, HGVs re-enter the atmosphere at high altitude and glide at about Mach 20 velocity towards a target 8–10 thousands km away. HGVs maintain near constant velocity by trading altitude for speed.

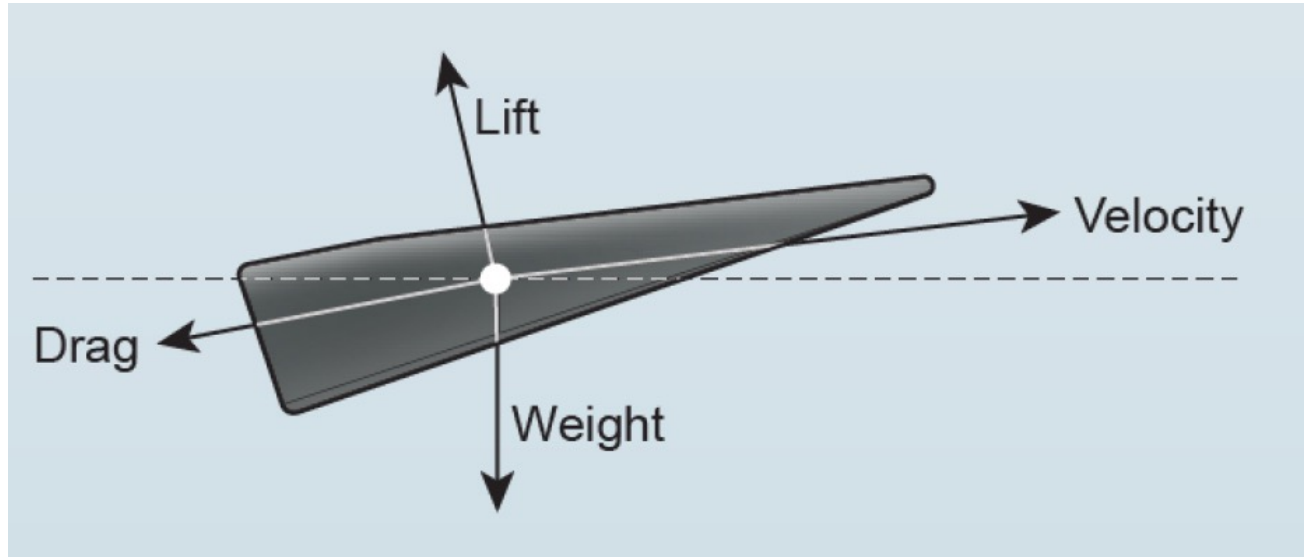


Comparison of ballistic and HGV trajectories



Gravity, lift and drag govern flight trajectories

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



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

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

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 has to decrease.

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

$$D \propto C_D \rho v^2$$

It slows down gliders and makes them harder to manoeuvre.

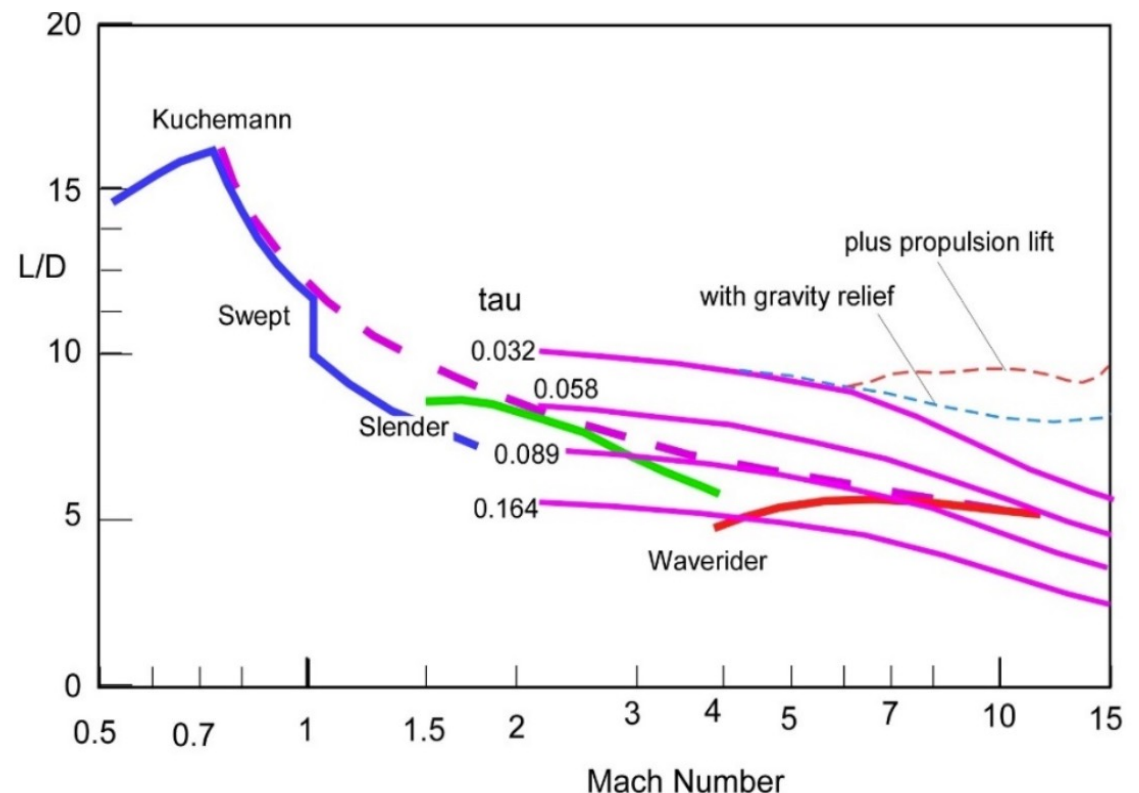
Making matters worse, drag drains kinetic energy from the vehicle, converting it to shock waves and thermal energy in the surrounding air; temperatures up to several thousand degrees are reached.

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 $L/D \approx 2.6$



Equation of motion for a gliders flying over the Earth

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

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

ρ = air density

R = radius of the Earth

v = glider's initial speed

β = ballistic coefficient = $m / (C_D A)$

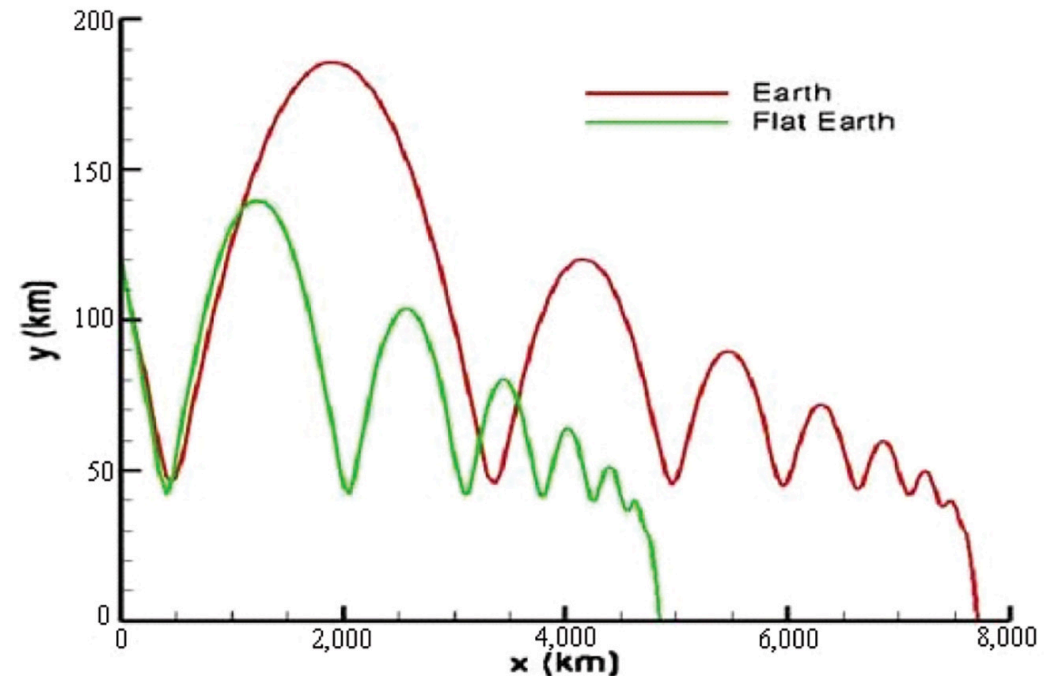
g = gravitational acceleration

[Tracy and Wright, 2020]

The range of a glider of Mach 20 and $L/D = 2.6$ is about 10,400 km

Phugoid (skip-glide) trajectory

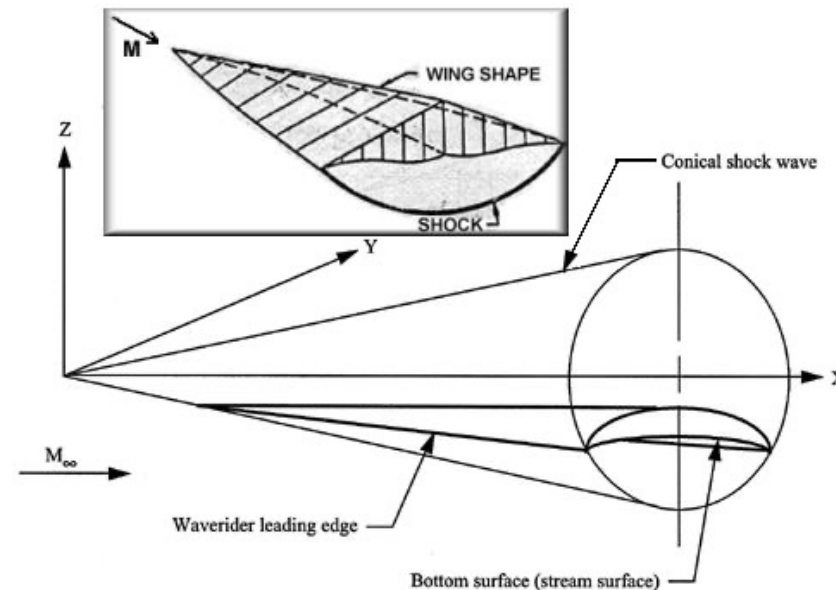
A HGV, launched at high apogee and re-entering to gliding flight at a minimum angle, proceeds with a skip-glide (phugoid) trajectory, bouncing in and out of the atmosphere several times; since most of the flight takes place in vacuum, where drag is almost zero, the HGV can reach great distances



“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.



waveriders require caret wings

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 performance of the overall system and the necessary trade-offs between some of its capabilities.

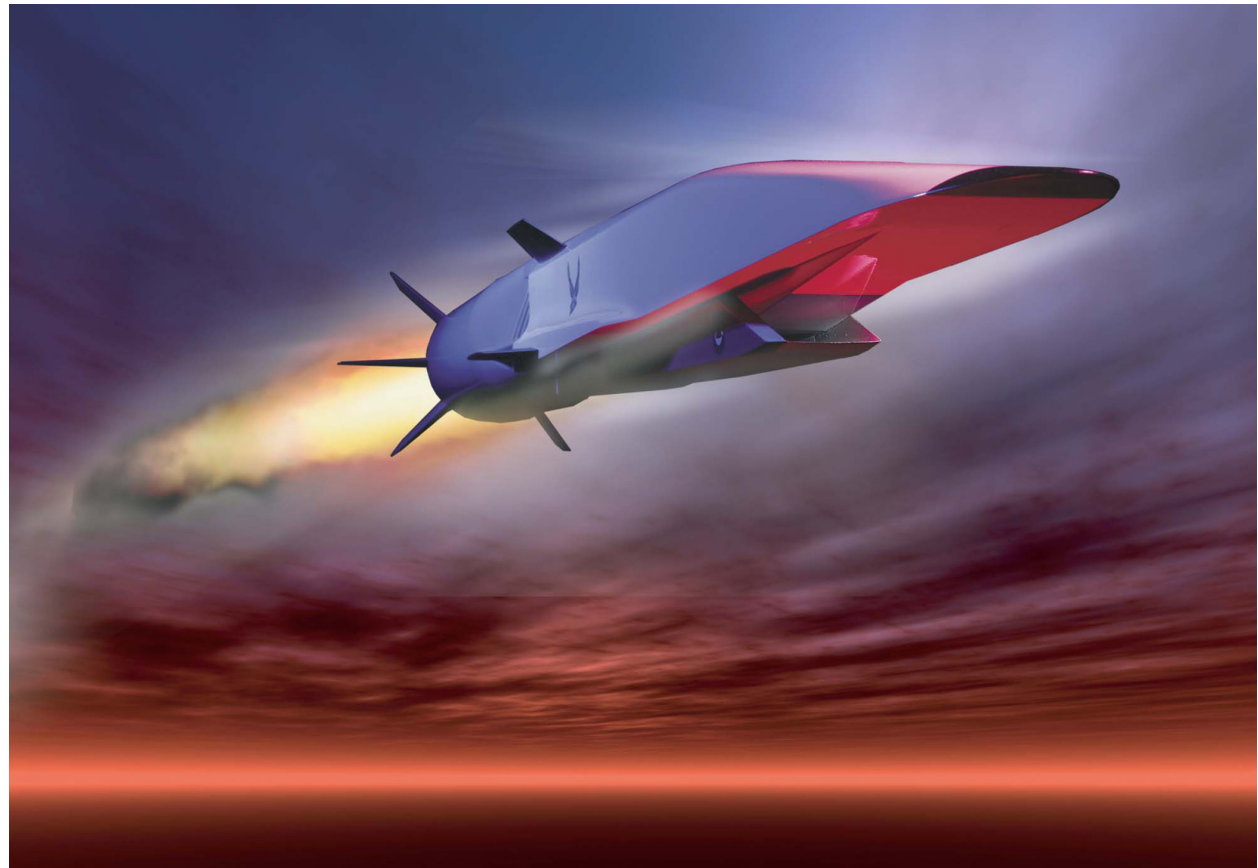
Hypersonic cruise missiles (HCMs)

HCMs are launched from a rocket or an aircraft at 20 – 30 km altitude; they are powered by scramjet engines up to Mach 8 – 10 velocity towards their target, at about thousand km away.

By using air as oxidizing agent, they must fly at limited altitude, where air is dense enough

x

X-51 waverider



Jet engines

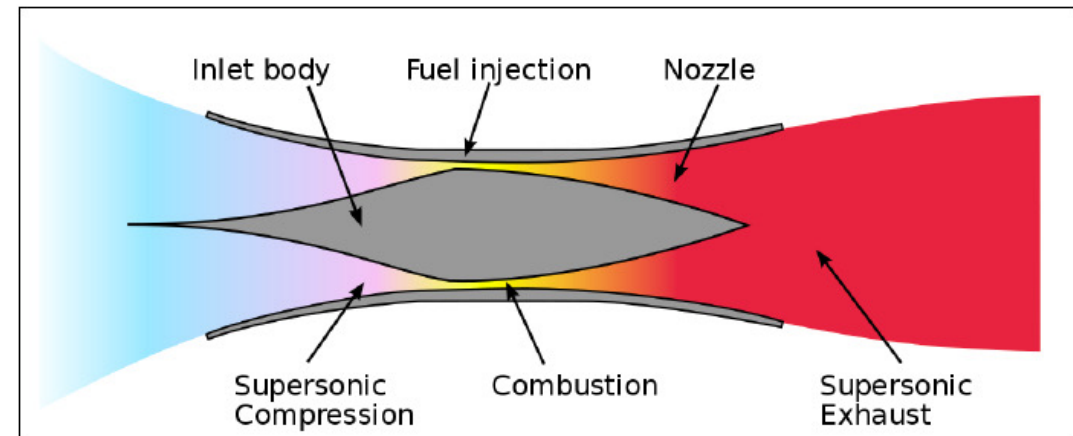
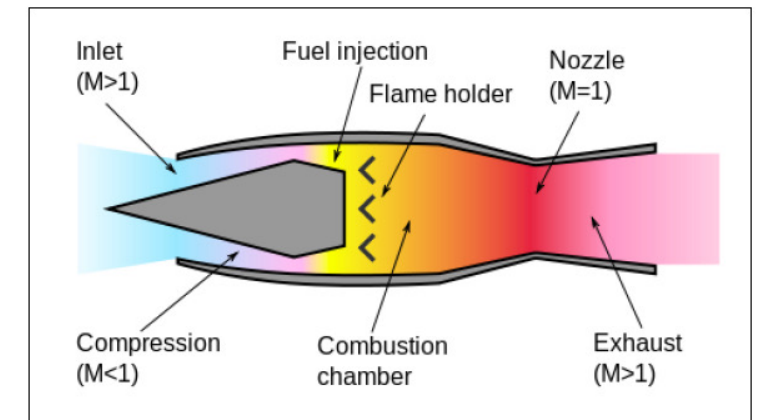
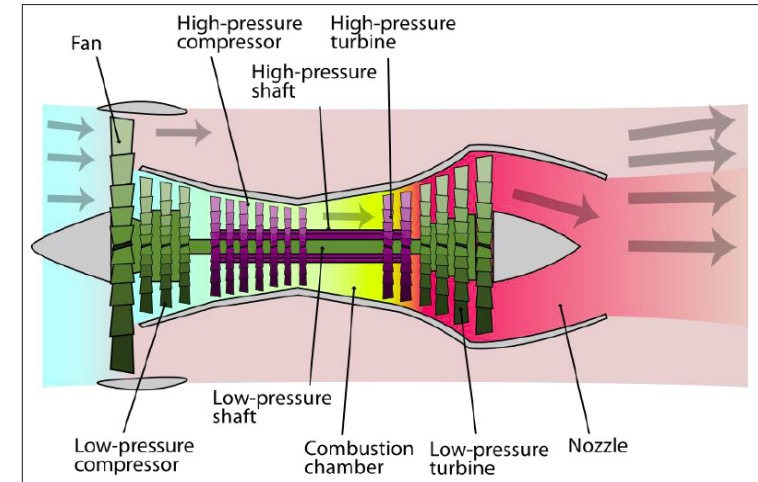
Air-breathing propulsion is a special challenge at high Mach numbers.

Traditional jet engines do not work in this regime.

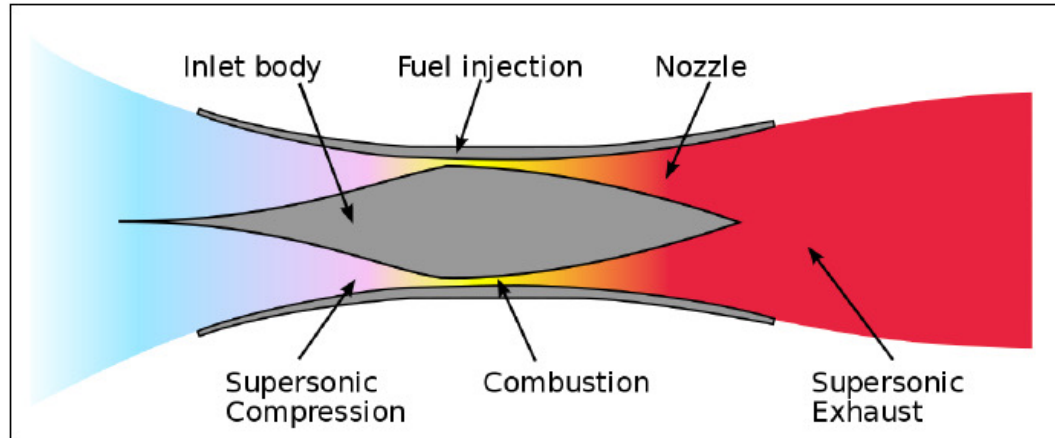
a. turbojet [subsonic]: the incoming flow must be compressed for combustion

b. ramjet [supersonic]: the incoming supersonic flow is made subsonic for the combustion

c. scramjet [hypersonic]: ramjet with a supersonic combustion



The hypersonic engine of choice, the scramjet, slows the airflow to supersonic velocity using shockwaves produced by its ignition source.



Maintaining combustion in the supersonic flow presents additional challenges: the engine that power the craft has to swallow air through an inlet, inject and mix fuel into the air, ignite and 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.

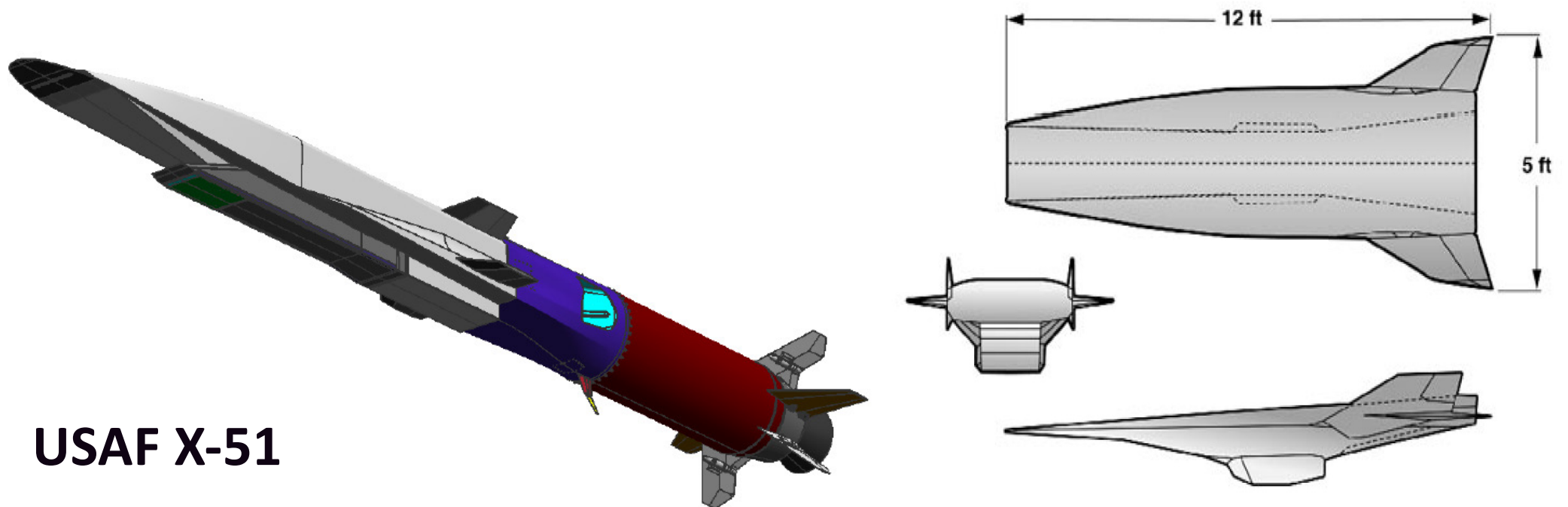
As speed rises, the internal energy of the flow after diffuser grows rapidly, so the relative addition of energy due to fuel combustion becomes lower, leading to decrease in efficiency of the engine.

Hypersonic versus subsonic and supersonic airplane design philosophy

For subsonic and supersonic aircraft, the components for providing lift (the wings), propulsion (the engines), and volume (the fuselage) are separate and distinct components, not strongly coupled with each other. They can be treated as separate aerodynamic bodies with only a moderate interaction when they are combined in the total aircraft.

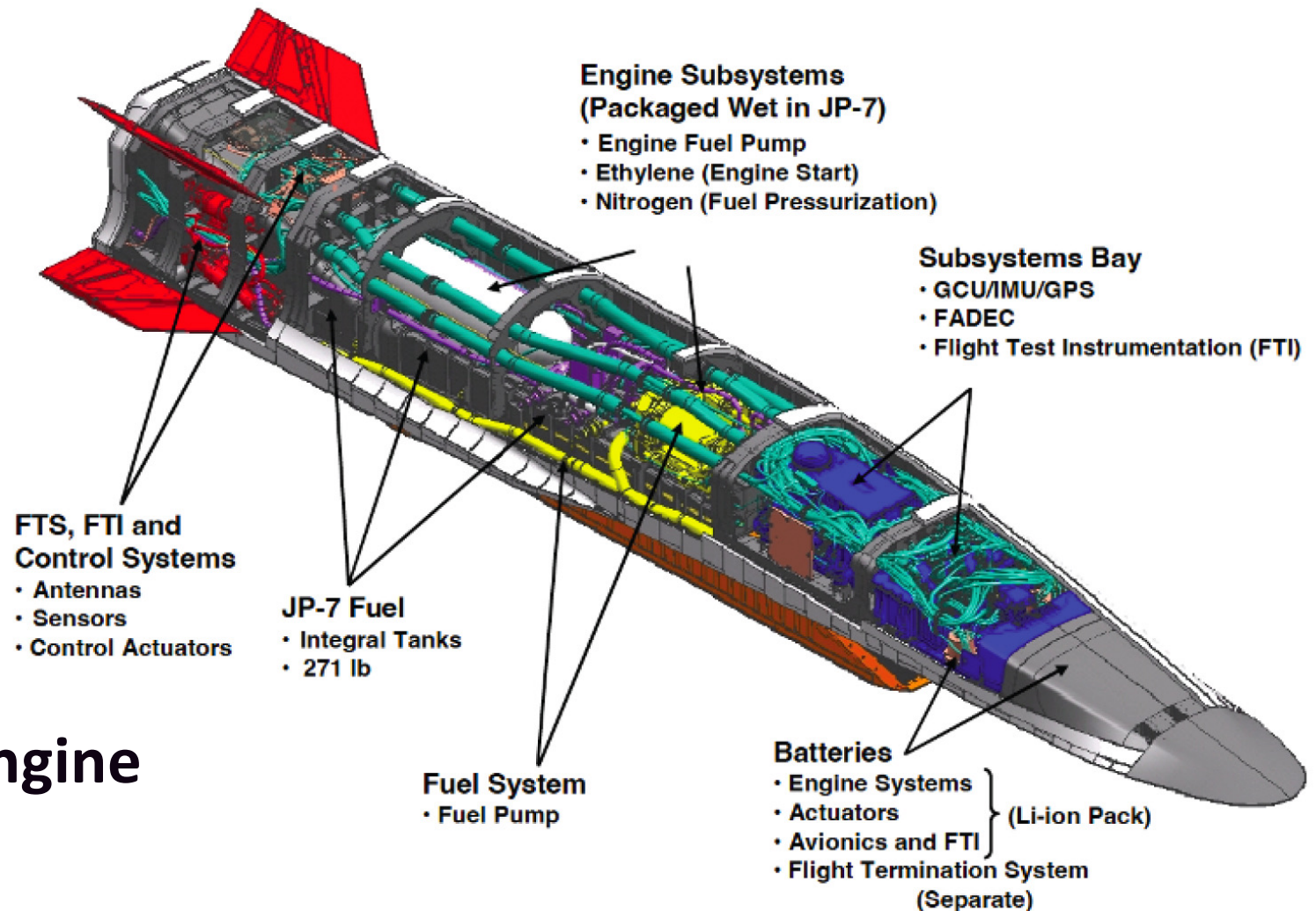
Hypersonic aerodynamic design is exactly the opposite, wherein the entire undersurface of the vehicle is part of the scramjet engine. Hence, the propulsion mechanism is intimately integrated with the airframe.

In a hypersonic vehicle the components to generate lift, propulsion, and volume are not separate from each other; they are closely integrated in the same overall lifting shape, in direct contrast to conventional subsonic and supersonic vehicle design.

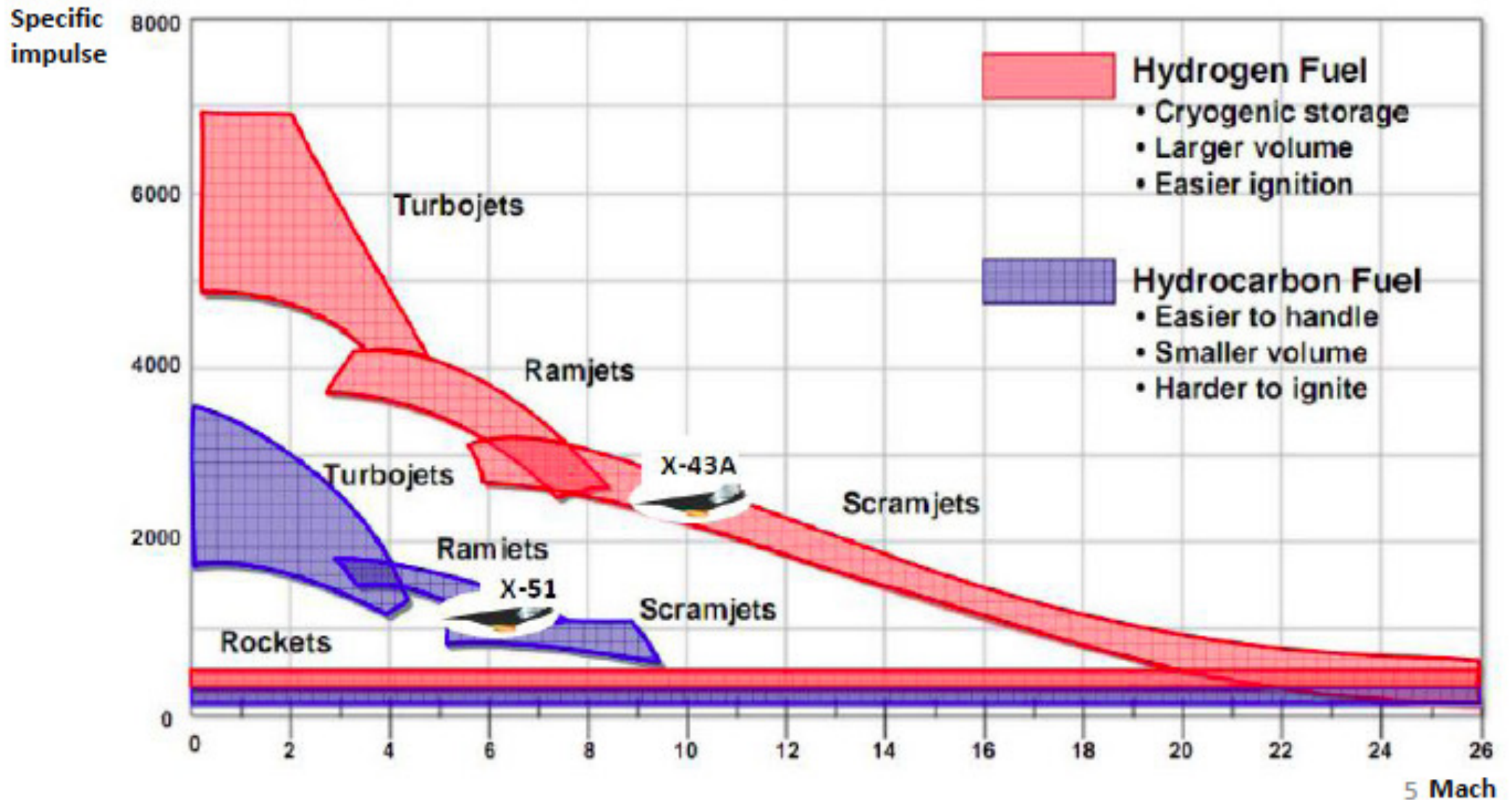


In order to start the scramjet engine the vehicle must reach hypersonic velocities by means of a rocket or a turbine-based combine cycle (inlet-turbine-ramjet)

**subsystems of the
X-51-A scramjet engine
demonstrator**

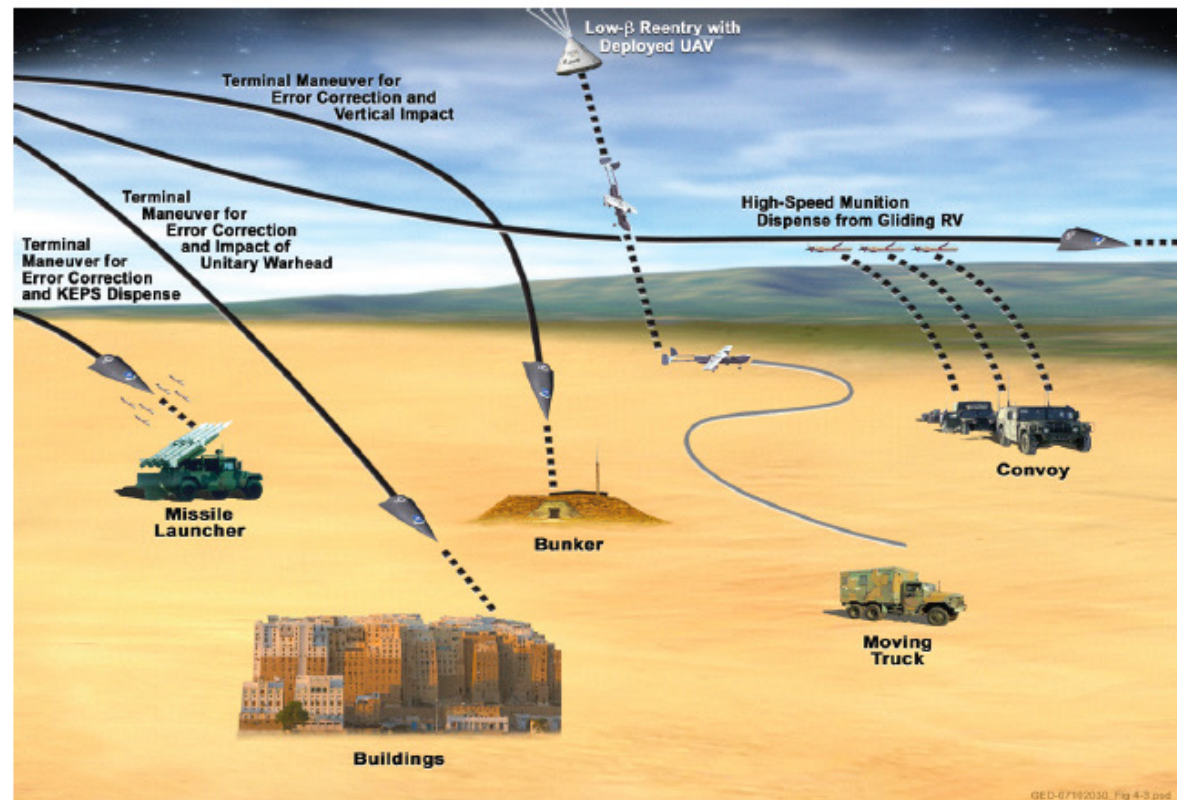


Current scramjet technology requires the use of high-energy fuels and active cooling schemes to maintain sustained operation, often using hydrogen and regenerative cooling techniques



Armaments for hypersonic weapons

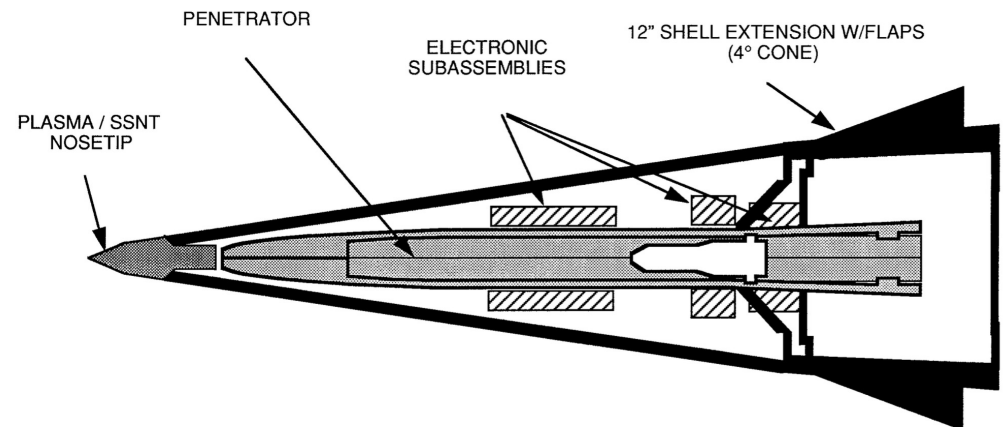
- nuclear warhead
- conventional armaments
 - ▷ high explosive against missile silos or underground targets
 - ▷ fast ammunition to disperse over distributed targets
 - ▷ UAV against mobile systems
 - ▷ kinetic energy projectiles
- ◆ indicative useful load:
 - ▷ over 500 kg for HGV
 - ▷ around 450 kg for HCM



Kinetic energy armaments

- kinetic energy projectiles (KEP): a rose of 750 g tungsten cylinders (shock darts); at impact speed of 2 km/s each KEP reaches the energy of 1.5 MJ ($\approx$ 360 g of TNT equivalent)
- kinetic energy particles: thousands particles of 75 g mass with energy 150 kJ each at impact speed of 2 km/s
- a HGV or HCM could potentially rely on its own kinetic energy of impact alone (a mass of 2000 kg at impact speed of 2 km/s has an energy of 8 GJ $\approx$ 2 ton of TNT)
- kinetic penetrator: a 1000 kg penetrator impinging at 2 km/s has an energy of 2 GJ = 0.5 t of TNT.

*** a 20 kJ bullet seriously damages an aircraft**



* DRAWING NOT TO SCALE

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

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.**

limits and competitors

The myth

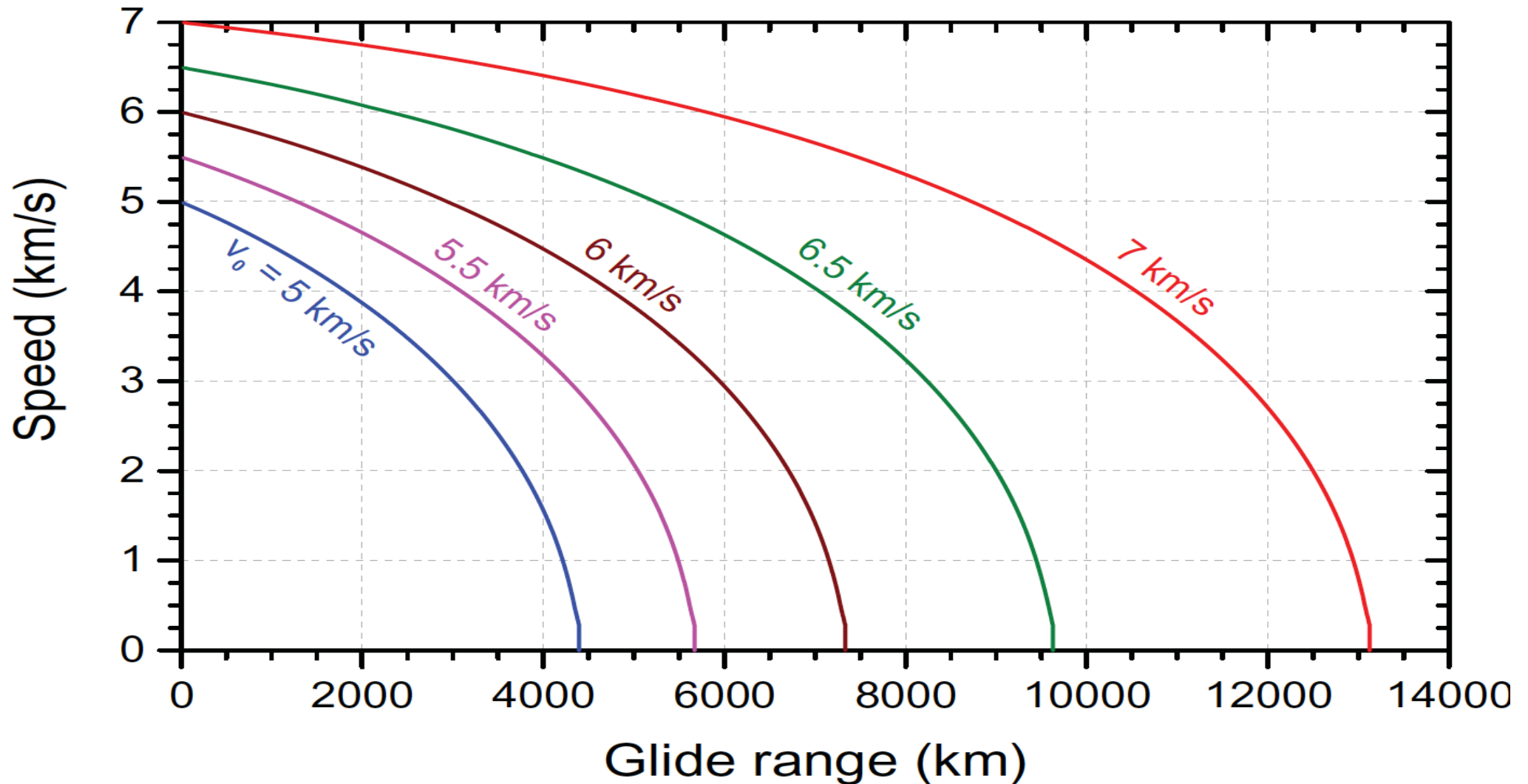
Hypersonic missiles are depicted as a “game changer”:

- 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”

“unmatched speed”

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

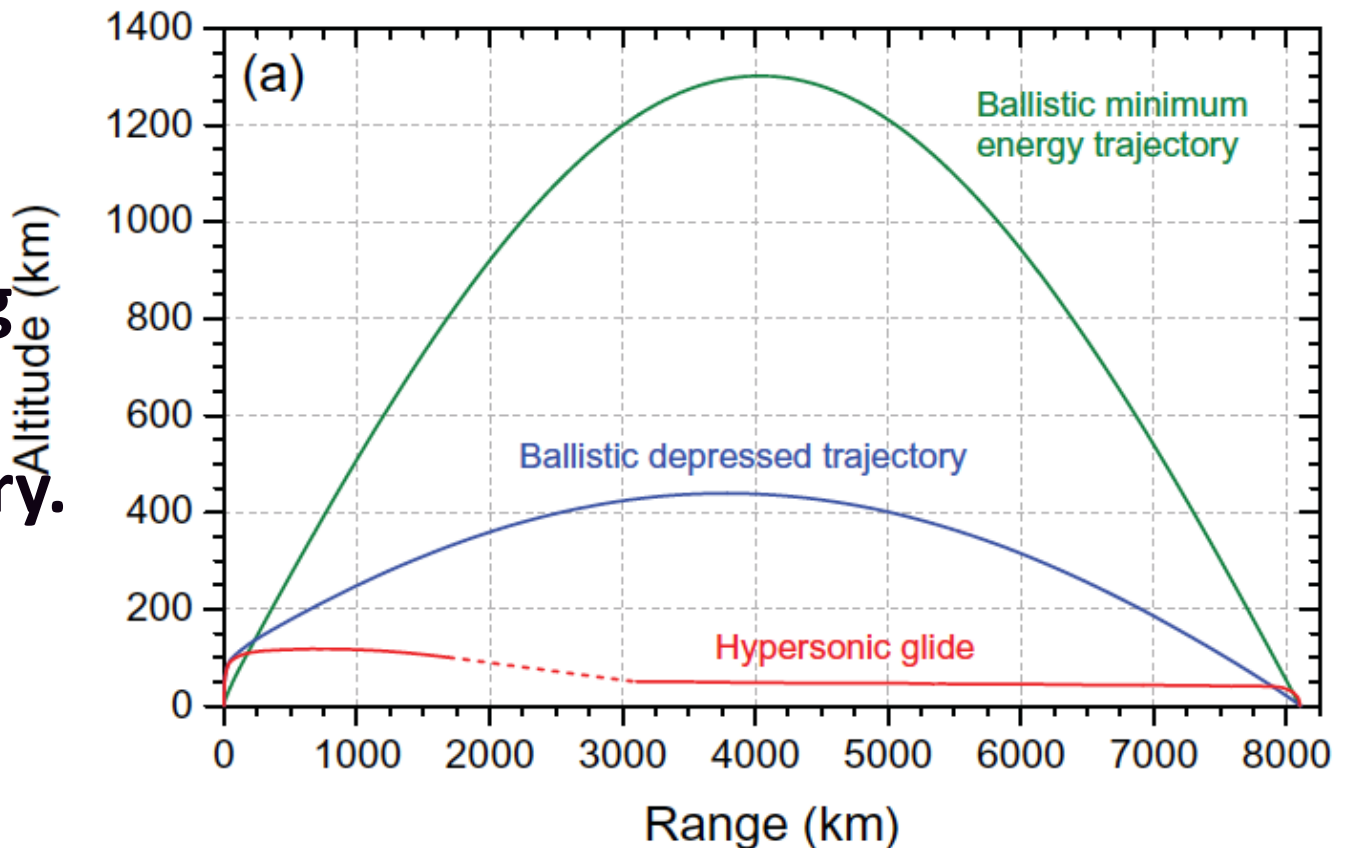


Depressed trajectory ballistic missiles

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.

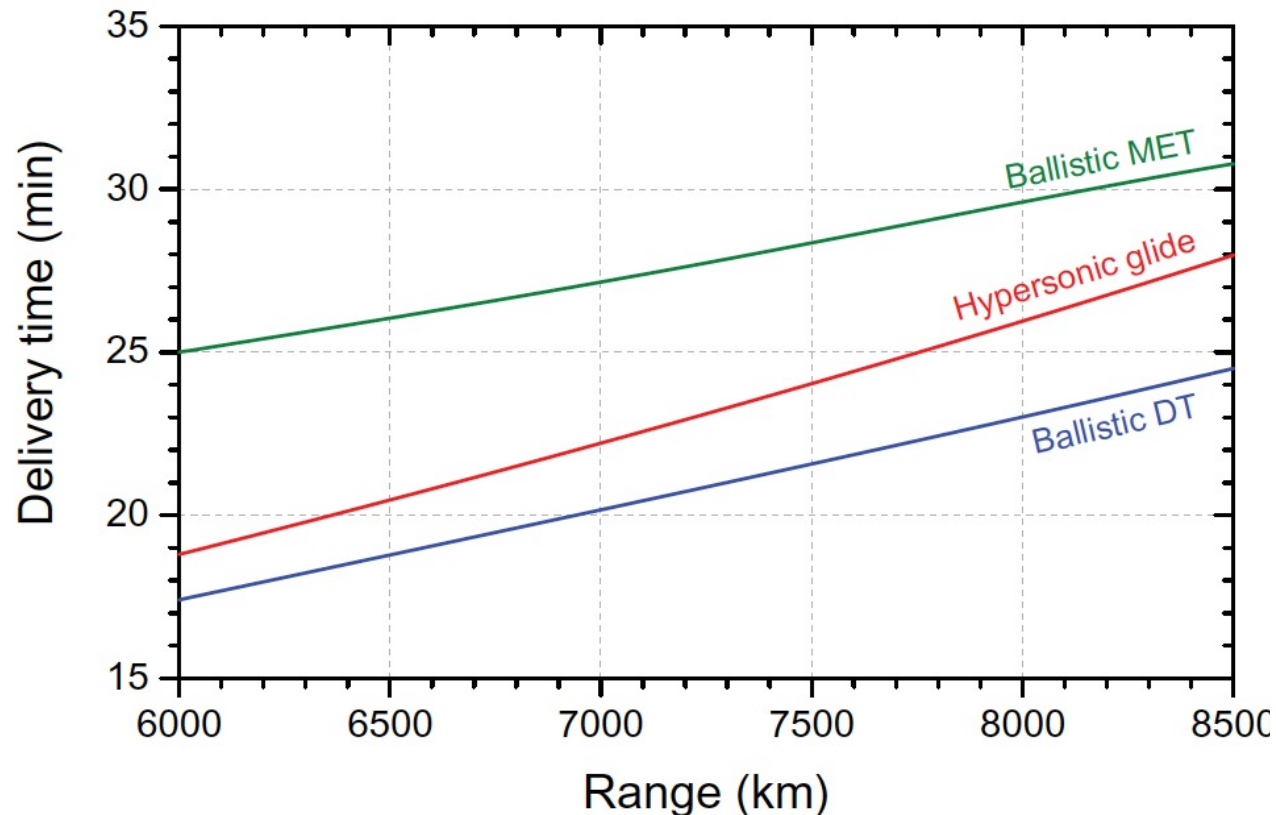
Such a path would be much shorter than a minimum-energy one, and a warhead following it would also avoid drag over most of its trajectory.



“shortest delivery time”

A HGV can reach targets at long ranges 3 to 6 minutes faster than a reentry vehicle delivered by a ballistic missile on a typical minimum-energy trajectory.

But ballistic missiles fired on depressed trajectories reach faster arrival times. In fact, an RV delivered on a depressed trajectory would arrive 2 to 4 minutes faster than a HGV and its delivery time advantage over hypersonic gliders increases with range.



“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.

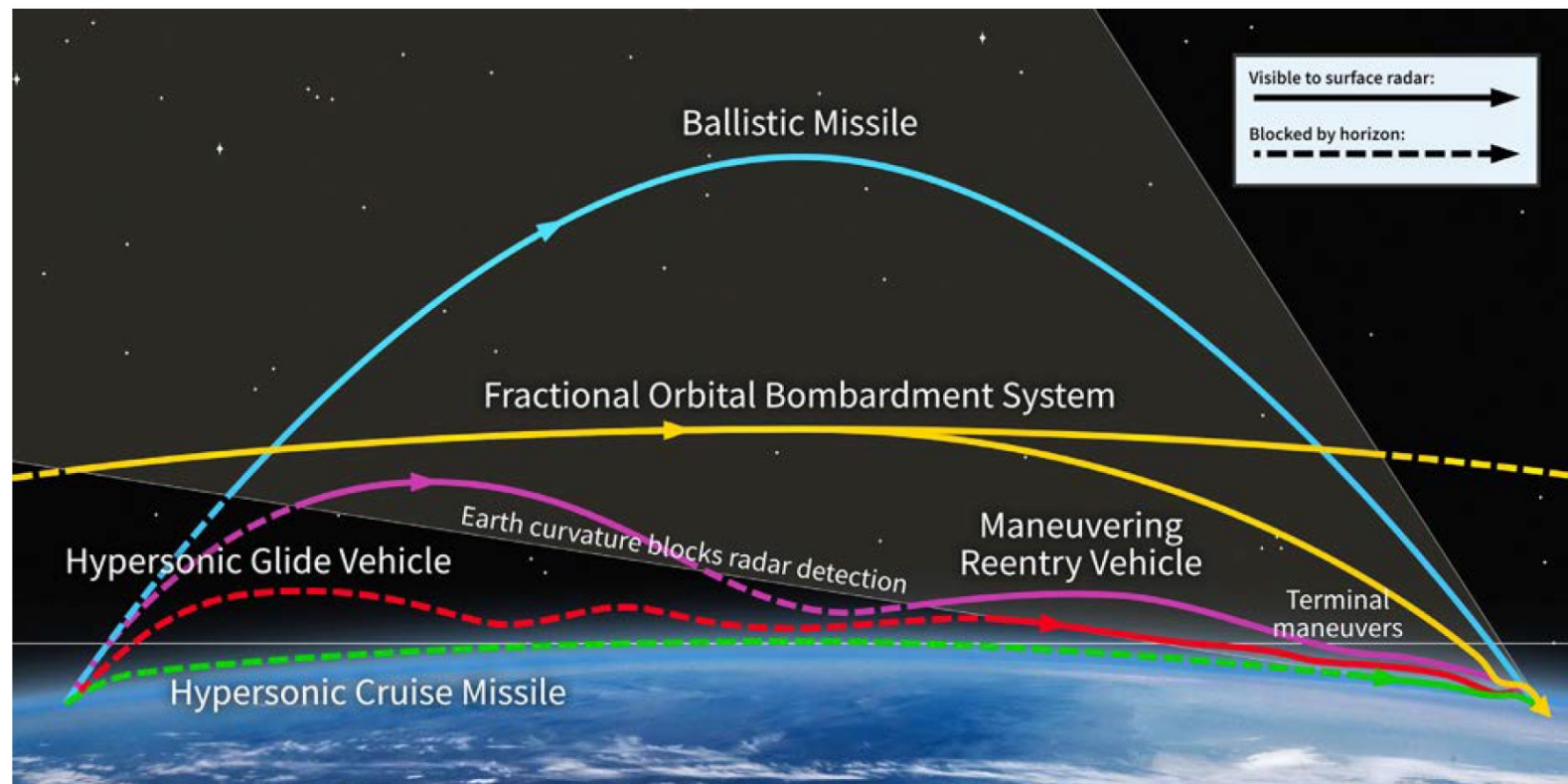
For example, to turn by 30 degrees, a glider as the HTV-2 flying at Mach 15 (4.5 km/s) at an altitude of 40 km, must generate a horizontal velocity of Mach 7.5 (2.3 km/s).

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.

“nearly invisible to early-warning systems”

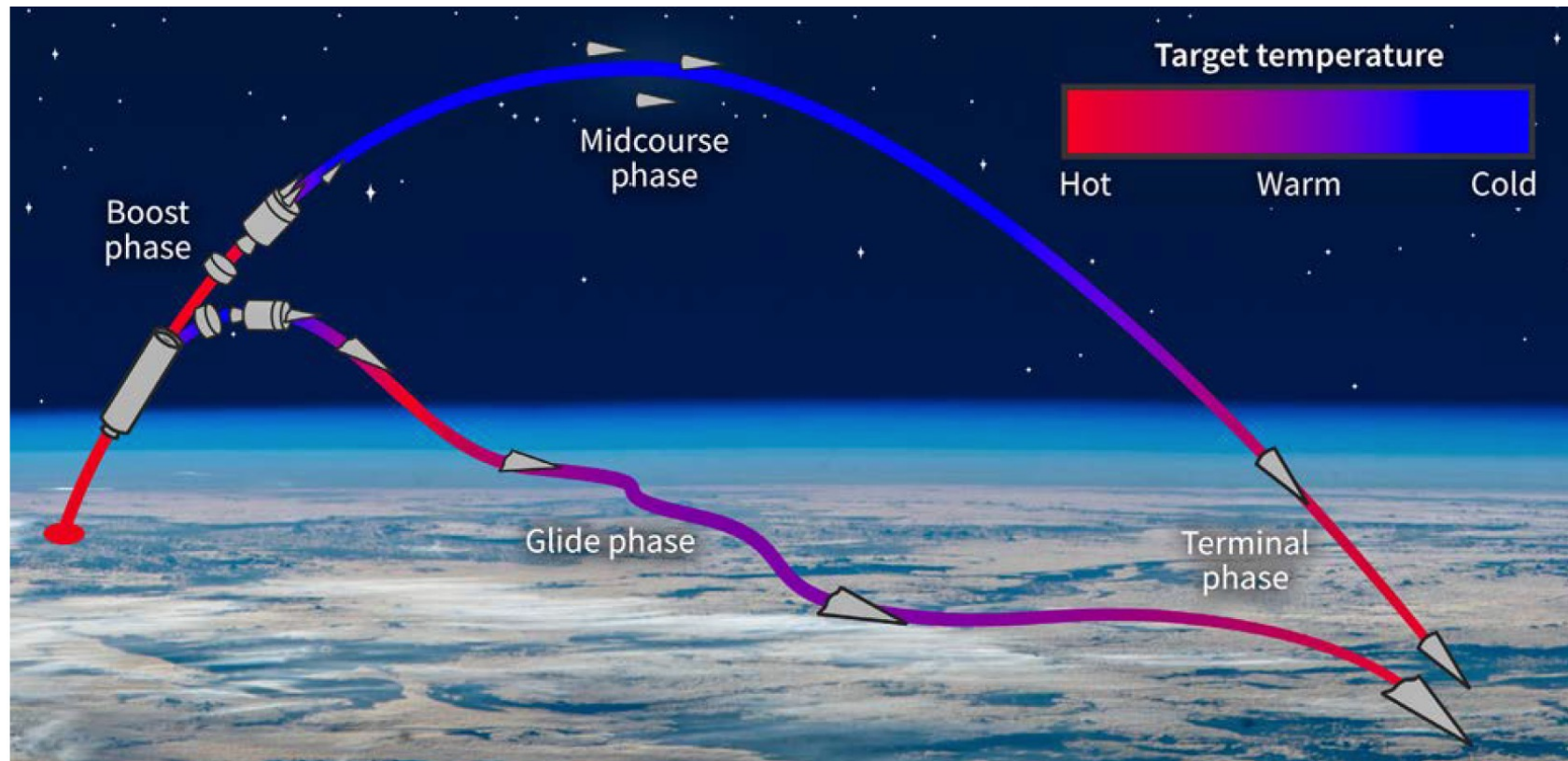
A ground-based radar system can spot a warhead at an altitude of 1,000 km from about 3,500 km away, but because of the Earth's curvature it would not see a glider approaching at a height of 40 km until it was only about 500 kilometers away. The formation of a high-temperature plasma sheathe around a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



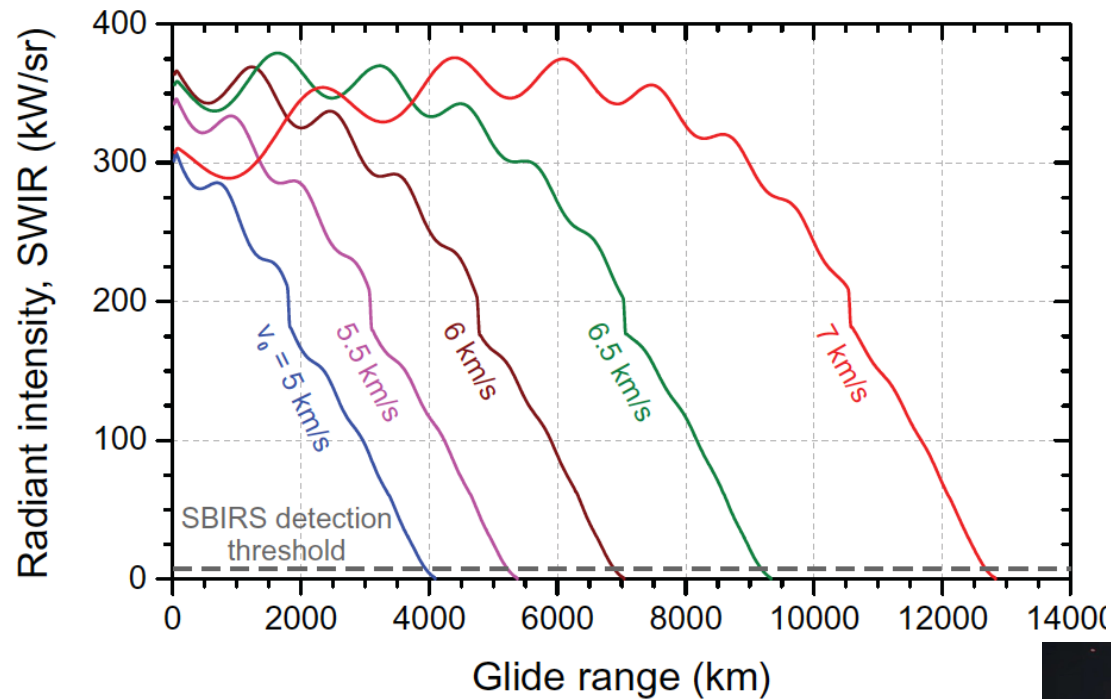
“undetectable”

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

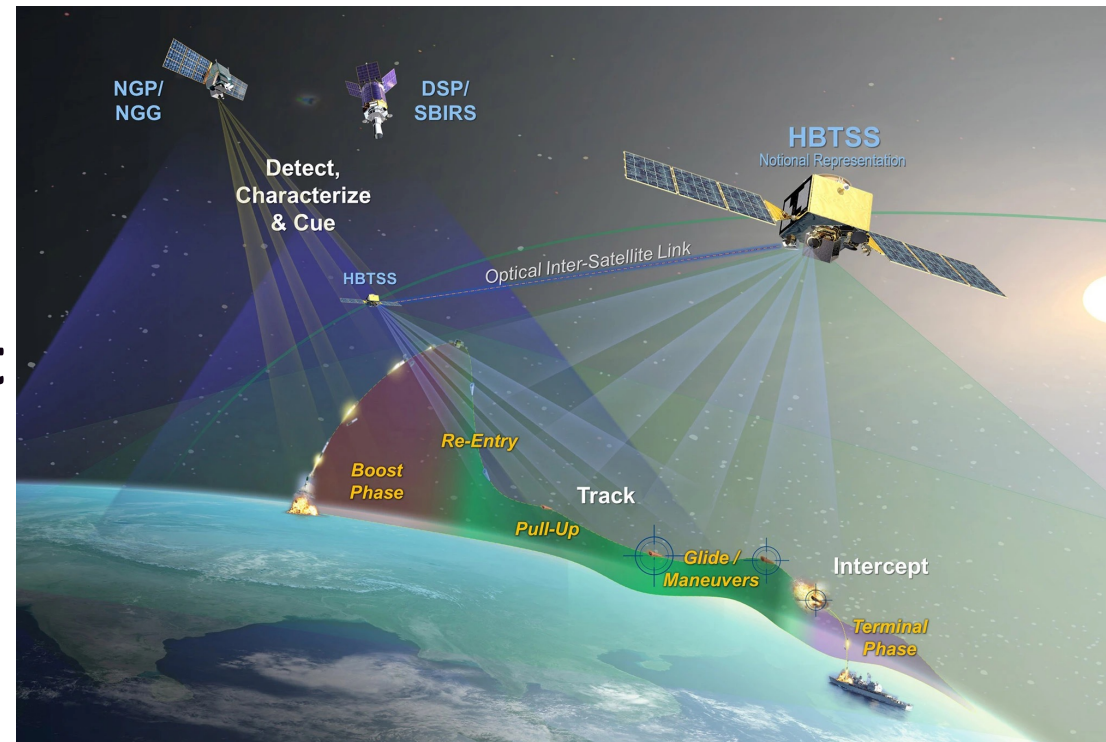
The high temperature surfaces produce a line of ionized gas that is more visible on radars and space-based sensors than the vehicle itself.



“undetectable”



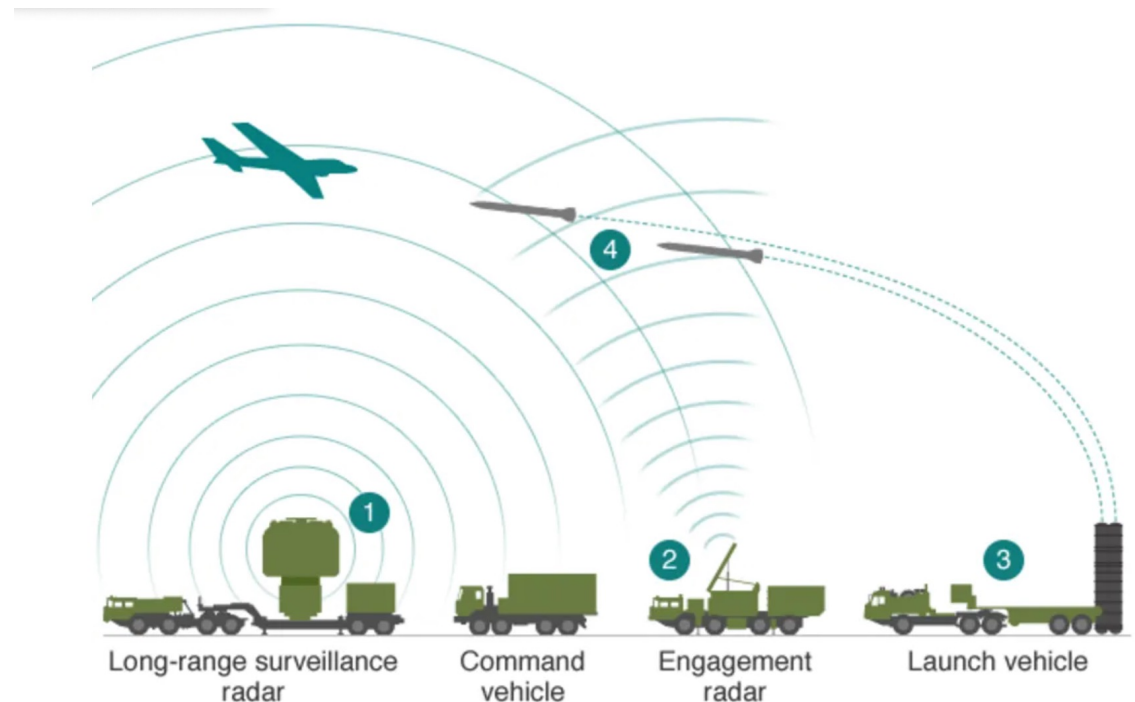
Both the US and Russia have early-warning satellites with sensitive infrared sensors that could spot the intense light that gliders emit.



“forces that cannot be intercepted by ABMs”

HGV cannot be intercepted by present midcourse defences, such as the US Ground-based Midcourse Defense (GMD) and Aegis Standard Missile-3 (SM-3) systems, because they operate at high altitudes (100 km or higher) above the atmosphere.

But terminal defenses, including the US Patriot and Aegis SM-6, and Russia's S-400 and S-500, operate at tens of kilometers altitude, manoeuvre aero-dynamically and could engage HGVs



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.

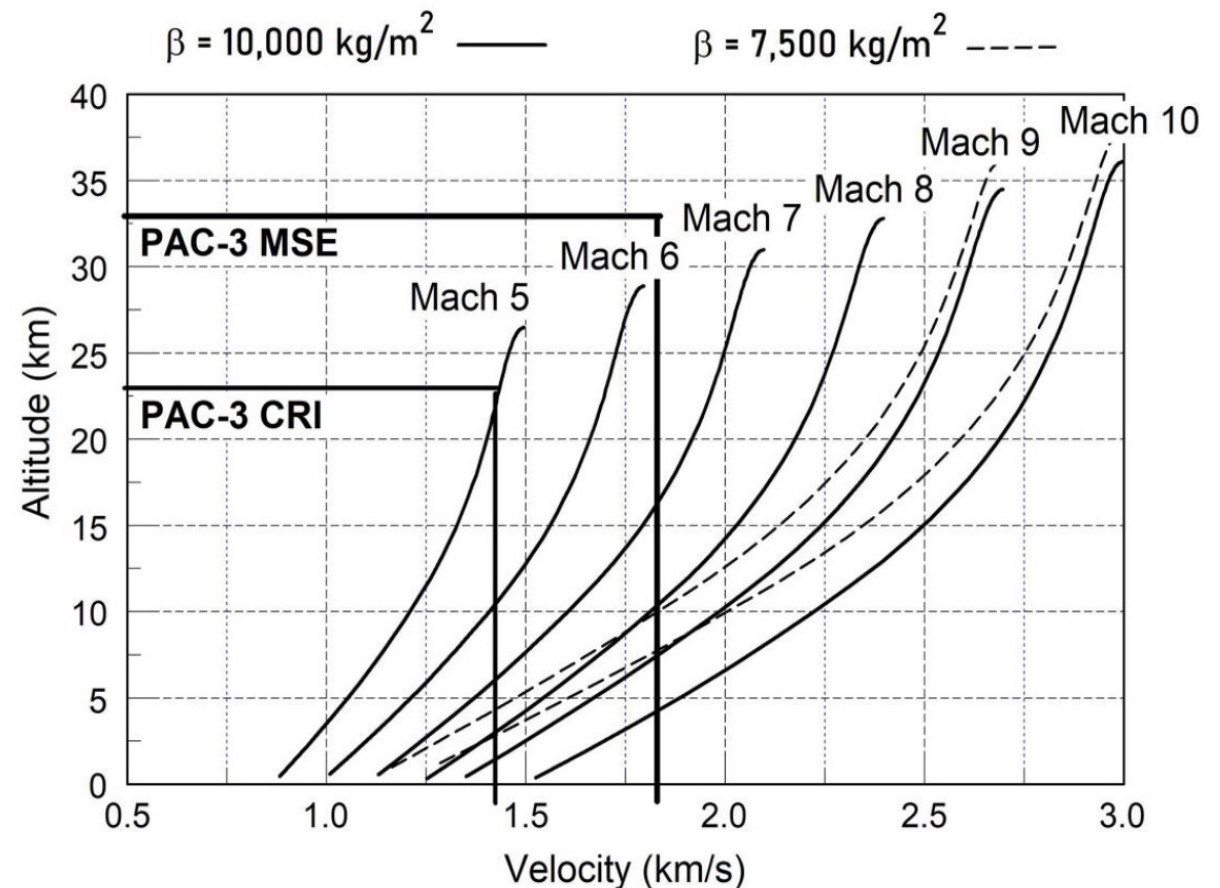
The MSE intercepts in a range of 60 km at altitudes of 30+ km, compared to 20+km for CRI. The cylindrical MSE body will generate zero lift. To manoeuvre, a set of small thrusters around the body give it a non-zero angle-of-attack, which creates lift. The hit-to-kill MSE interceptor has a “lethality enhancer”: a set of rods that shoot out from the body to give it a larger lethal diameter



“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).



The primary motivations given by those leading US HGV development are:

- 1. to quickly attack targets from long ranges**
- 2. to achieve high accuracies and home on targets
(which requires terminal manoeuvring)**
- 3. to retarget over a large area during flight
(which requires terminal and/or midcourse manoeuvring)**
- 4. to evade or destroy air- and missile- defences.**

In order to accomplish these goals there are several types of weapons that could do so.

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 threats

- depressed trajectory ballistic missiles (DTM)
- HGV

strike options against time-critical threats

- depressed trajectory ballistic missiles
- HCM

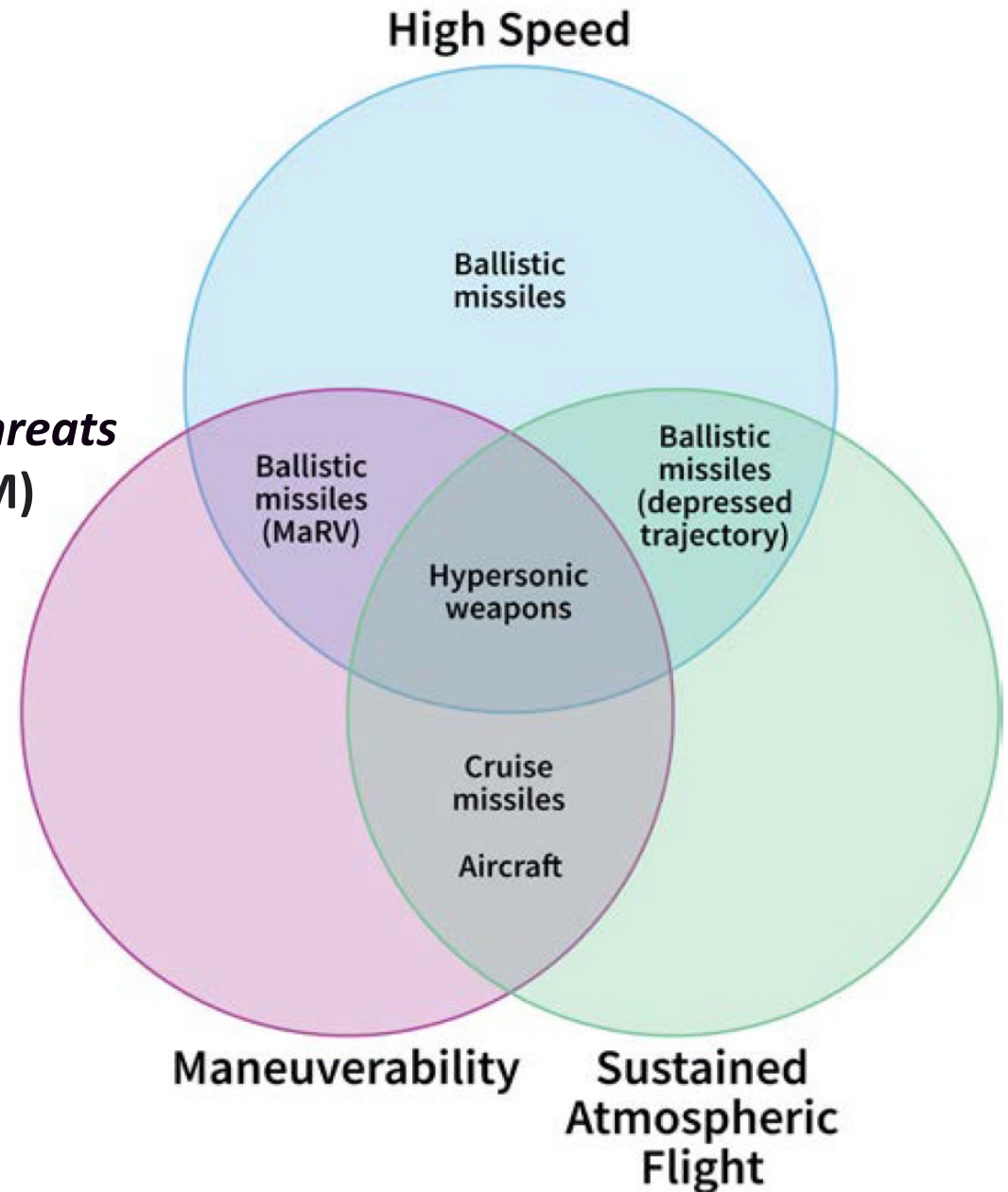
high precision strikes

- aircraft
- cruise missiles
- MaRVs
- HGV and HCM

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

- HGV and MaRV on DTM

Figure 4: Relation of Weapon Categories



Source: CSIS Missile Defense Project.

“game changer”

There are important missions in which MaRVed depressed trajectory ballistic missiles 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 manoeuvrable 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 and MaRVs
- 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.

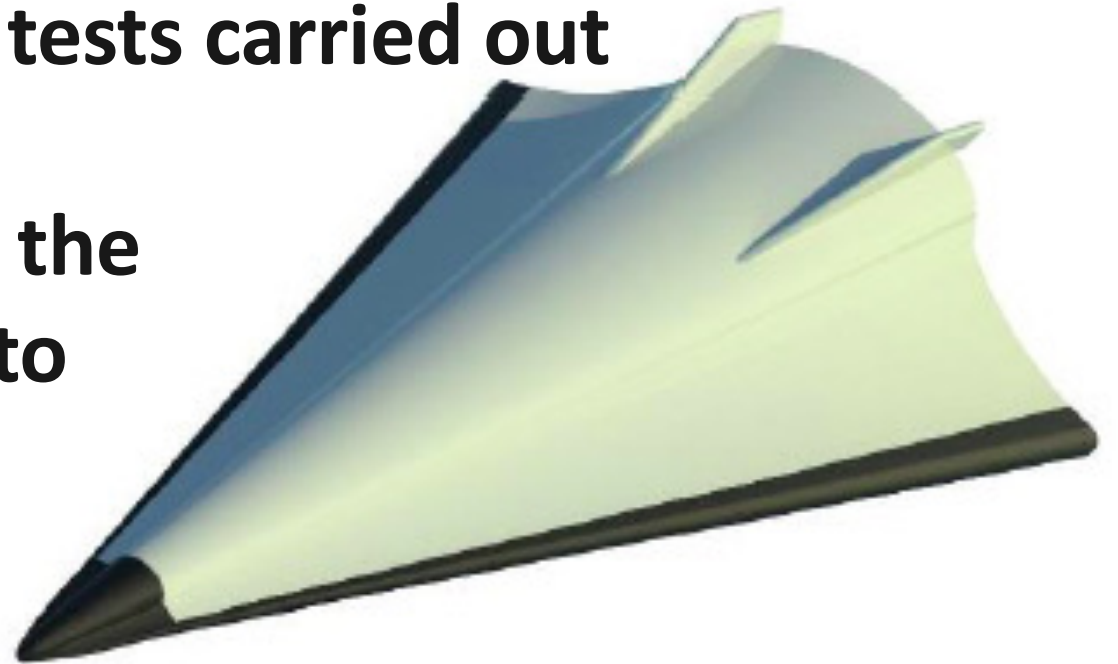
President Putin (March 1, 2018)

- development program includes
 - ▷ nuclear armed HGVs
 - ▷ hypersonic dual-capable ship-launched cruise 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 combat duty.**

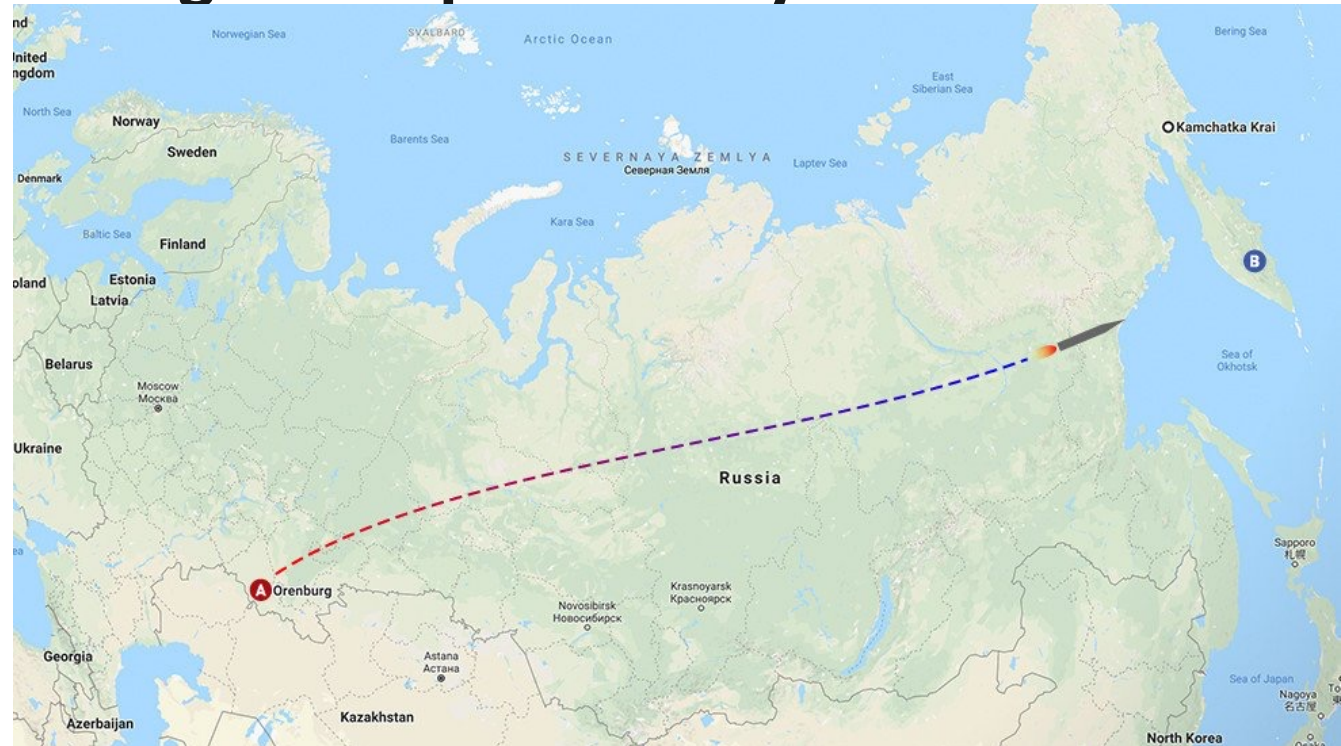


Avangard

The first Avangard division (12 missiles) is operational at the Dombrovsky base. Each nuclear 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 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 dual-capable 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 – 8.

**test of a Tsirkon from the
frigate *The Admiral Gorshkov***



Tsirkon deployment and use

In January 2023 it was first deployed on a Project 22350 frigate and is scheduled for Project 885 Yasen-class submarines. Other platforms which will receive Tsirkons are *Gremyashchiy*-class corvettes, Project 22350 frigates, modernised *Udaloy*-class destroyers, and modernised *Oscar*-class submarines (Project 949AM).

Tsirkon has been used in a land-attack role during the Russian invasion of Ukraine. After a first attack on 7 February 2024, on 25 March 2024, Russia used two land-based Tsirkons from Crimea to strike the centre of Kyiv.

Ukrainian sources claim both missiles were successfully intercepted by air defence systems, based on Patriot and SAMP/T, capable of destroying the Tsirkon in the terminal phase when the missile slows to speeds around Mach 4.5



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, which could enable a preemptive, decapitating strike on China's nuclear arsenal**
- to counter US missile defence deployments, which could limit China's ability to conduct a retaliatory strike**
- 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.**

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. Starry Sky-2 is a “waverider” that uses powered flight after launch and derives lift from its own shockwaves.**
 - ▷ **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



Donfeng 21 D and DF 26 anti-ship ballistic missile

China may be planning to mate conventionally armed hypersonic glide vehicles with the DF-21 and DF-26 ballistic missiles in support of an anti-access/area denial strategy.

Donfeng 21 D is an anti-ship ballistic missile that has a maximum range exceeding 1,450 km and Mach 10 maximum speed.

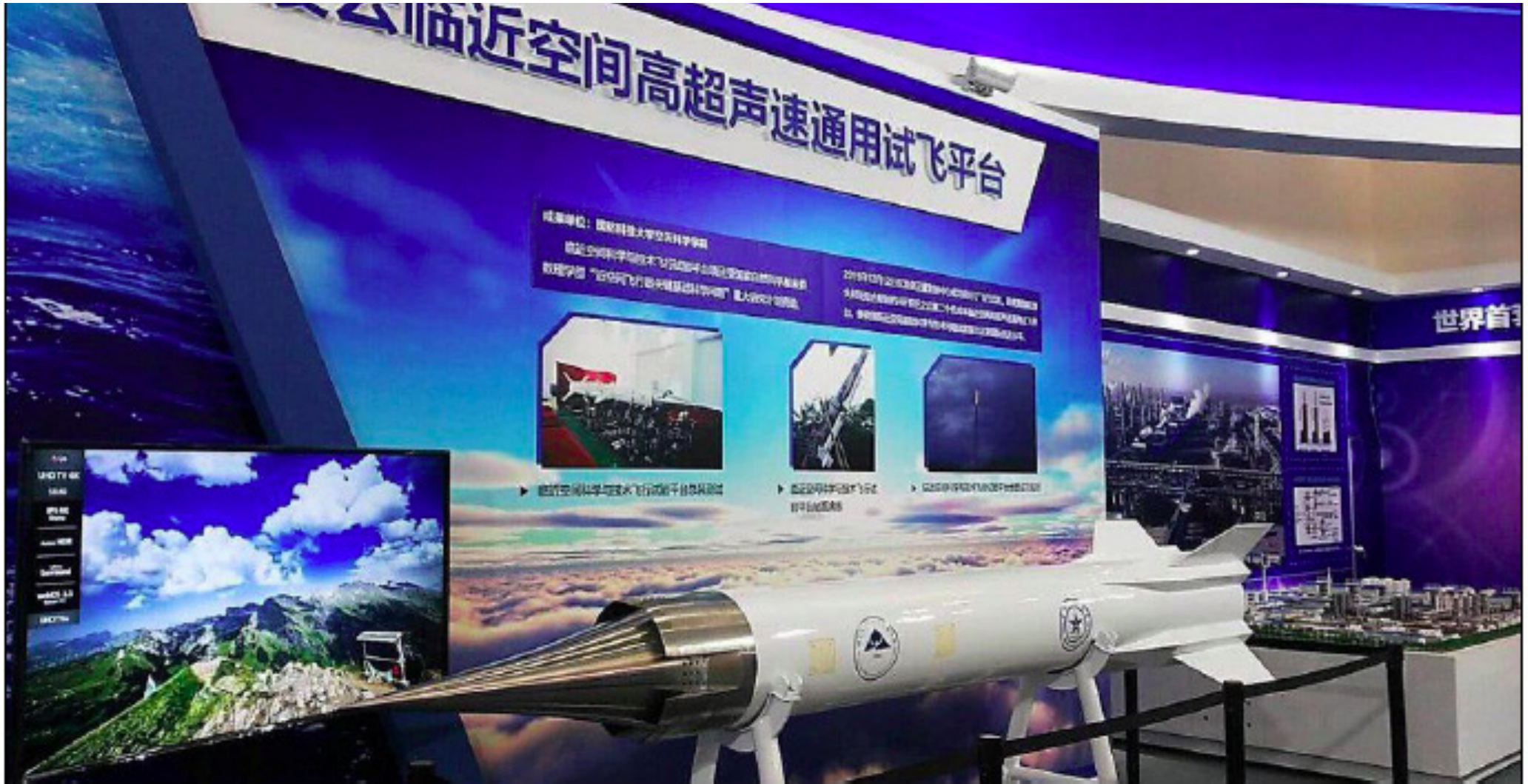
The DF-21D is thought to employ MaRV with a terminal guidance system similar to Pershing II's

PLA anti-ship missiles

Weapon	Estimated Range (miles)	VLS Capable	Platform Compatibility	Speed	Estimated Max Flight Time
YJ-83	110	No	Multirole aircraft Surface warships	Subsonic	12 minutes
YJ-12	290	No	Bombers Land-based launchers Surface warships	Subsonic (w/supersonic terminal sprint)	30 minutes
YJ-18	330	Yes	Surface warships Submarines	Subsonic (w/supersonic terminal sprint)	35 minutes
DF-21	930	No	Land-based launchers	Hypersonic cruise phase, supersonic terminal descent	15 minutes
DF-26	1,850	No	Land-based launchers	Hypersonic cruise phase, supersonic terminal descent	20 minutes



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.

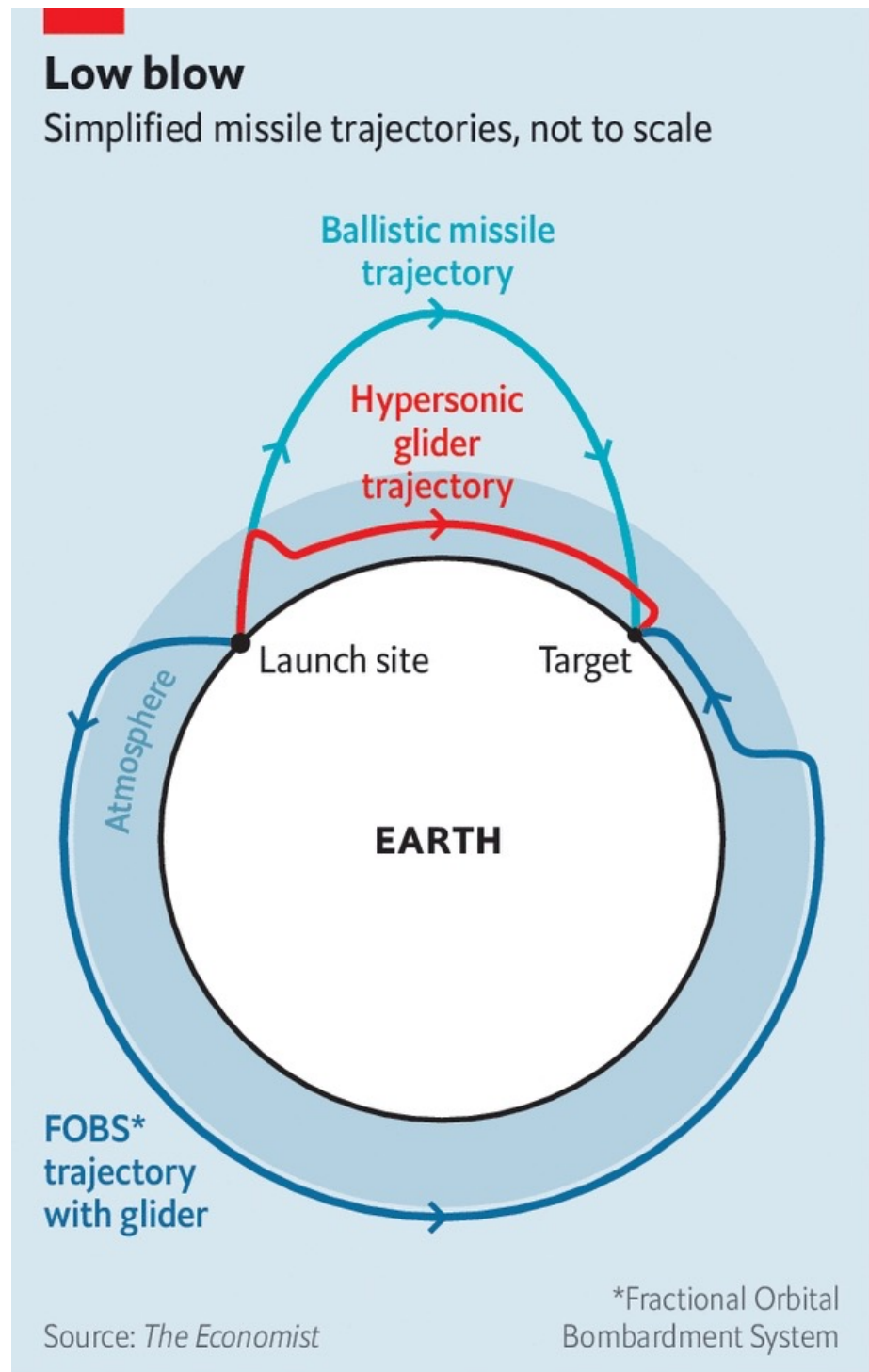


Chinese FOBS

China may have tested a nuclear-capable hypersonic glide vehicle launched by a Long March rocket in August 2021.

The Long March, a fractional orbital bombardment system (FOBS), launches the hypersonic glide vehicle into orbit before the hypersonic glide vehicle deorbits to its target.

This could provide China with a space-based global strike capability and further reduce the amount of target warning time prior to a strike





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 hypersonic policy

At present, the Department of Defense 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. US programs are only intended to produce operational prototypes.

The Pentagon's FY2025 budget for hypersonic research is \$6.9 billion up from \$4.7 billion in the FY2023.

The Missile Defense Agency additionally requested \$182.3 million for hypersonic defence.

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)**

These programs only aim to intermediate-range capability after the failure of the wedge-shaped HTV-2 intercontinental-range tests (2010-11).

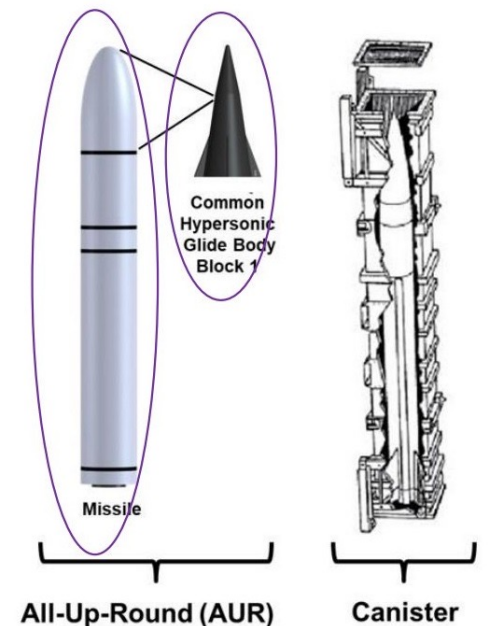
Present US programs are based on older conical designs (of a MaRV developed in the 1970s), with lower range and less manoeuvrability, but less risky.

All US programs only foresee conventionally armed devices

Conventional hypersonic glide Prompt Strike (CPS) weapon system

The Navy's Conventional Prompt Strike program "is intended to provide the US military with the ability to strike hardened or time-sensitive targets with conventional warheads, in order to defeat capabilities such as advanced air and missile defence systems that form anti-access/area denial strategies."

The CPS AUR missile includes a two-stage solid rocket motor intermediate-range booster and a Common Hypersonic Glide Body containing a kinetic energy projectile warhead.



USS *Zumwalt* (DDG-1000) is the first guided-missile destroyer fitted for the CPS weapon system. The two other Zumwalt-class destroyers (DDG-1001 and DDG-1002) are also being fitted with the Common Hypersonic Glide Body (C-HGB) missiles. Strike tests scheduled for 2027



Navy's HALO

The Offensive Anti-Surface Warfare Increment 2 (OASuW Inc 2), also known as Hypersonic Air-Launched OASuW (HALO) program started in FY2023. HALO is a cruise missile likely compatible with the Navy's F/A-18 fighter jet. Navy could also arm its ships and submarines.



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

The program, also known as Dark Eagle, is expected to pair the common glide vehicle with the Navy's booster system. It is intended to have a range of over 1,725 miles. The Army has fielded prototype LRHW equipment and “intends to field two additional batteries of LRHW by FY2027 ”



Joint Statement from United States and Germany on Long-Range Fires Deployment in Germany, 10 July 2024

The United States will begin episodic deployments of the long-range fires capabilities of its Multi-Domain Task Force in Germany in 2026, as part of planning for enduring stationing of these capabilities in the future.

When fully developed, these conventional long-range fires units will include SM-6, Tomahawk, and **developmental hypersonic weapons, which have significantly longer range than current land-based fires in Europe.**

The long range precision fires portfolio currently includes surface-to-surface missiles that will provide commanders with options to attack critical and time-sensitive area and point targets. Army units will fire the Extended Range-Guided Multiple Launch Rocket System rockets from the wheeled M142 High Mobility Artillery Rocket System and M270A2 launcher.

US Air Force—Hypersonic Attack Cruise Missile (HACM)

The Australian-American Hypersonic Attack Cruise Missile program aims to develop a hypersonic scramjet-powered air-launched cruise missile that integrates Air Force and DARPA technologies.

HACM is intended to be launched from both bombers and fighter aircrafts (a B-52 could potentially carry 20 HACMs or more and the B-1 up to 36 HACMs).



DARPA programs



DARPA, in partnership with the Air Force, continues to test Tactical Boost Glide, a wedge-shaped hypersonic glide vehicle capable of Mach 7 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.”

Hypersonic Air-breathing Weapon Concept (HAWC) aims “to an effective and affordable air-launched hypersonic cruise missile.”

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 seeks to field a regional, sea-based Glide Phase Intercept (GPI) capability in FY2034

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.”

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.

The United States Department of Defense, along with the Australian Department of Defence and the United Kingdom Ministry of Defence, today announced the signing of an agreement to enhance testing of hypersonic vehicles and accelerate implementation of related technologies.

Under AUKUS Pillar II, the three nations have entered the Hypersonic Flight Test and Experimentation (HyFliTE) Project Arrangement to use each other's testing facilities and share technical information to develop, test, and evaluate hypersonic systems.

Pentagon spokesperson Maj. Pete Nguyen, Nov. 18, 2024

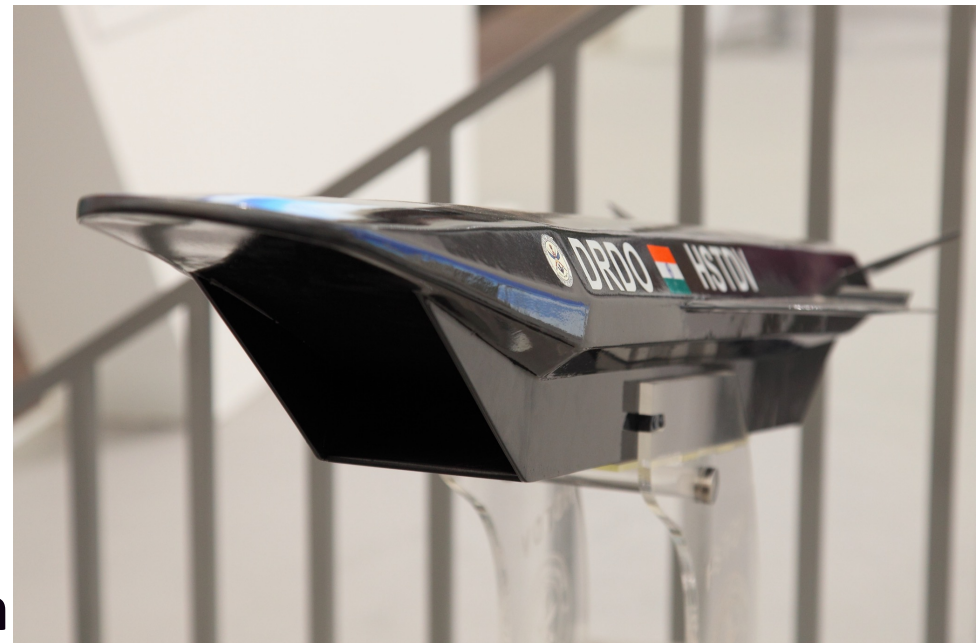
India

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 tested in 2023 a modified air-to-surface ASN4G supersonic missile for hypersonic flight. 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.

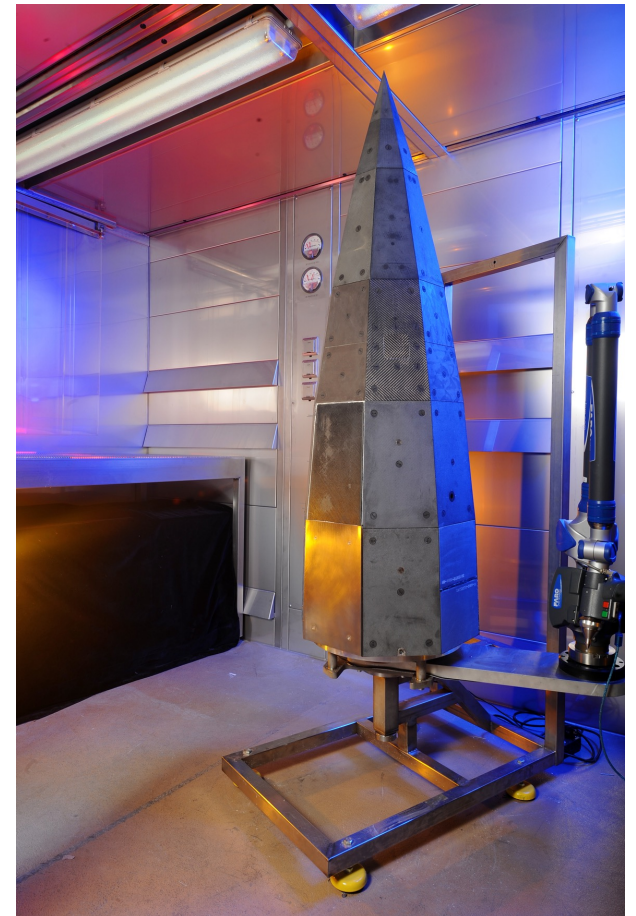


Germany

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.

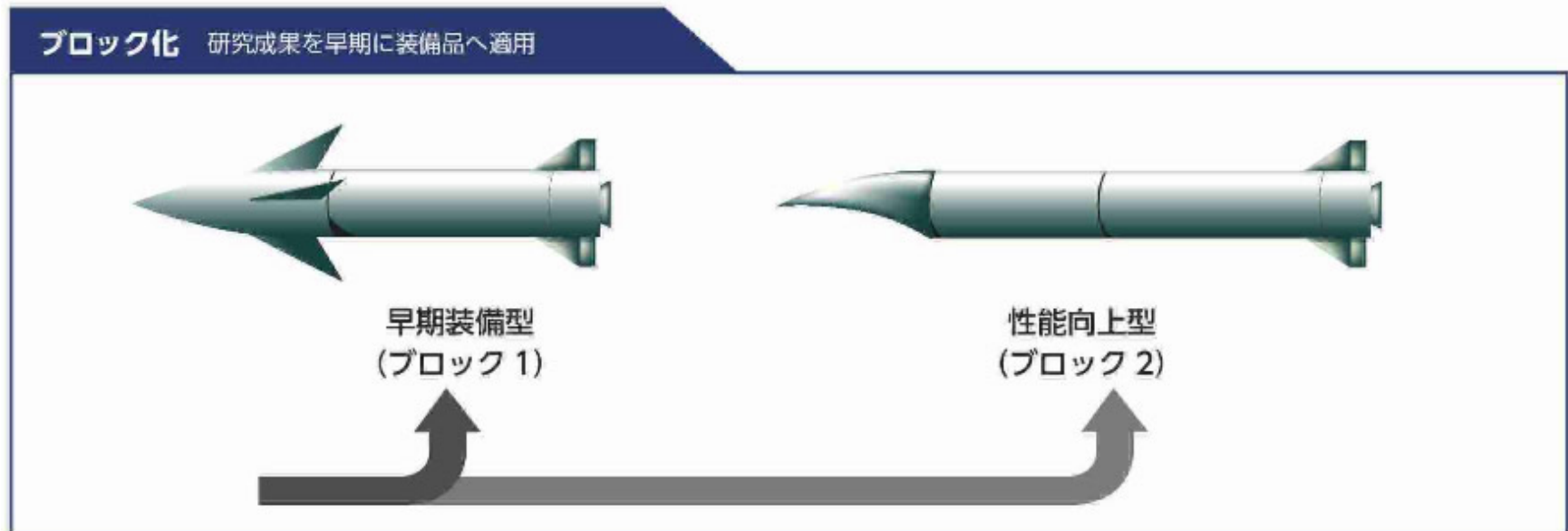
Germany operates three hypersonic wind tunnels and is capable of testing speeds of up to Mach 11.



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 2022, 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 Korea, 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 Reusable spacecraft 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.**

Hypersonic missiles with nuclear payloads defy the spirit of the NPT's disarmament obligations and this could lower the confidence of non-nuclear weapon states parties in the NPT.

- **The 1967 Outer Space Treaty banning the stationing of weapons of mass destruction in outer space prevents deployment of nuclear FOBS**
- **The nuclear hypersonic weapons of Russia and US would count under the limits in New START, as it is the case with the Avangard deployment.**

Conventionally armed hypersonic weapons and arms control

- **After the demise of the Intermediate-Range Nuclear Forces Treaty (INF) 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.

Confidence Building Measure: the 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

Russia and US are members of HCoC

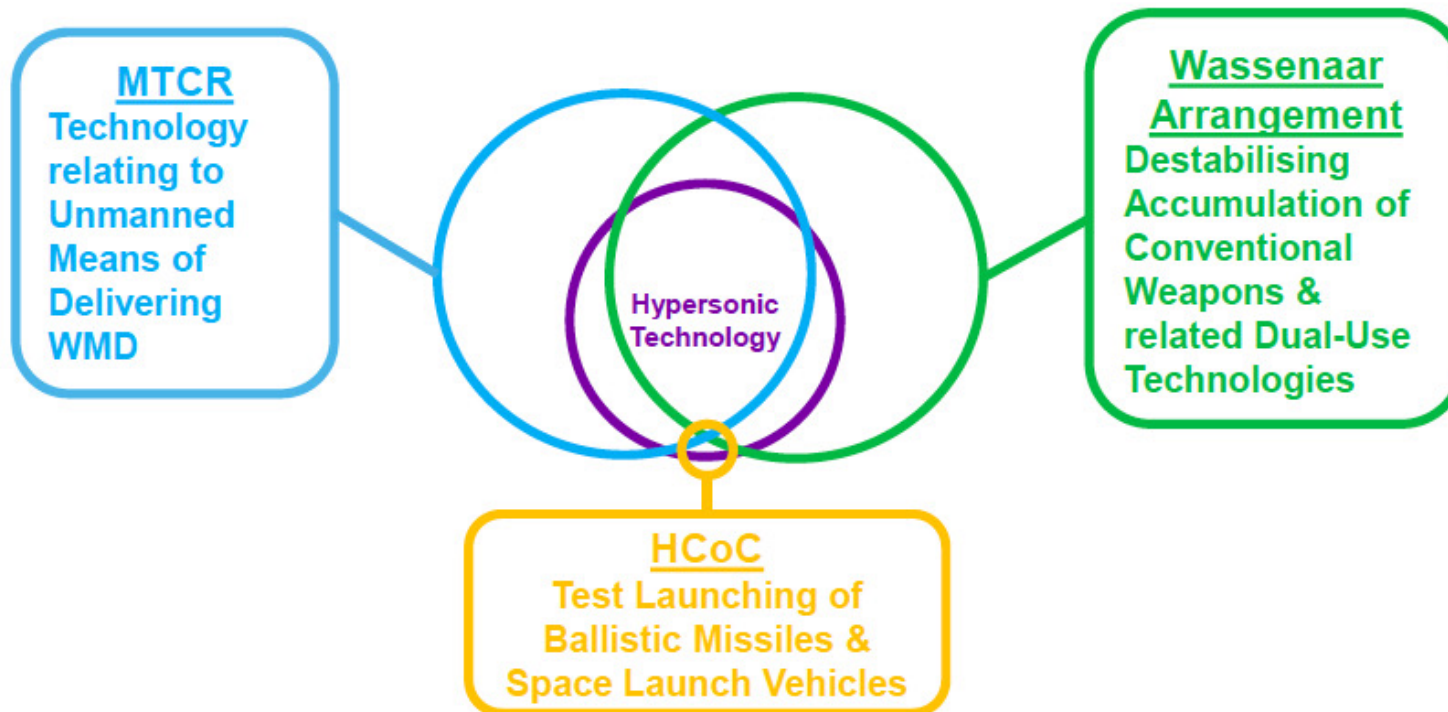
Non proliferation

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

Multilateral export control regimes are relevant:

- Missile Technology Control Regime (MTCR)
- Wassenaar Arrangement

Multilateral Export Control Regimes (MECRs)



N.B. Hague Code of Conduct (HCoC) isn't technically one of the MECRs

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?).

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Hypersonic Technology and MTCR: System Overview

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

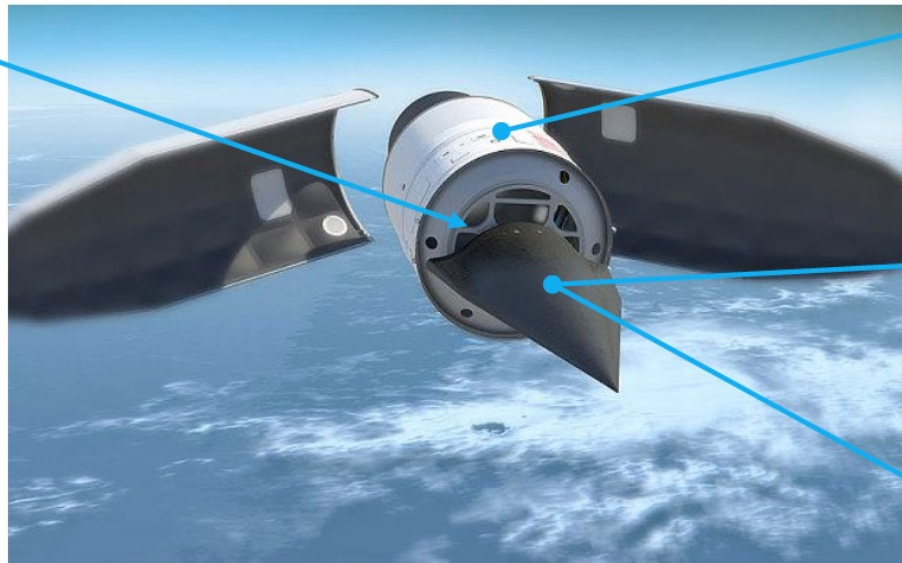


Image: Defense Advanced Research Projects Agency DARPA

Booster MTCR Category-I
Ballistic System
(Boost Phase)

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 the ample 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.

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

strategic implications

Nuclear-armed strategic hypersonic weapons

- **HGVs would not avoid attack warning and tracking and therefore would not raise concerns about surprise attack or reduced warning time; they are not the reason for the launch on warning (LOW) or launch under attack (LUA) postures already in place**
- **considering their prospective impact on delivery times, attack warning and manoeuvrability, HGVs should not negatively affect the survivability of nuclear forces**
- **to the extent that HGVs can penetrate national missile defences more effectively and reliably than traditional RVs, they could strengthen deterrence by providing additional confidence in second-strike retaliatory capabilities**

complications for nuclear deterrence

- **introduction of hypersonic weapons could lead to an offense-defence spiral and impact arms race stability. The United States have already embarked on efforts to bolster its BMD system to counter incoming hypersonic missiles. Russia and China are likely to follow a similar strategy.**

The stage is thus set for an arms race

- **this development would take the offense-defence developments into outer space, placing sensors (and may be interceptors also) as counter-measures. This can this can further strengthen the weaponization of outer space**

The shift of interests in hypersonic weapons

- from nuclear- to conventionally armed devices
- from intercontinental-range to intermediated-range weapons makes their actual use easier
- as an escalation control system
- as a “tactical” anti-force weapon

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

The speed of war

The pace of development of hypersonic weapons in conjunction with areas such

- robotics and uninhabited land, sea and air vehicles**
- quantum detectors and quantum computing**
- artificial intelligence and autonomous systems**
- nano-sciences and material science**
- space militarization**
- directed energy weapons**

will accelerate the speed of battle, making conflict faster and more complex.

It raises the demand for yet quicker weapons.

Operative implications of hypersonic weapons

Interconnection of advanced technologies, swifter weapons, and faster C₄ISR systems (command, control, communication, computers, intelligence, surveillance and reconnaissance) are changing the way military leaders can operate on the battlefield as well as how they plan and execute missions. The increasing speed of both weapons and decision making cycle will challenge military professionals.

This synergy of complementary technologies will also allow a broader range of targeting options than hitherto, with hypersonic weapons allowing more fleeting targets to be engaged than was previously possible.

They will enable even more sophisticated and disruptive “grey zone” operations

it is time for nightmares

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