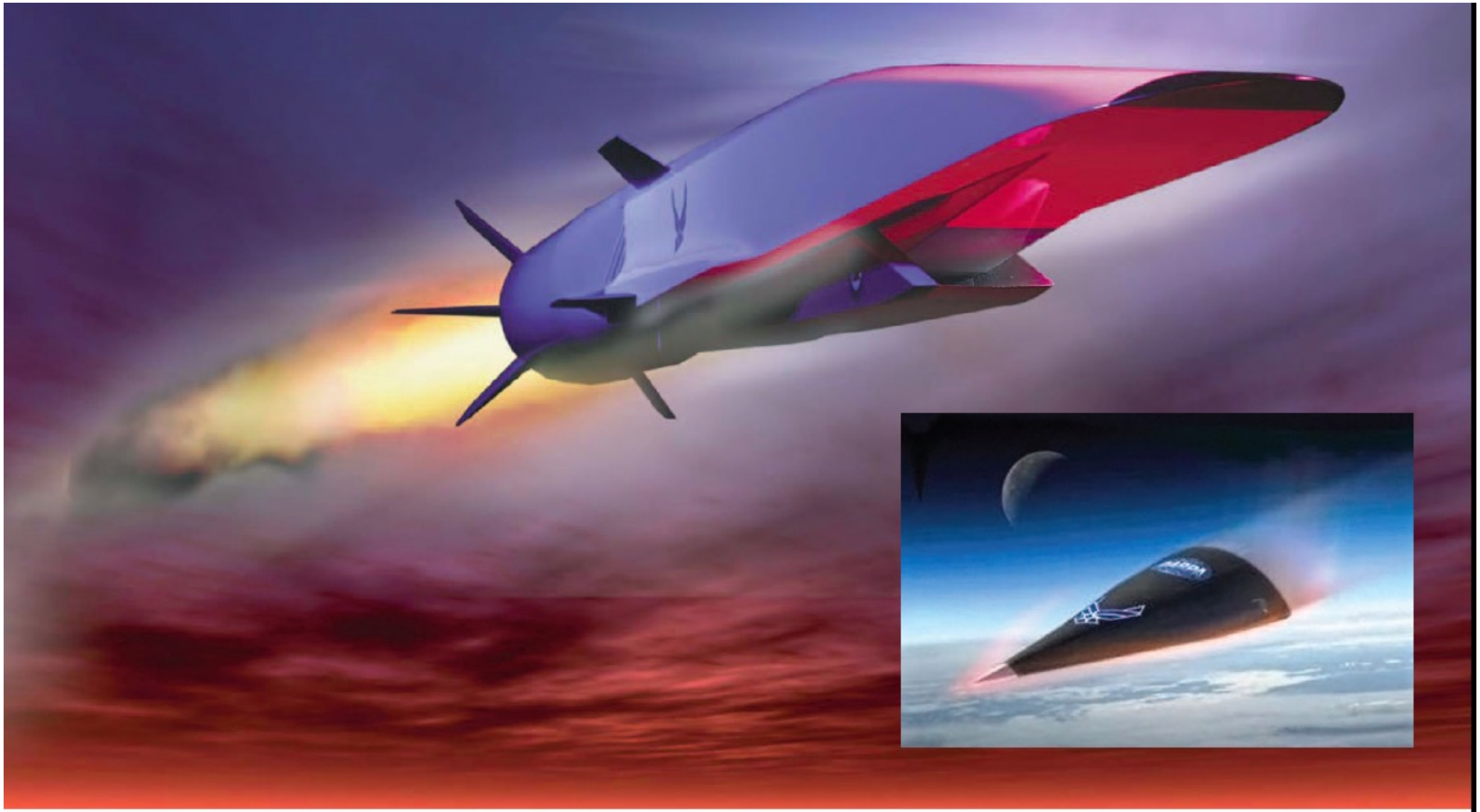


Hypersonic weapons:
how does the technology impact stability

January 2023   Alessandro Pascolini

first use of a hypersonic weapon in actual war

The Russian Ministry of Defense announced on March 18 that it had deployed the Kinzhal to destroy an underground warehouse for missiles and aviation ammunition in the western part of Ukraine.

The Kh-47M2 “Kinzhal” (“Dagger” in Russian) is a nuclear-capable, air-launched, hypersonic ballistic missile

A new arms race?

A competition is intensifying between China, Russia and the United States on the militarization of hypersonic vehicle technology. Several additional states are actively developing the technology.

Today's hypersonic weapon programmes appear to be driven by developments in technology rather than specific military objectives.

This creates a dynamic in which development in one country provides impetus for others to follow suit even if military applications of the system under development have yet to be clearly understood.

By all indications this reinforcing effect between different programmes will continue.

The secrecy surrounding these programmes also fuels exaggerated threat perceptions, leading the arms racing dynamic.

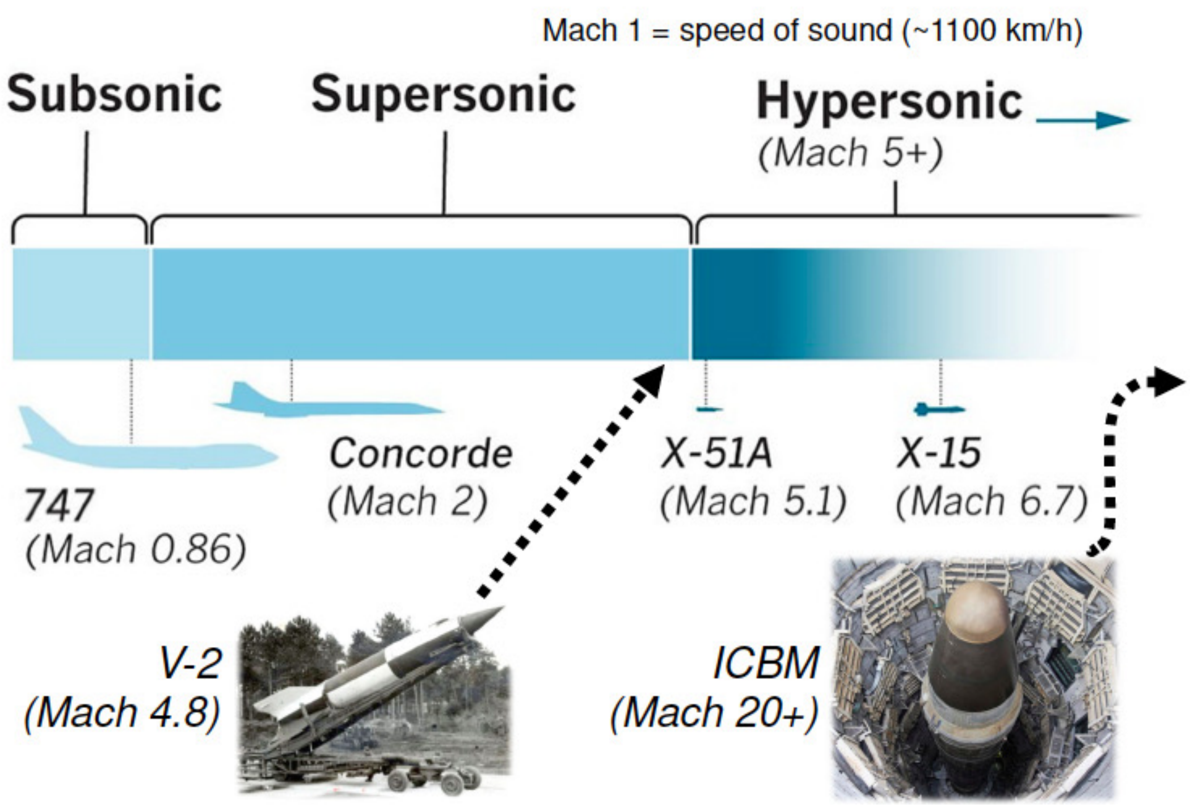
today's offer

- hypersonic flight technology
- hypersonic weapons
- hypersonic weapon programs
- strategic implications
- arms control

hypersonic flight technology

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

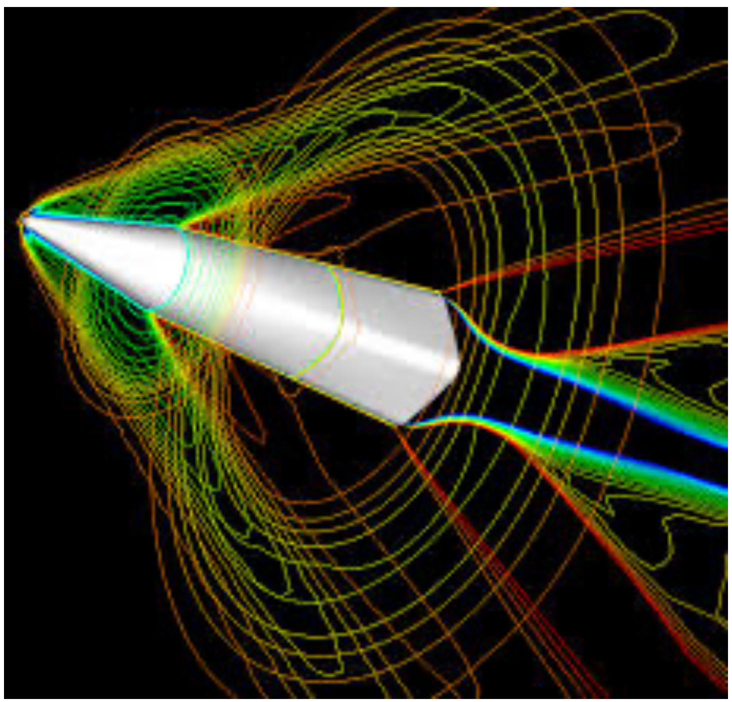
The hypersonic regime poses more and more serious problems with increasing speed due to:

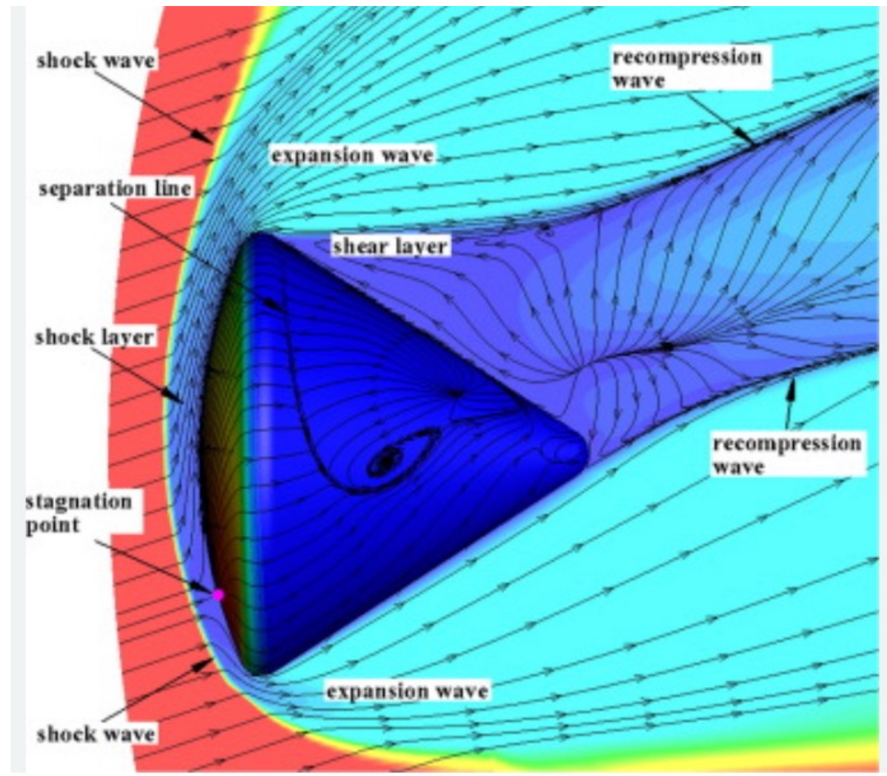
- **highly non-linear gas-dynamics**
- **thermodynamics far from equilibrium with critical entropy gradients**
- **chemical alterations of the air flow**
- **ionization processes and plasma formation**

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

The environments faced by vehicles flying at hypersonic velocities are very different and harsher than vehicles flying at subsonic and supersonic speeds.

Around the vehicle extremely high compression waves of great amplitude (shock waves) are formed, within which the density, pressure and speed of the fluid vary drastically





physical effects are different on the various parts of the vehicle

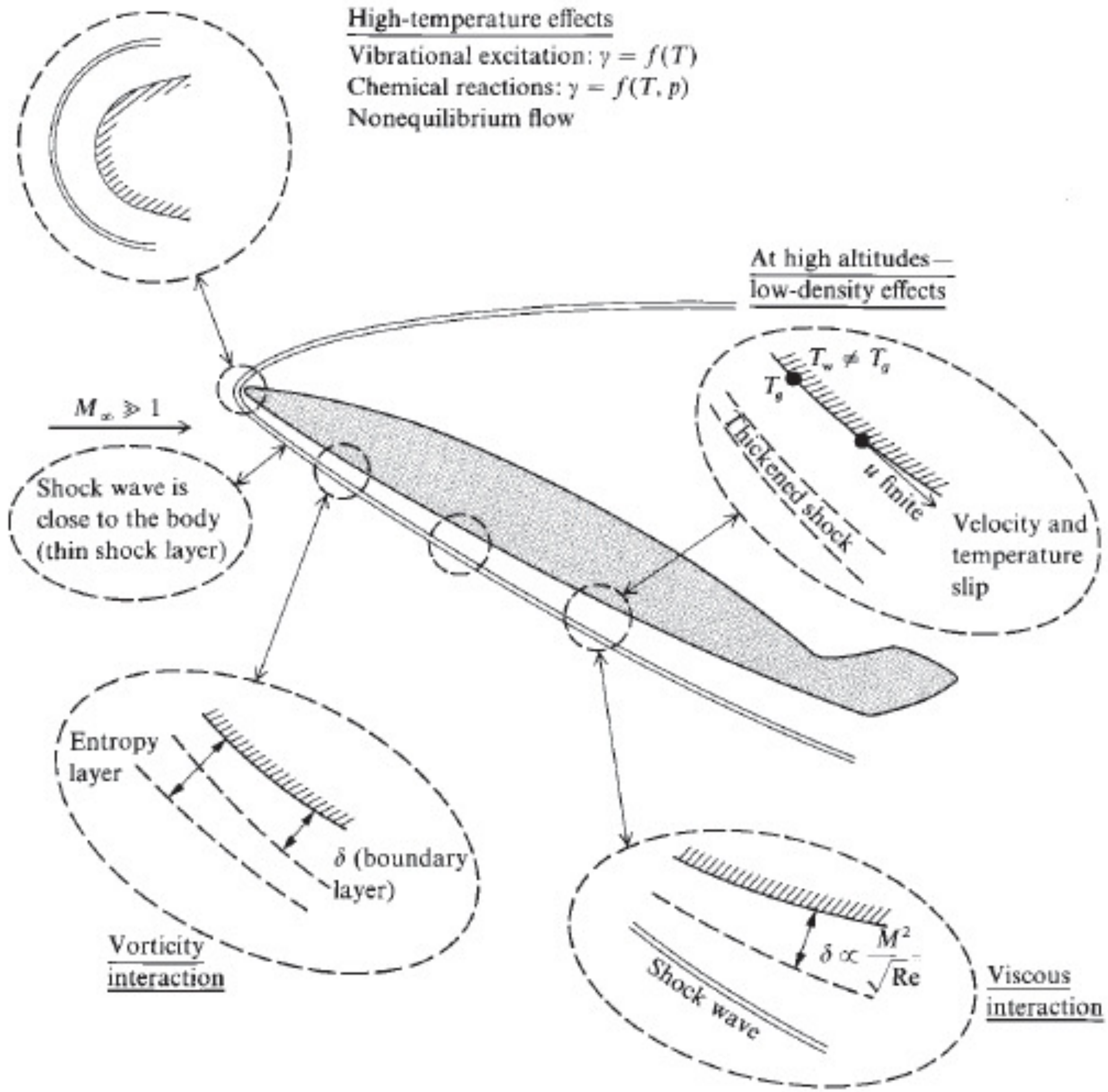
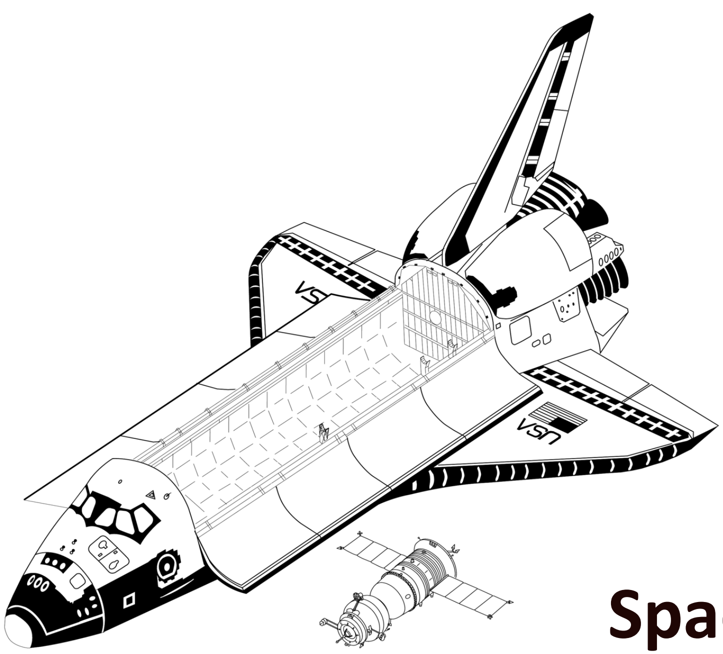
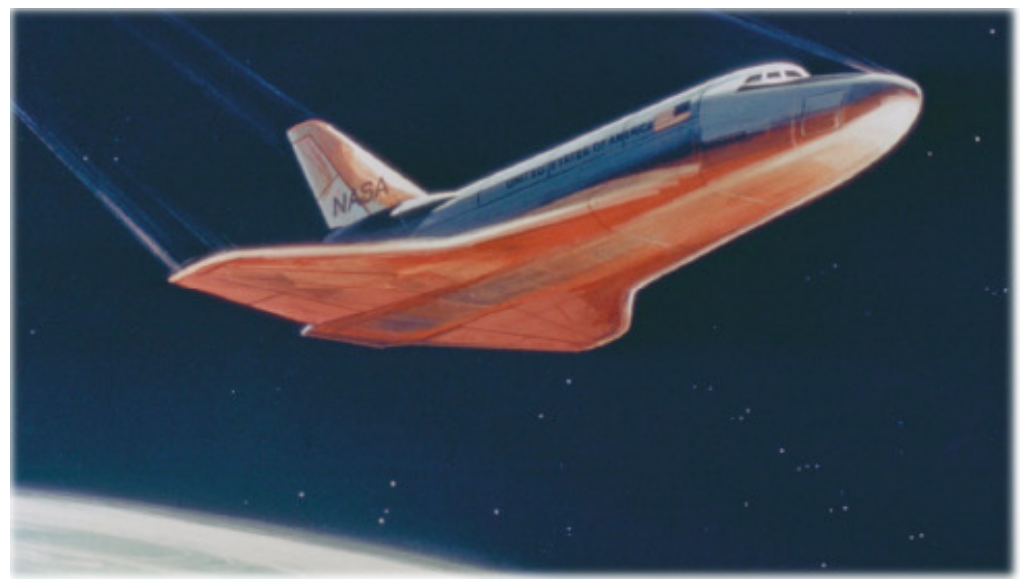


Fig. 1.20 Physical effects characteristic of hypersonic flow.

Hypersonic vehicles

Hypersonic vehicles have aerodynamic features which make them glide over the generated shock waves, receiving an upward lift which can lead them to perform “jumps” outside the atmosphere. The friction with the atmosphere particles (drag) reduces the speed and generates high quantities of heath: temperatures up to several thousand degrees are reached





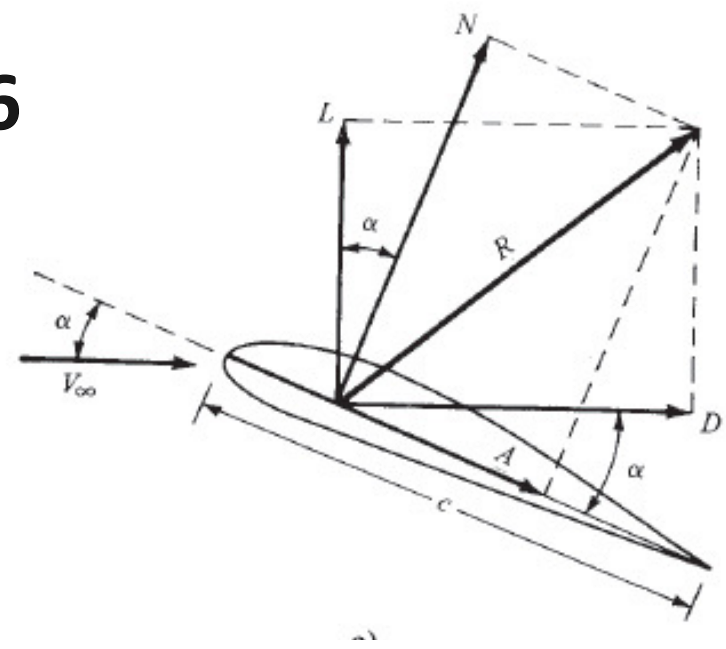
Space Shuttle, Mach 25 hypersonic vehicle

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 < 2.6**

For the Space Shuttle L/D ranged from 1 in hypersonic phase to 2 in supersonic phase and 4.5 in the landing phase



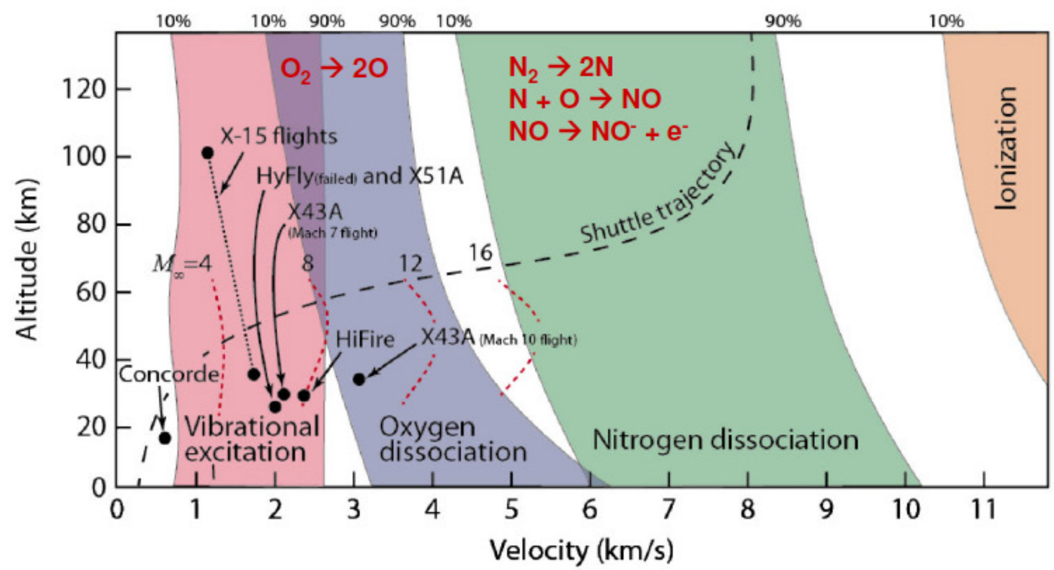
free molecular flow

At high altitudes approaching 100 km, 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.

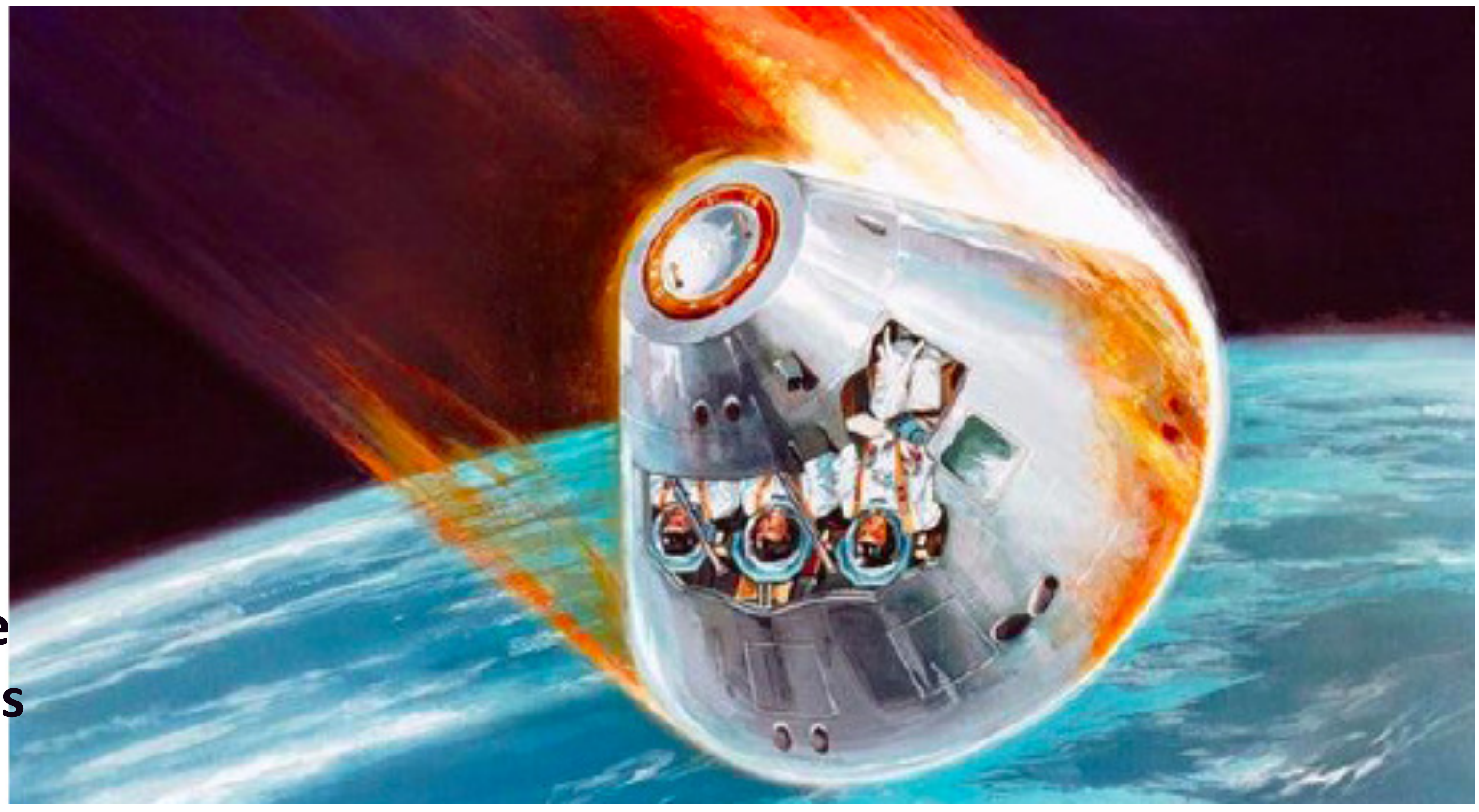
The critical parameter for the transition from the regime described by continuous equations to that of low-density flow and free molecules is the Knudsen number Kn, given by the ratio between the average free path of the gas molecules and the characteristic size of the vehicle: as Kn increases, one moves from the continuous regime to the low-density phase and finally to the free molecular limit.

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.
The chemical reactions must be accounted for when designing any part of the vehicle: structure, engine, thermal protection system, oxidation inhibitors, leading edges, and sensors.



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 with its plasma layer

heating effects on hypersonic vehicles

The high aerodynamic heating experienced by an HV creates difficulties in maintaining the temperature below the maximum allowable limit for the structure, leading edges, control surfaces, and internal components.

These high temperatures, along with the thin structures that HVs are typically composed of to minimize mass, 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.

Extreme surface temperatures, especially at leading edges, can destroy all but the most robust materials.

on-board sensors

the performance of all on-board sensor systems (the Global Positioning System (GPS), 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.

in order to control overheating, the front profile of the hypersonic spacecrafts are stocky

$$Q_{total} \propto \int (\rho/Rnose)^{0.5} v^3 dt$$

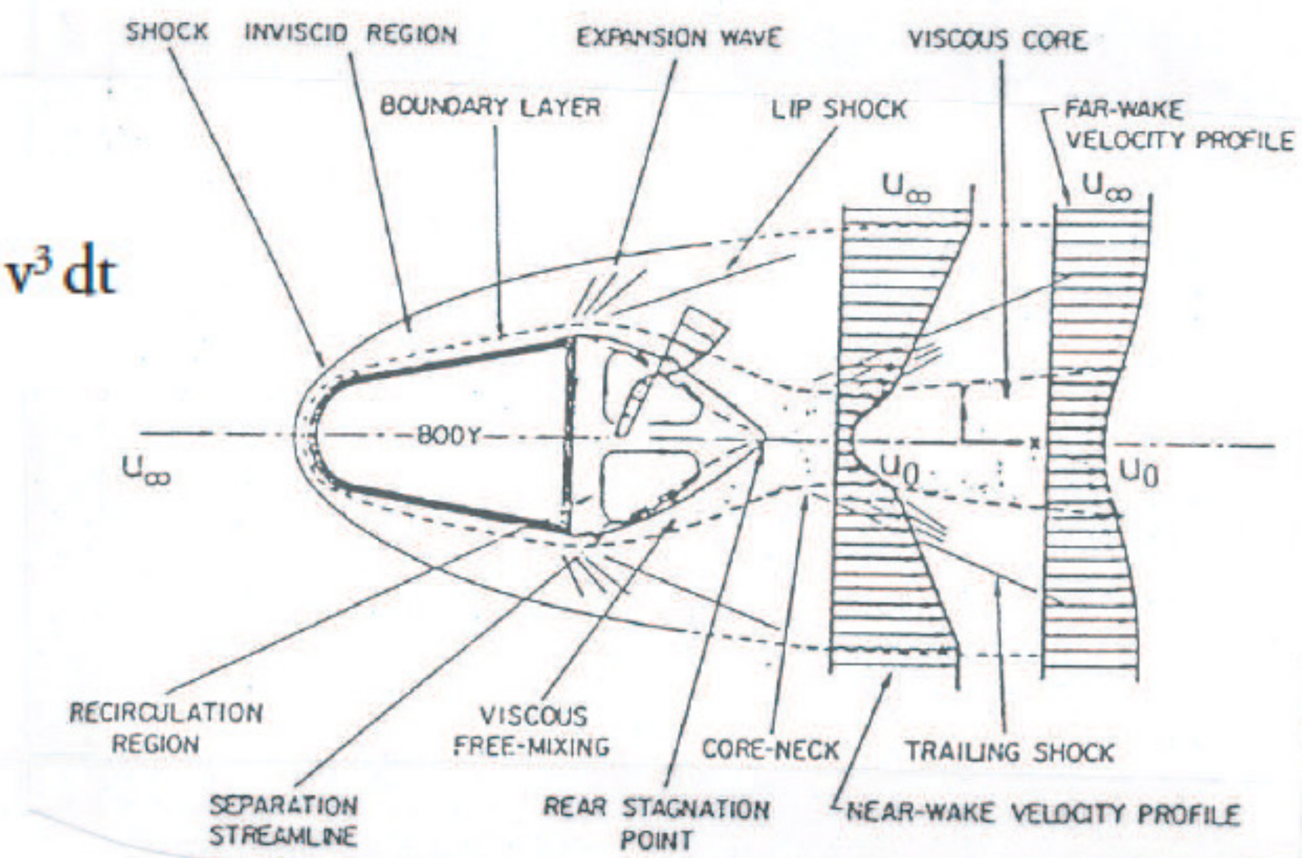


Fig. 1.2 Features of hypersonic flow around a blunt-nosed vehicle.

blunt versus sharp leading edges

Spacecraft and missile nosecones have typically been designed with blunt shapes that have high drag and can also handle the heating associated with high-speed flight through the atmosphere.

Blunt shapes are not suitable for a vehicle designed to fly an extended distance through the atmosphere, which requires an aerodynamic form which has low drag, which means sharp leading edges and a slender form.

That combination not only allows for sustained flight through the atmosphere, but maneuvering using aerodynamic forces

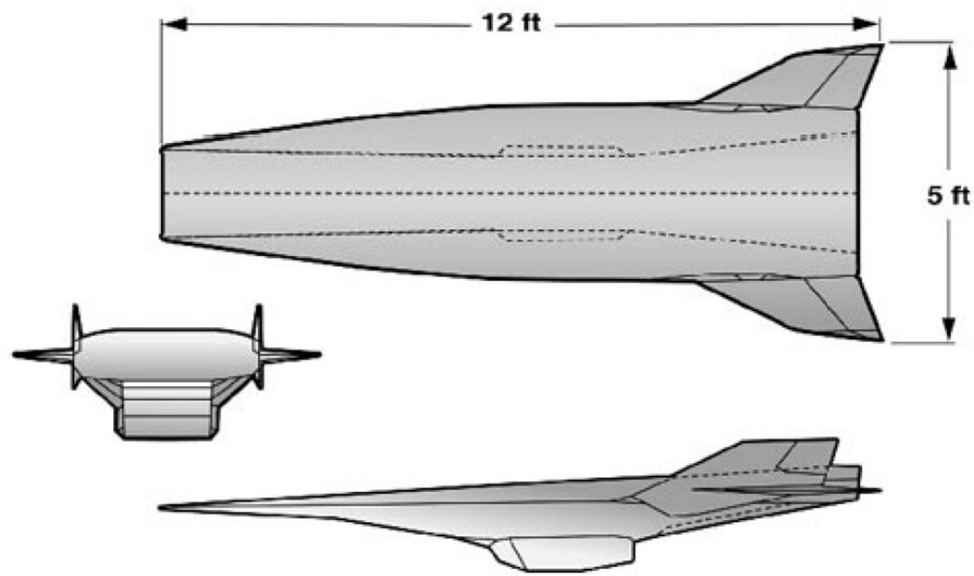
Hypersonic versus subsonic and supersonic airplane design philosophy

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

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

The lift exerted by the shock wave makes the use of distinct wings not necessary for the production of high lift.

All of these considerations combine in a hypersonic vehicle in such a fashion that the components to generate lift, propulsion, and volume are not separate from each other; rather, they are closely integrated in the same overall lifting shape, in direct contrast to conventional subsonic and supersonic vehicle design.



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.

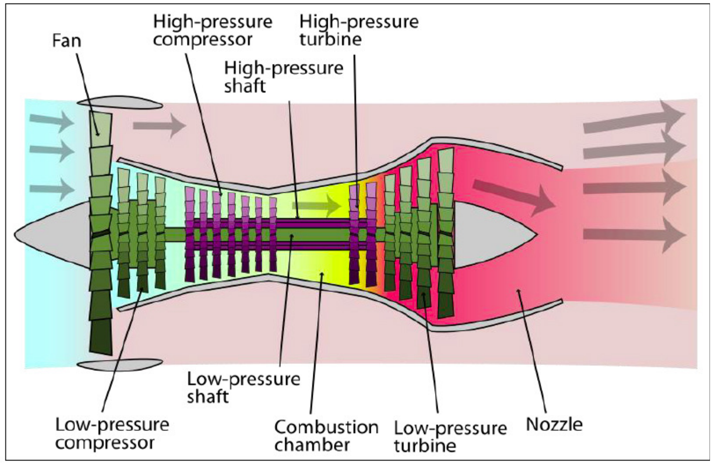
The likely hypersonic engine of choice, the scramjet, functions by allowing the air that passes through the engine to remain essentially at flight speed. This keeps temperatures inside the engine at levels where fuel can still burn.

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

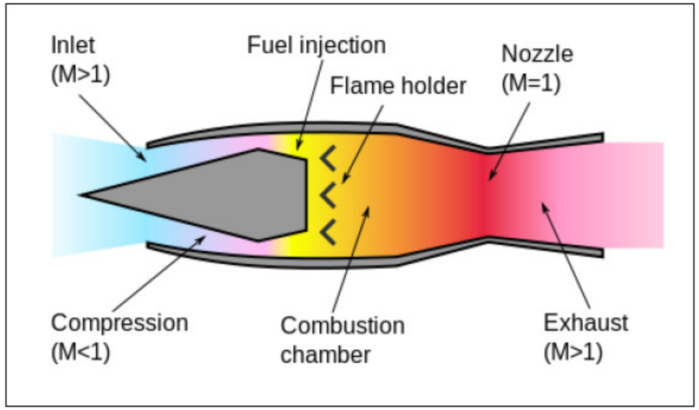
a. turbojet

the incoming flow must be compressed for combustion



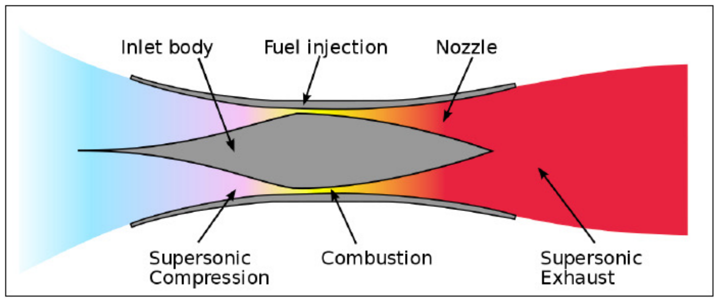
b. ramjet

the incoming supersonic flow is made subsonic for the combustion

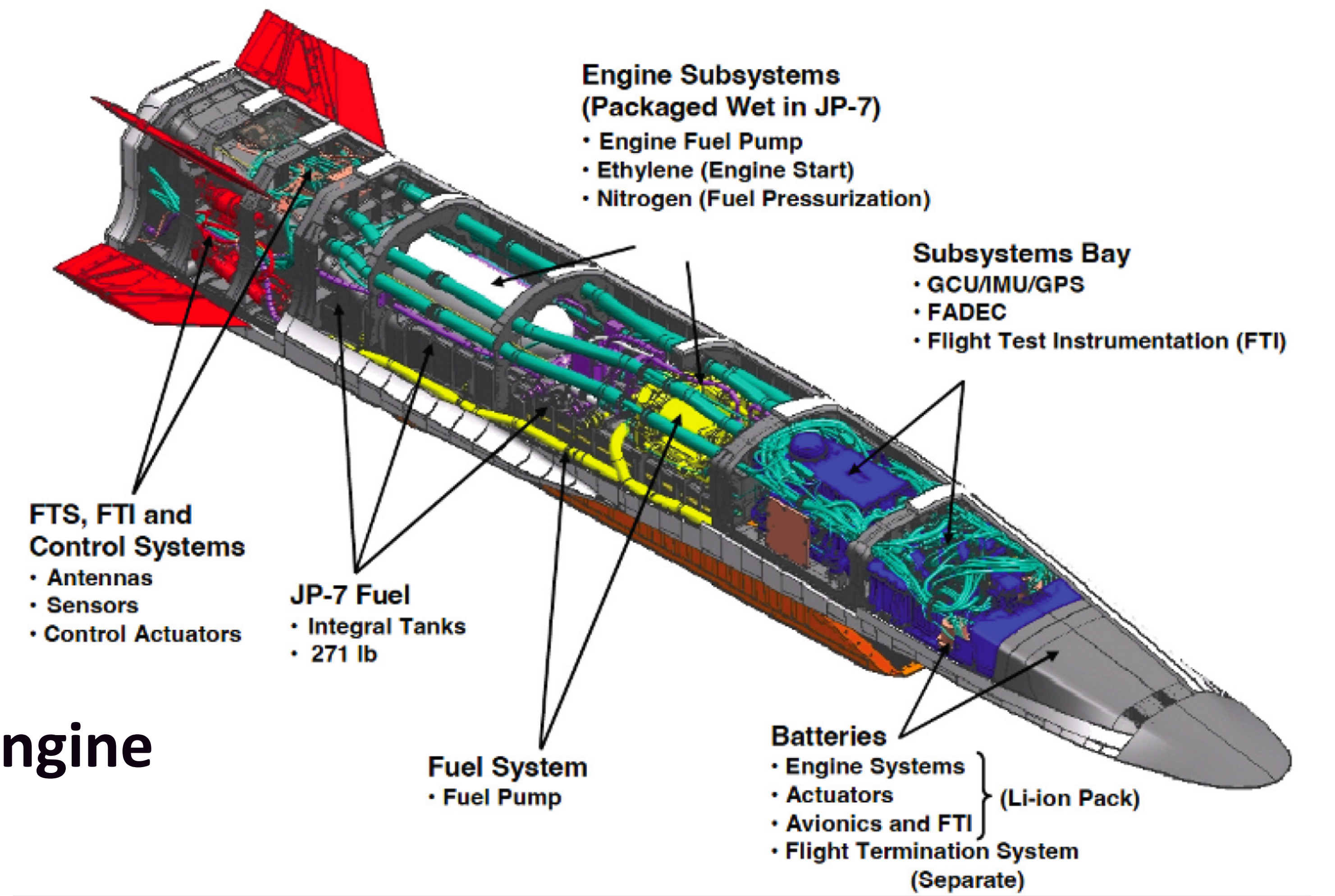


c. scramjet

ramjet with a supersonic combustion

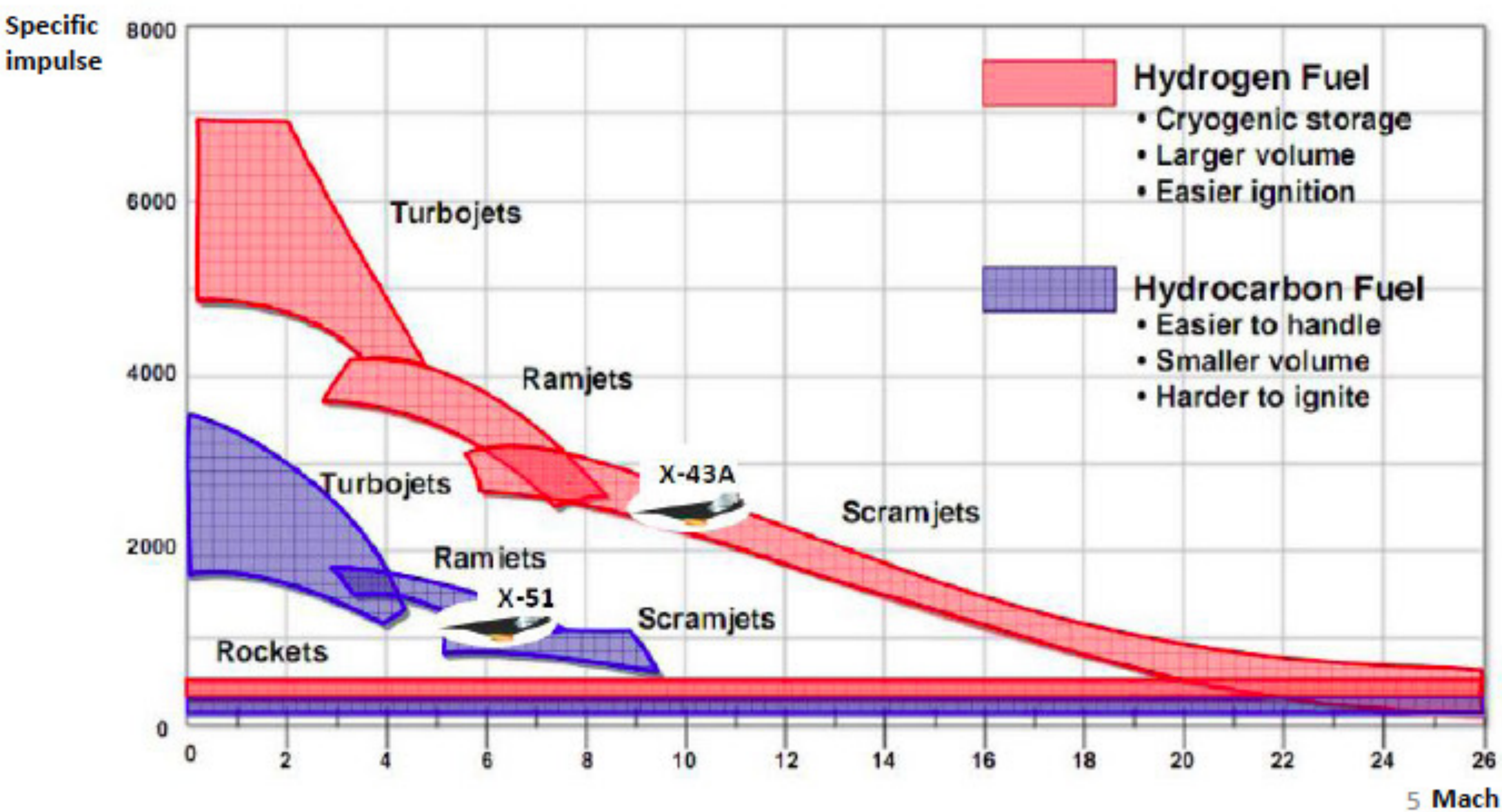


in order to start the scramjet engine the vehicle must reach hypersonic velocities by means of a rocket or a turbine-based combine cycle (inlet-turbine-ramjet)



subsystems of an X-51-A scramjet engine demonstrator

scramjets collect oxidizer from atmosphere and use hydrogen or hydrocarbon liquid fuels



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, ... in addition to Cina, Russia and the USA.

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.

hypersonic weapons

Hypersonic military applications

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

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

the most advaced hypersonic weapons belong to two primary categories (designed for one-time use):

- **Hypersonic glide vehicles (HGVs)**
  invest all of their propulsion energy up front, and then deplete that energy gradually
- **Hypersonic cruise missiles (HCMs)**
  release their energy at a steady rate until a short final terminal dive.

They can be nuclear or conventionally armed

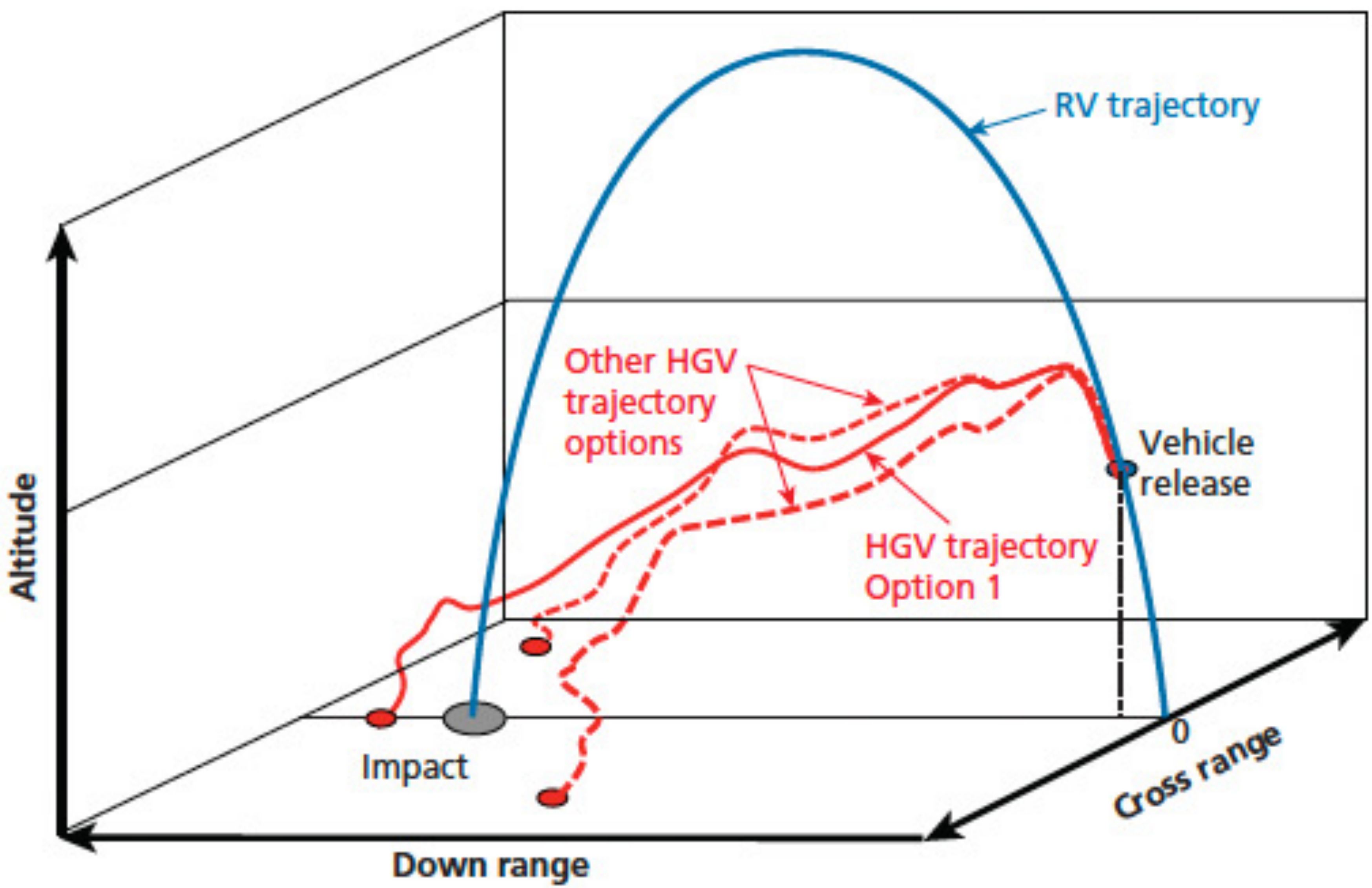
Hypersonic weapons

What characterises HGV and HCM 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



Both cruise missiles and boost glide weapons would be manoeuverable, and operate within the atmosphere at altitudes above those of conventional aircraft, but significantly below that of ballistic missiles.

In addition to flying at high speed through most of their trajectories, both categories of hypersonic weapons will also likely decelerate, but still impact their targets at velocities in the high–supersonic (Mach 3–4) range.

They could maintain significant manoeuverability with precision even in the terminal phase

Note:

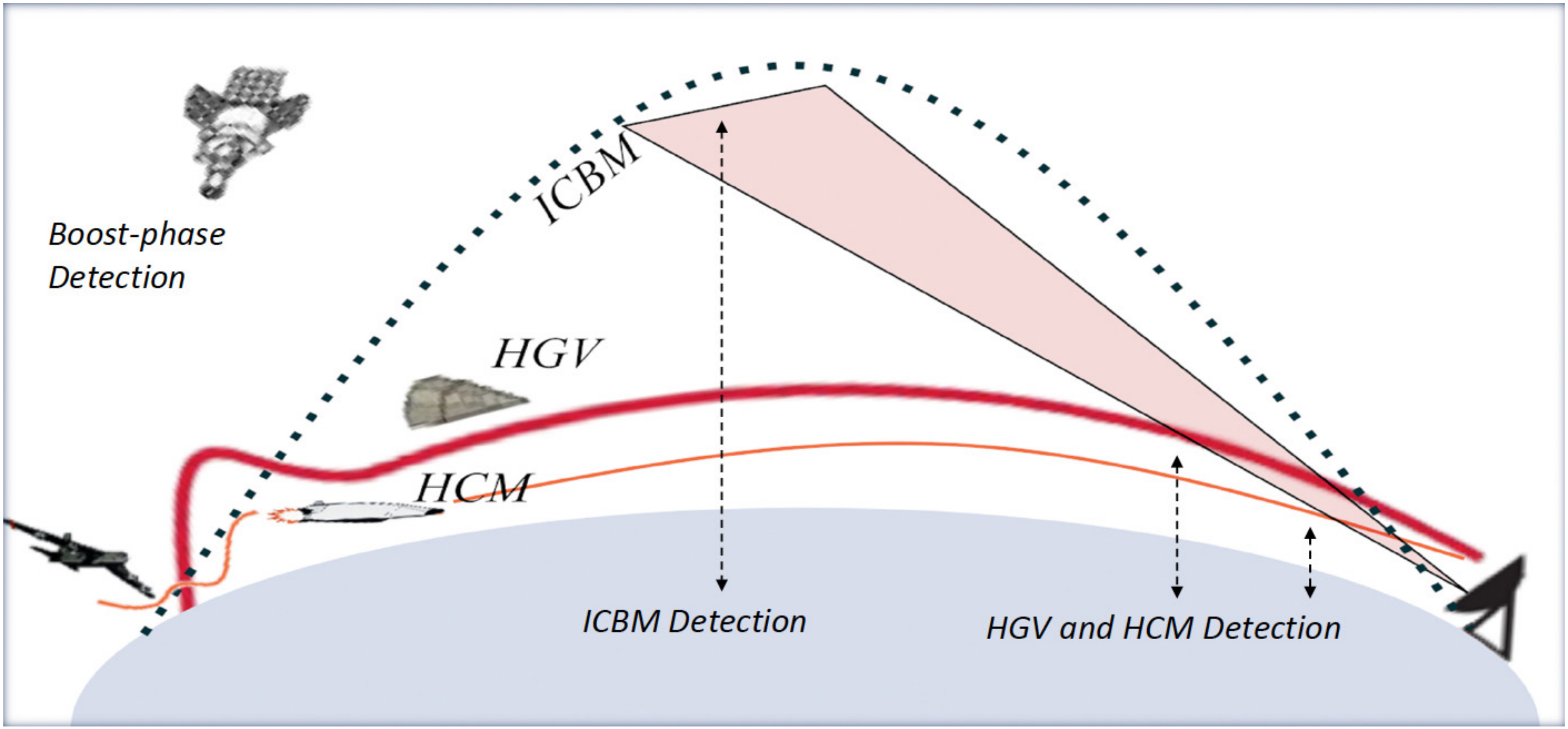
Anything that travels at least five times the speed of sound needs to either slow down to turn or turn in a radius large enough to avoid damaging the missile.

- **high speed $\Rightarrow$ high G-force**
  $\Rightarrow$ high turning force
- **high G-loading $\Rightarrow$ strong airframe**
- **strong airframe $\Rightarrow$ more weight**

manoeuvering at high-speed comes at a price:

- **loss of speed (loss of energy) $\Rightarrow$ loss of range**

Detection of ICBMs and HM



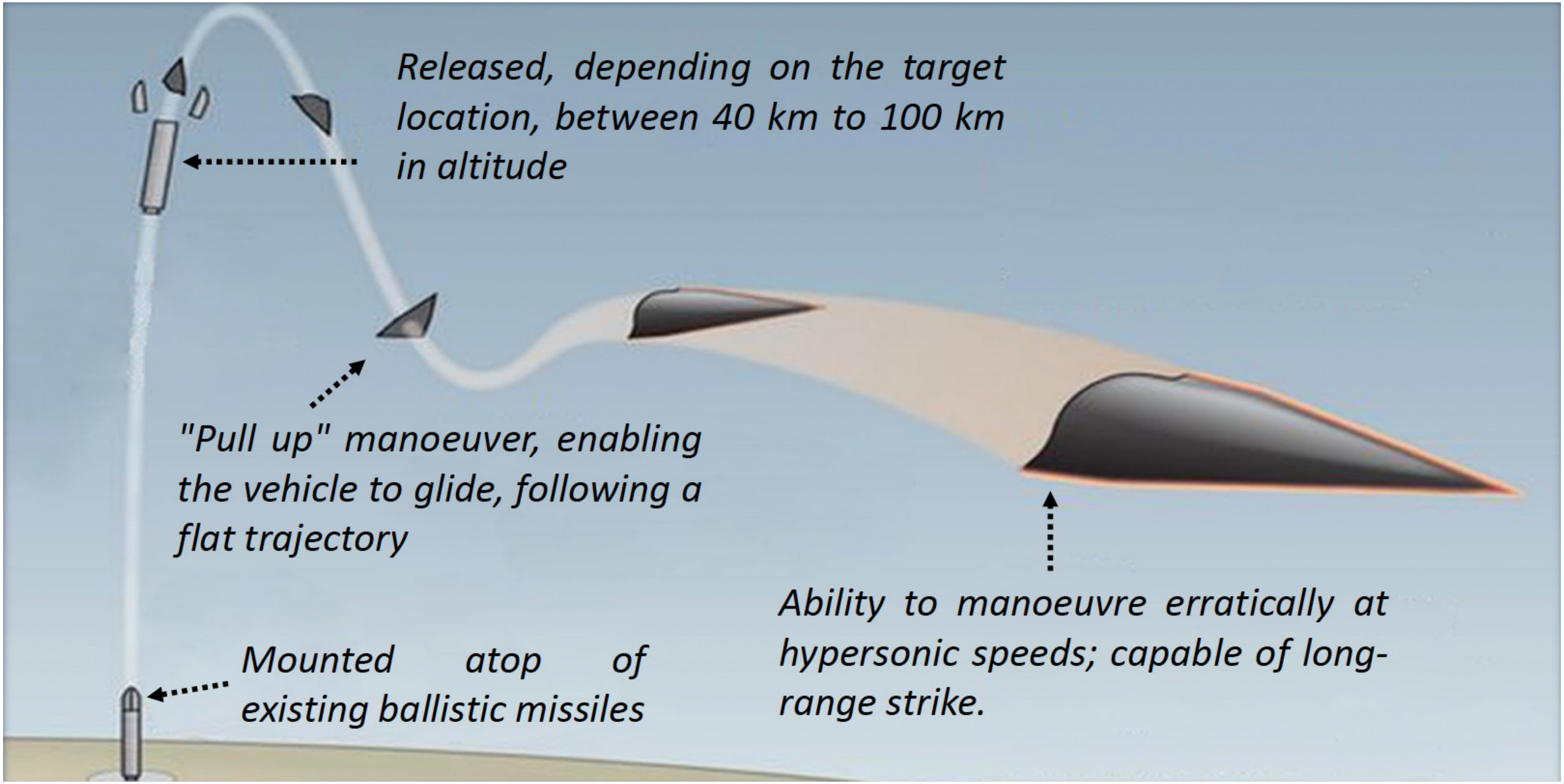
the HGV and HCM are weapons of surprise: with satellite systems it is possible to identify the launch of the missile that releases an HGV, but the radars can see it again only a few minutes before arriving on the target

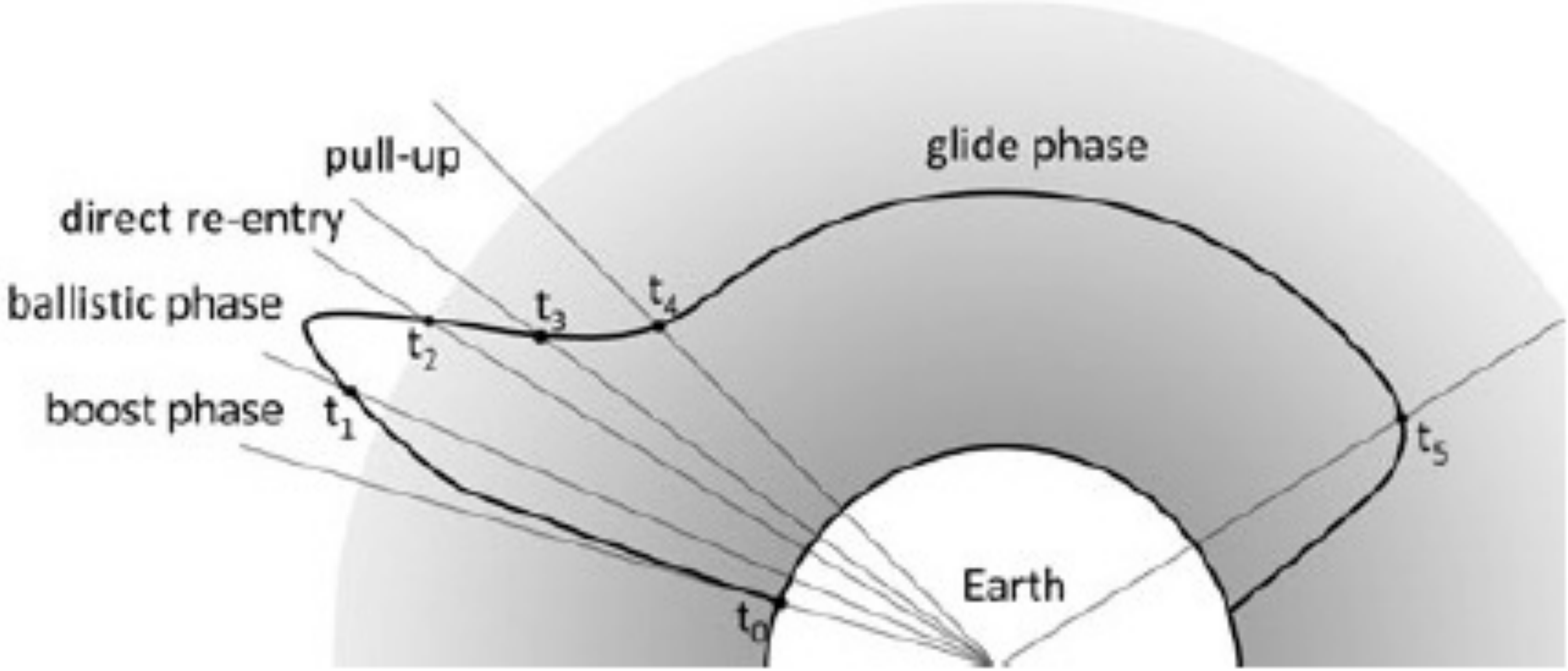
Hypersonic glide vehicles (HGVs)

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 then 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

Range of a glider

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

R = radius of the Earth

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

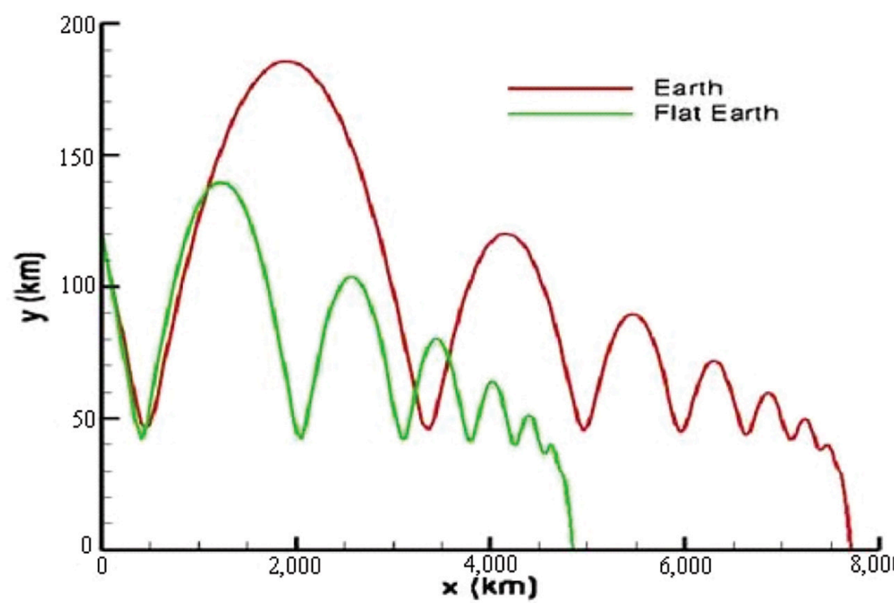
v_i = glider's initial speed

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

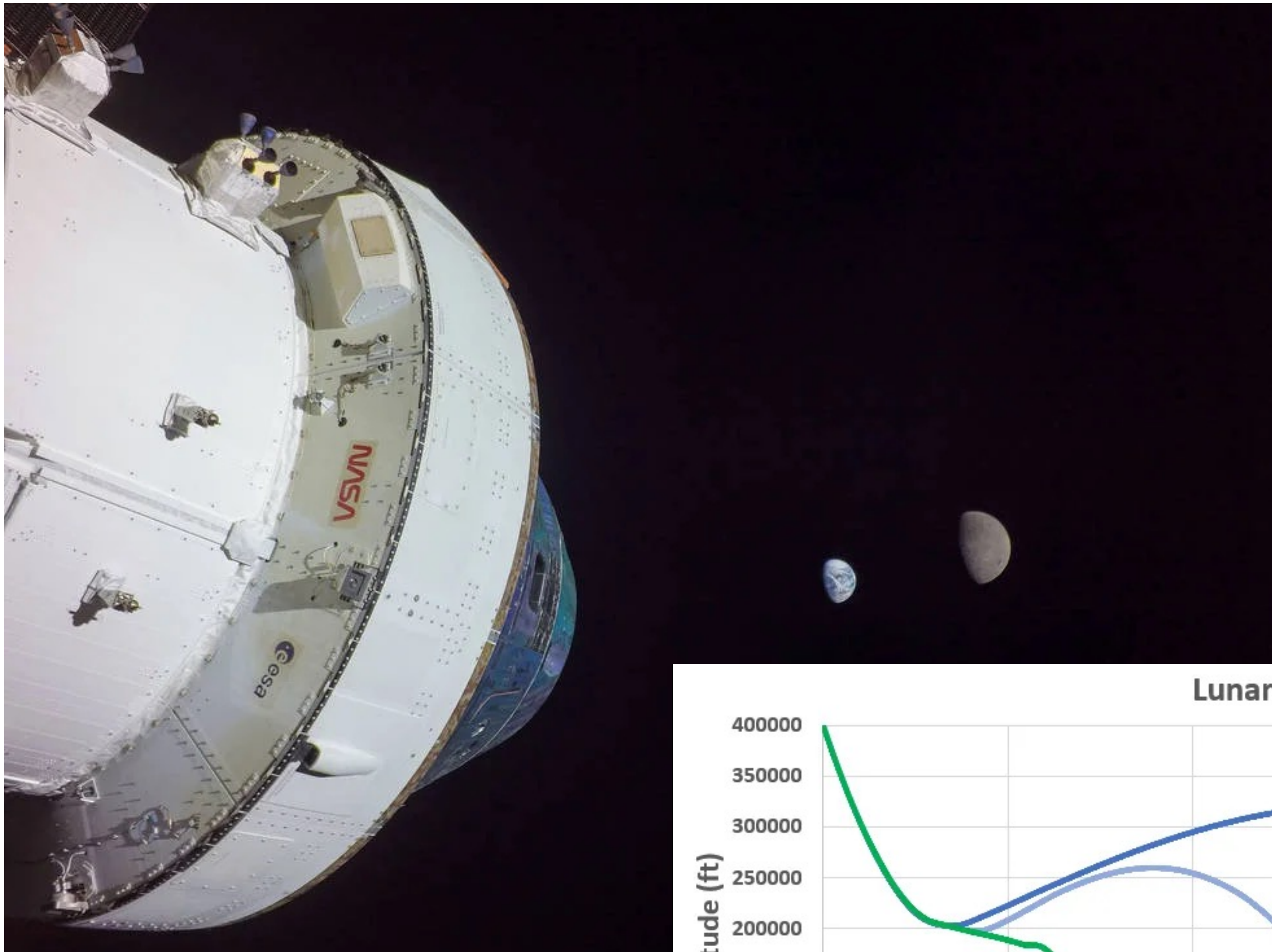
$l_{GLIDE} \approx 10\,400$ km

A HGV launched on a strongly depressed trajectory never leaves the atmosphere, if the carrier missile achieves a horizontal flight at exactly the right altitude for the release of the HGV in an equilibrium glide flight without the need for further manoeuvring.

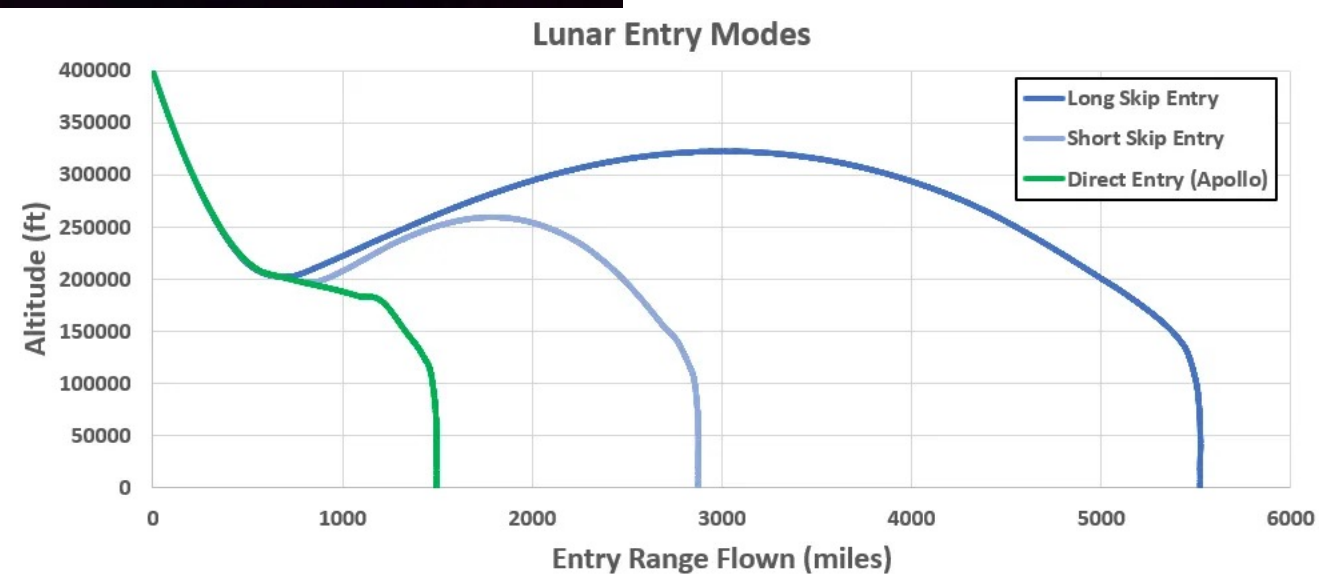
Another possibility involves a minimum-energy launch for the carrier missile, with a high apogee and the transition from ballistic reentry to gliding flight at a minimum angle, so that the HGV proceeds with a phugoid (skip-glide) trajectory, in which the aircraft bounces in and out of the atmosphere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



Orion Mach 32 rehentering vehicle



The spacecraft initially plunged to an altitude of about 61 km. Rolling 180 degrees it changed its center of gravity, causing it to skip off the atmosphere, but not so hard and fast that it would fly off into space. Instead, it climbed back up to 99 km.



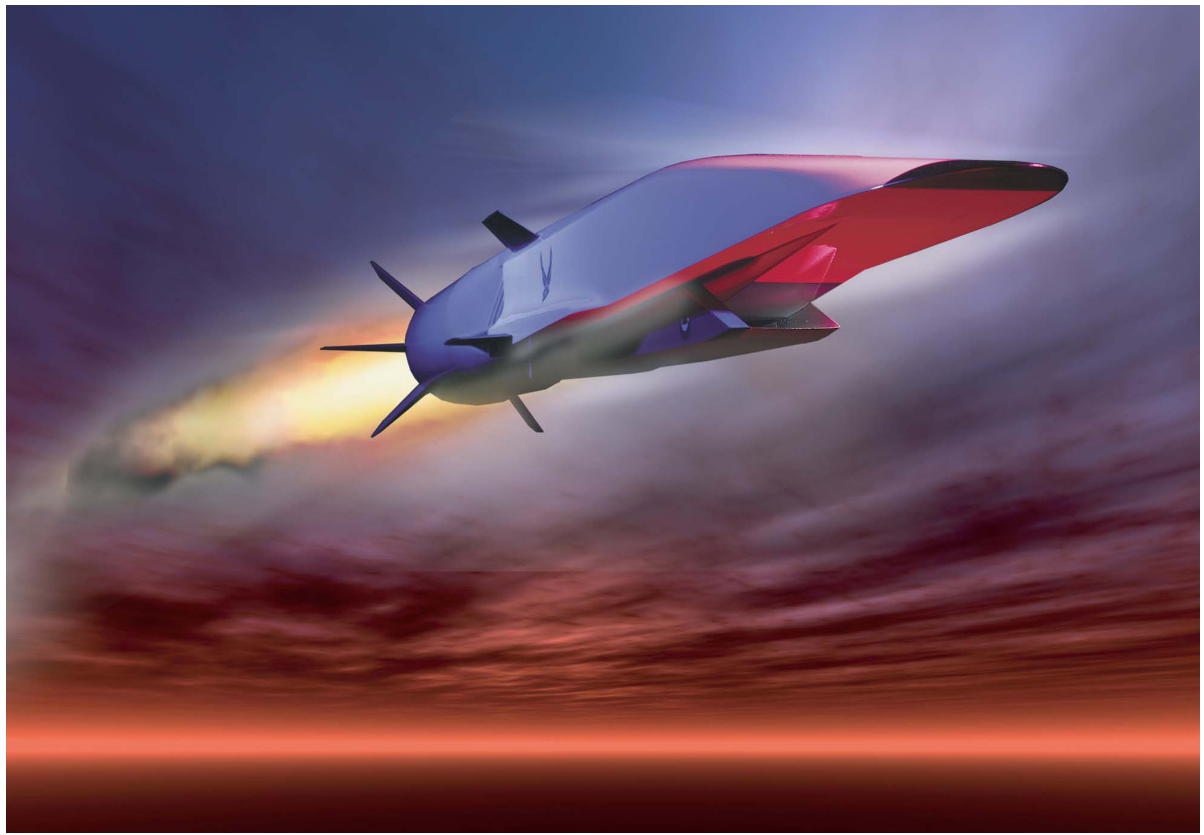
After that maneuver, it resumed its descent, under its guidance system.

Hypersonic cruise missiles (HCM)

HCM 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 10 velocity towards their target, some 1–3 thousands km away

x

X-51 wavereider



The principal advantages of a HCM: speed and manoeuverability

Combined, these would provide a very responsive and flexible offensive weapon that could, for example, aim targets within a 1,000 km radius of the launch aircraft, and strike these targets within several minutes.

Cruise missiles are difficult to defend against because of their unpredictable trajectories. The additional speed provided by a HCM would further complicate defence system timelines, and be more effective against missile interceptors.

HCMs would fly at altitudes higher than most current surface-to-air missile systems are capable of reaching.

HCMs would be smaller than hypersonic glide vehicles and could therefore be launched from a wider range of platforms

Armaments

✦ indicative useful load:
  ≈ 1000 kg for HGV
  ≈ 500 kg for HCM

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

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) (impact speed 2 km/s)

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

- an HGV could potentially rely on its kinetic energy of impact alone (a mass of 500 kg at impact speed 2 km/s has an energy of 2 GJ)

∗ a 20 kJ bullet seriously damages an airplane

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

- **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

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 manoeuvre
- 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.

HGV problems

HGVs suffer huge heat load and generate a plasma cloud around them.
This heat load puts a huge strain on the air frame, which should also be able to withstand any stresses generated by manoeuvres that the HGV is to execute.
The plasma cloud makes it very hard for any type of sensor to sense anything, let alone to identify and lock onto a target.
The HGV, therefore, must know exactly where it is without any help from the outside, thus requiring very precise inertial sensors, among others.
These variables need to be managed not only to maintain the structural integrity of the vehicle, but also to ensure that the on-board instrumentation and payload remain functional.

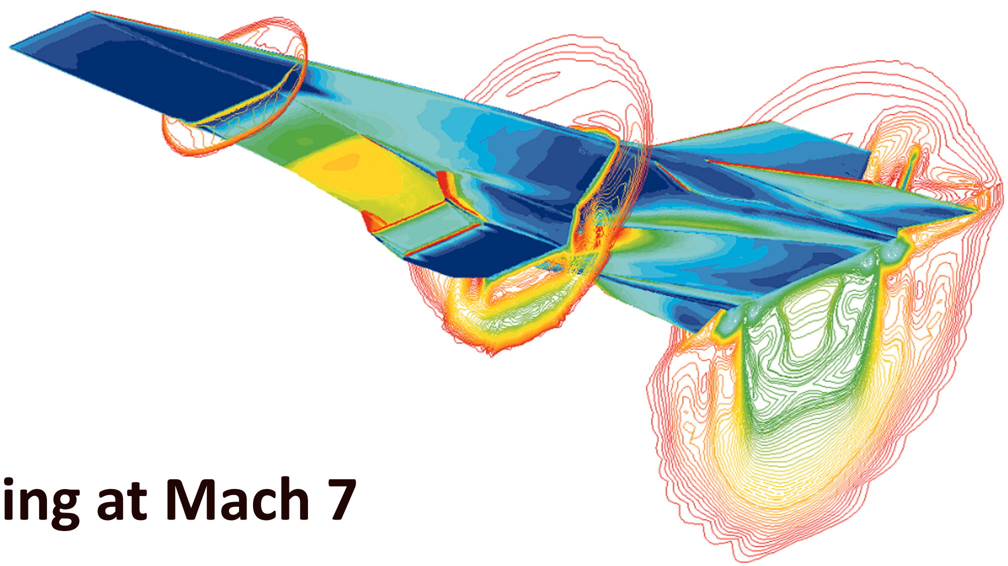
HCM problems

The basic requirements for HCMs are similar to those of HGVs, with the exception that the speeds may be lower.

In addition, 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, no state has deployed a missile system using a scramjet engine, but research, development and testing continue.



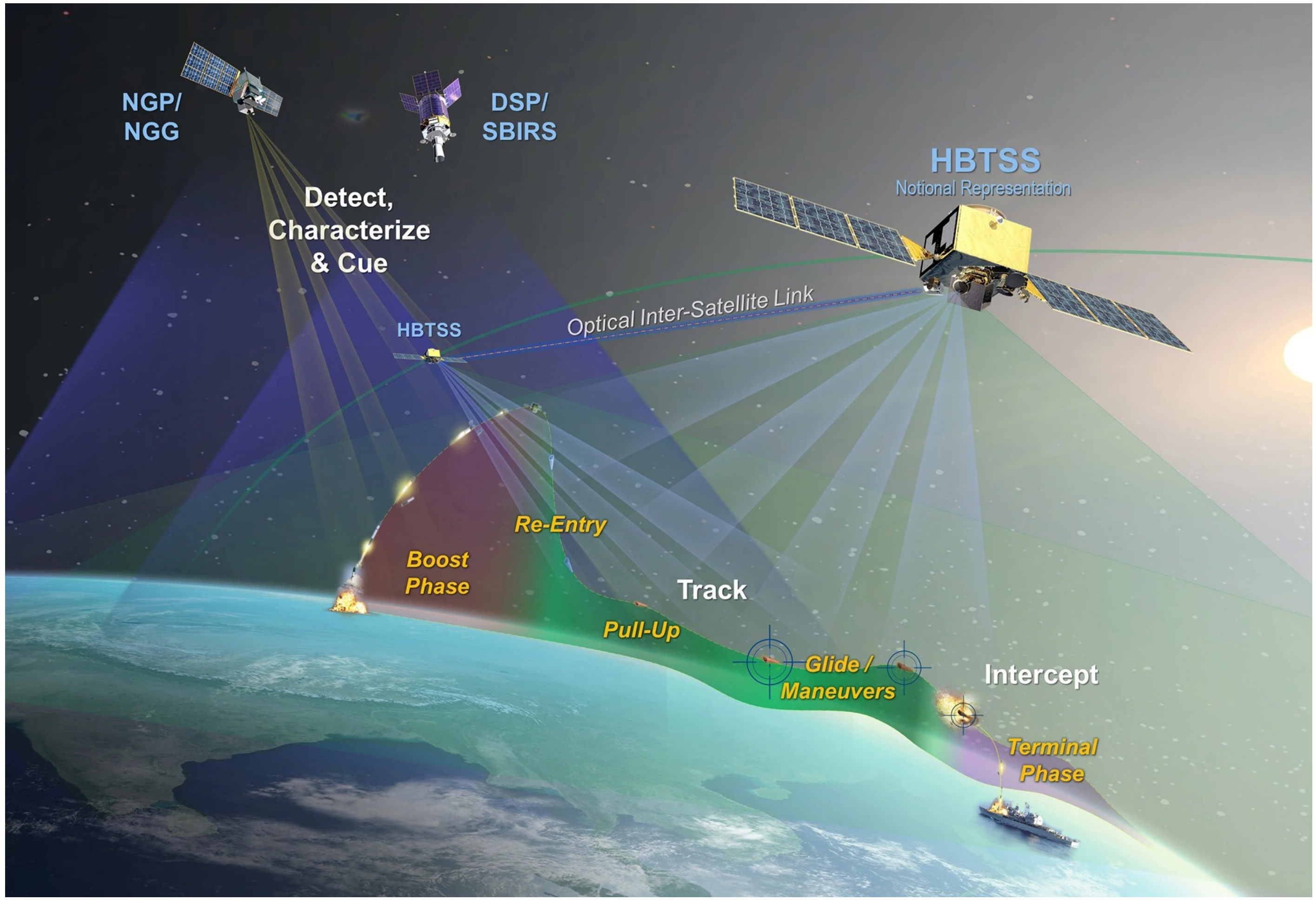
gasdynamic simulation of a HCM flying at Mach 7

HGV’s “invisibility”

The plasma surrounding a HGV in principle makes the vehicle invisible to radar. However experts doubt that hypersonic glide vehicles can manage their speed in a way that tailors the plasma envelope. The high temperature surfaces produce a line of ionized gas that is more visible on radars and space-based sensors than the vehicle itself.
In addition, the plasma can disrupt the navigating signal. HGVs would need to be traveling slowly enough to preclude plasma formation during the terminal phase to allow for GPS-guidance and radio communication.
This means that the US Patriot and the Terminal High-Altitude Area Defense may already be able to detect and track hypersonic weapons during the terminal phases, although they can cover only small areas.

hypersonic defence

Hypersonic flight is atmospheric flight. As such, hypersonic defence might be better understood as a complex form of air defence rather than as an adjunct to ballistic missile defence. Programs of hypersonic defence are already started



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, are hypersonic missile defence 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, 2022

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

conventional weapon strikes replacement of nuclear weapons requires extreme precision systems

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

Russian hypersonic weapons rationale

create strategic forces that cannot be intercepted by American ABMs and thus restoring strategic stability President Putin (March 1, 2018)

Chinese hypersonic weapons rationale

They know. China maintains a policy of deliberate opacity.

Experts assert that *hypersonics will be central to maintaining China’s regional hegemony by strengthening her anti-access/denial area capabilities in the Asia-Pacific zone*

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

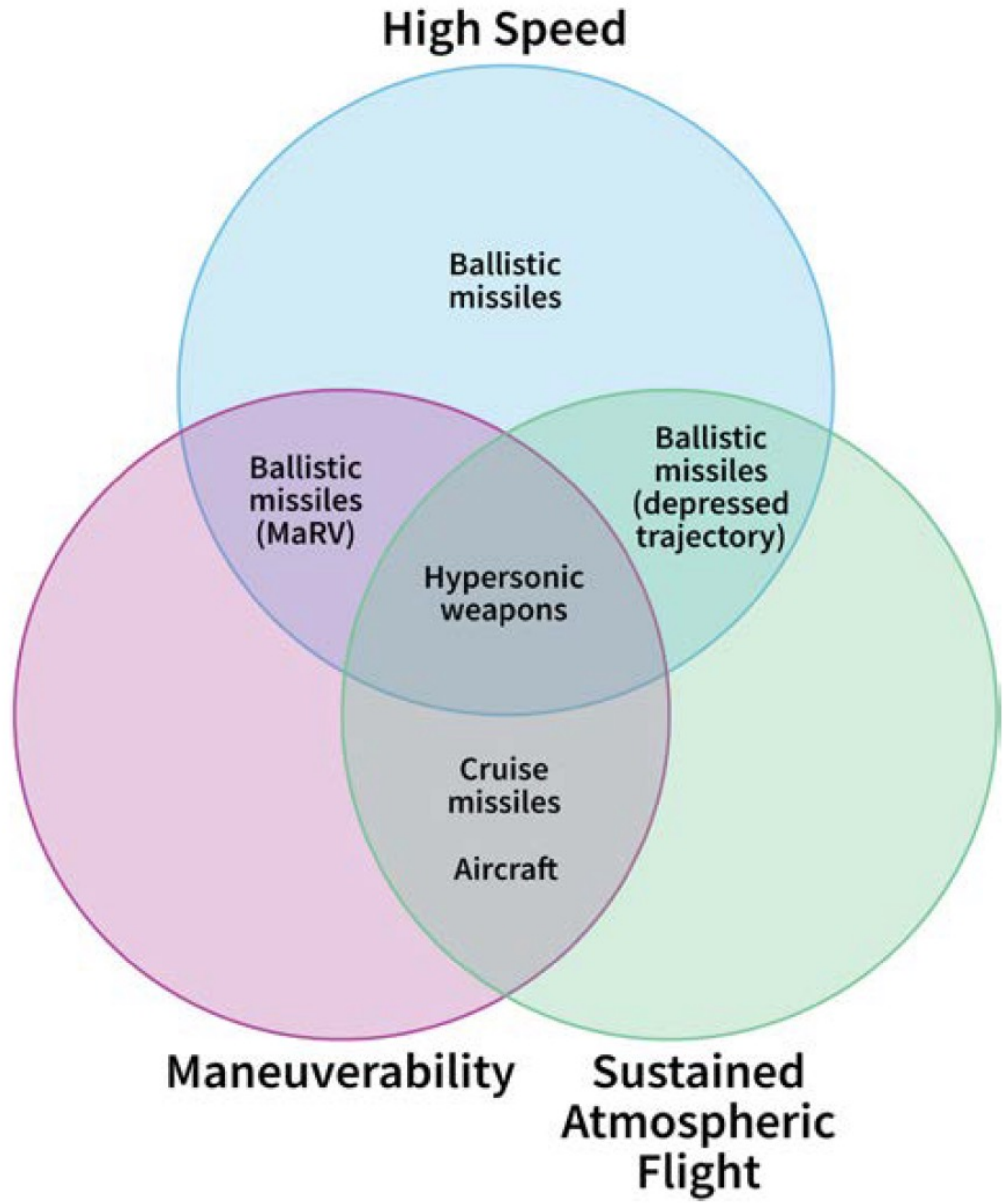
strike options against distant time-critical
- depressed trajectory ballistic missiles
- HGV

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

Figure 4: Relation of Weapon Categories



Source: CSIS Missile Defense Project.

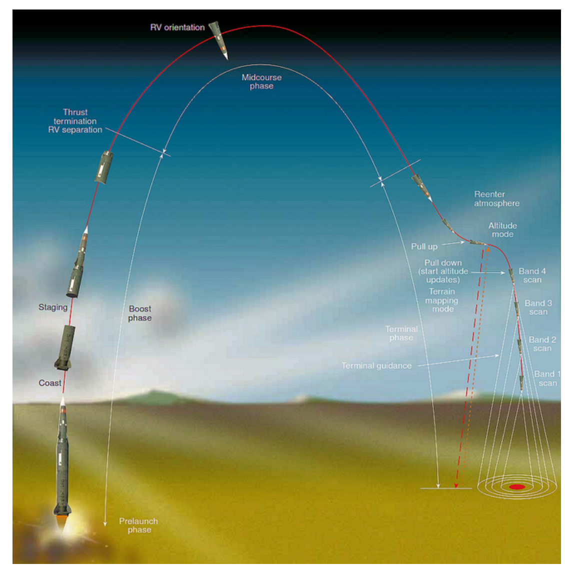
Depressed trajectory ballistic missiles

By reducing the payload weight, different trajectories can be selected, which can either increase the nominal range or decrease the total time in flight.

A depressed trajectory is a lower and flatter trajectory takes less time between launch and impact (some 40% less).

Maneuvering reentry vehicles (MaRVs)

MaRVs may also pull high-G turns at hypersonic speeds even though they do not sustain hypersonic flight or possess the same aerodynamic lift characteristics as HGVs. US AMaRV was guided by a fully autonomous navigation system designed for evading anti-ballistic missile interception.



At the current level of technology, taking into account
- the still limited effectiveness of ABM systems
- the continuing progress in ballistic missiles accuracy
- the necessary operational trade-offs reducing some of the peculiar properties of hypersonic weapons,

it does not appear at present that specific missions can only be accomplished by hypersonic weapons.

Therefore, it appears that HCMs and HGVs will be integrated into the current operational framework and for existing missions.

From a military-technological perspective, they are evolutionary, rather than revolutionary characteristics of missile technology.

In this respect, hypersonic weapons appear an unnecessary waste of money as they do not present a new strategic advantage.

hypersonic weapon program

- ❖ 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

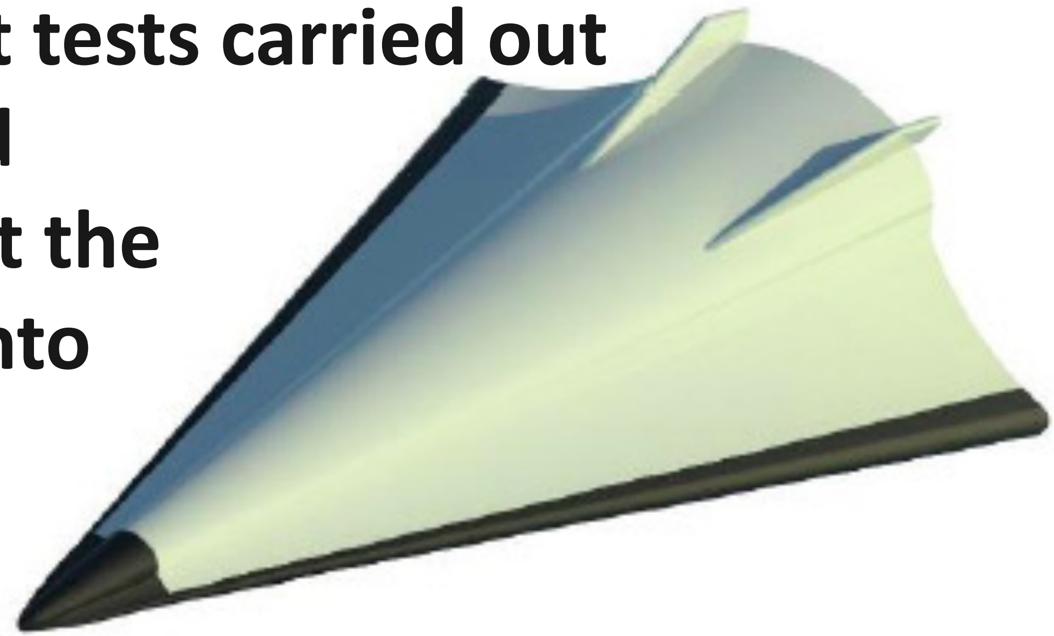
The US is permitting constant, uncontrolled growth of the number of anti-ballistic missiles, improving their quality, and creating new missile launching areas. If we do not do something, eventually this will result in the complete devaluation of Russia's nuclear potential. Meaning that all of our missiles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

- development program includes
  - ▻ nuclear armed HGV
  - ▻ hypersonic ship-launched cruise missile
  - ▻ nuclear-capable maneuvering air-launched ballistic missile
  - ▻ nuclear-capable (possibly propelled by a nuclear reactor) scramjet HCM

Avangard (Project 4202 o Yu-74)

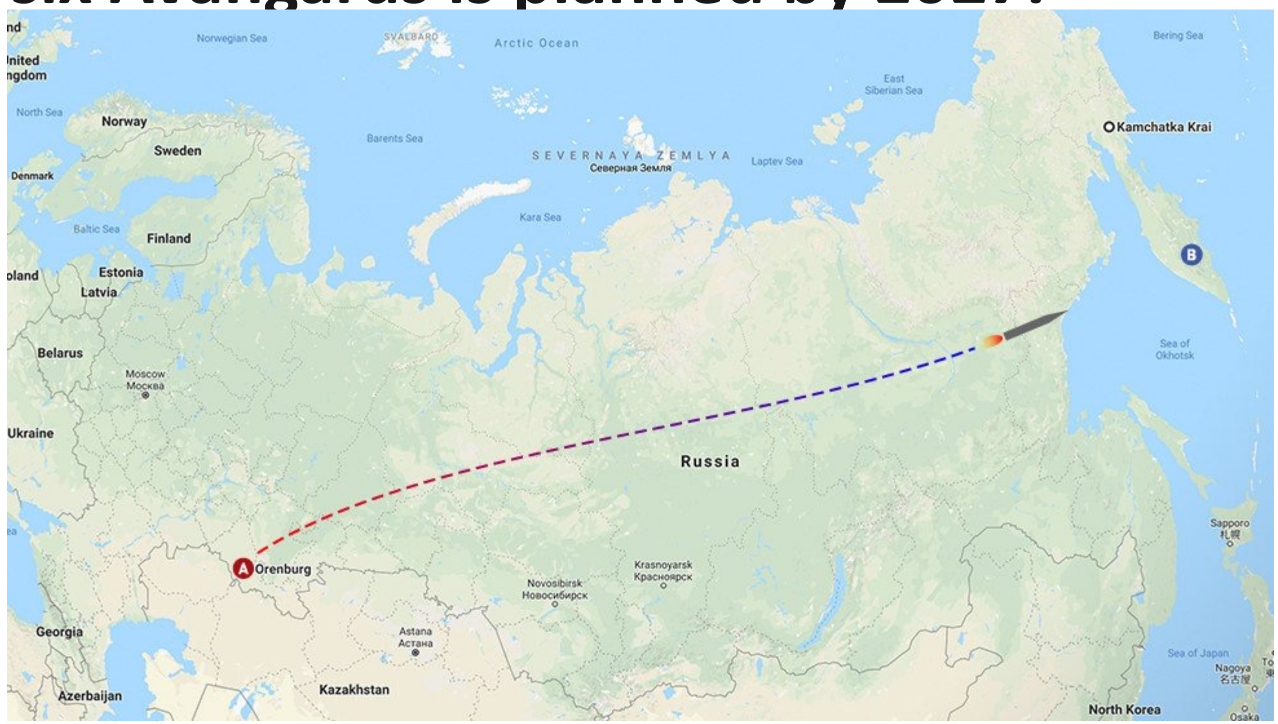
nuclear armed maneuvered HGV: released at its apogee (about 100 km height) from a ballistic missile like the SS-19 (UR-100NUTTH, RS-18), and in the future from the R-28 “Sarmat”, then it should glide for over 6,000 km at speeds up to Mach 20

- 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)

maneuvering, winged hypersonic ship-launched cruise missile with a lift-generating center 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 in the second stage accelerates it to hypersonic speeds.
The missile's maximun range is estimated to be 1000 km at a speed of Mach 6–Mach 8.
It is scheduled to became operational in 2023 and is likely to be fielded on Project 22350 frigates.

Last July in a positive test from the Northern Fleet's frigate *The Admiral Gorshkov* a Tsirkon hit a surface target in the White Sea

Kh-47M2 Kinzhal (“dagger” in Russian)

The Kinzhal is a nuclear-capable air-launched ballistic missile (ALBM), with a payload of up to 480 kg and a thermonuclear option with a 10–50 kt warhead. It has a claimed range of more than 2,000 km, Mach 10 speed, and an ability to perform evasive maneuvers at every stage of its flight.
It and can be launched at altitudes of about 18 km from Tu-22M3 bombers or MiG-31K interceptors.
The Kinzhal seems derived from the ground-launched 9K720 Iskander-M short-range ballistic missile;
launched by an airborne vehicle
rather than from the ground,
it becomes less predictable,
harder to intercept, and
potentially more survivable
than the Iskander ground system

9M730 Burevestnik ("petrel" in Russian)
NATO denomination: SSC-X-9 Skyfall

nuclear-capable cruise missile in a development phase.
Possibly propelled by a nuclear reactor scramjet, it might reach a unlimited range.

The realisation of a nuclear scramjet engine is a real technological challenge, which many experts still consider far off. The USA developed the Pluto project for such an engine at the turn of the 1950s; it was definitively closed in 1964.

On 9 August 2019, after a failed launch test, one of these missiles end up in the White Sea. During recovery attempt the missile exploded killing at least 7 specialists and causing a radiation leak.

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-21 and DF-26 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.

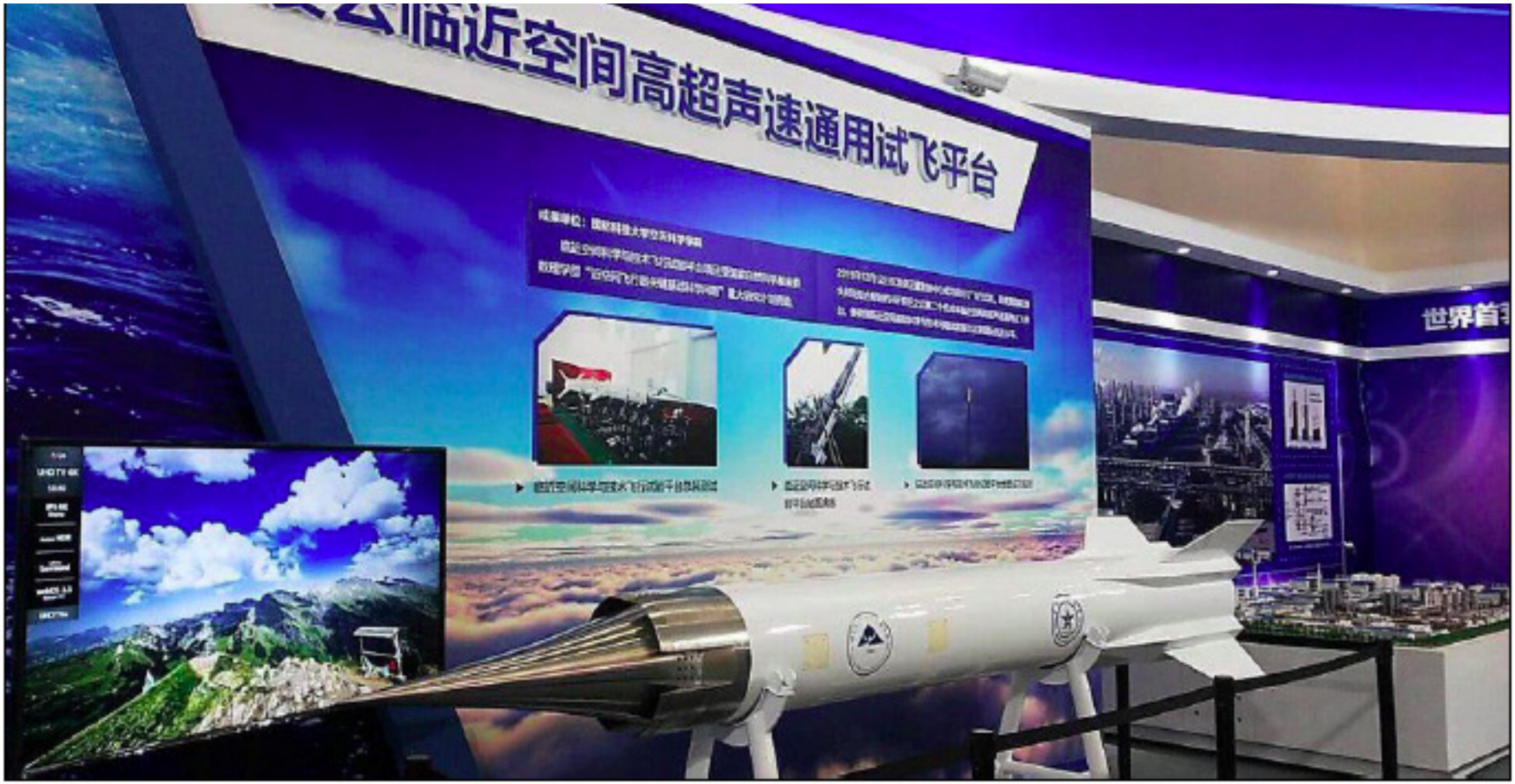
Chinese programs

- most advanced HGV: Dong Feng vehicle ("East wind") for speeds exceeding Mach 10 and a range 1800–2500 km
  - several tests launched by short and medium-range missiles
  - China reportedly fielded the Dong Feng in 2020

- XingKong-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 maneuvers 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 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 request 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 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 Cruise Missile (HCSW, "hacksaw")**
- **US Air Force—Air-launched Rapid Response Weapon (ARRW, pronounced "arrow", AGM-183)**
- **DARPA—Tactical Boost Glide (TBG)**
- **DARPA—Operational Fires (OpFires)**
- **DARPA—Hypersonic Air-breathing Weapon Concept follow-on (MoHAWC, pronounced "mohawk")**

The AGM-183 is 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 Air Force states that ARRW could be operational “as early as fall 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)—which it hopes to launch in March 2023—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.

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.

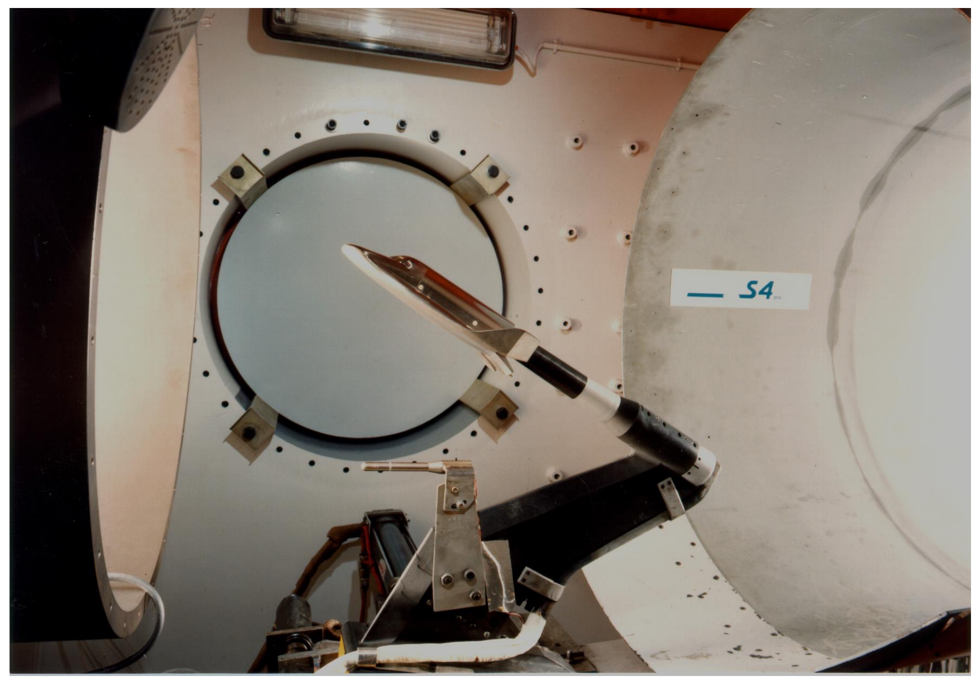
India operates approximately 12 hypersonic wind tunnels and is capable of testing speeds of up to Mach 13.

HSTDV integrated hypercarbon fuel scramjet engine vehicle on show at Berlin

France

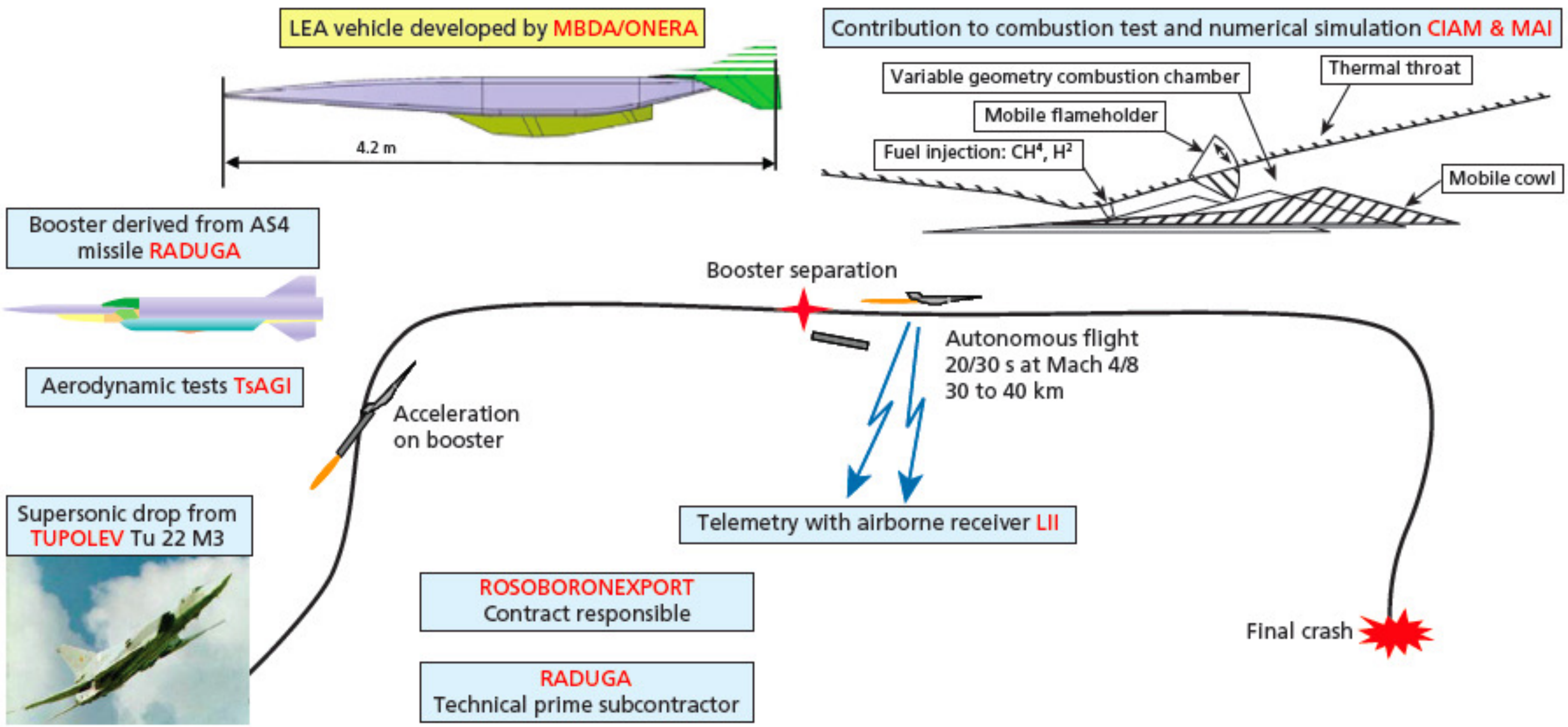
France has collaborated and contracted with Russia on the development of hypersonic technology. Although France has been investing in hypersonic technology research since the 1990s, it has only recently announced its intent to weaponize the technology. Under the V-max (Experimental Manoeuvering Vehicle) 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

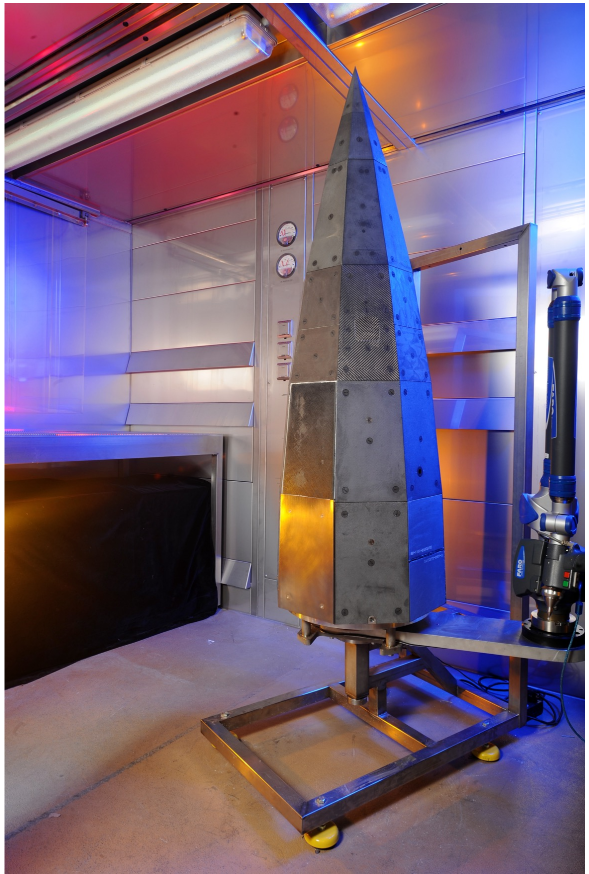


SOURCE: Francois Falempin and Laurent Serre, "French Flight Testing Program LEA Status," Washington, D.C.: NATO Research and Technology Organisation, RTO-EN-AVT-185, undated, p. 17-5, Figure 5.

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.

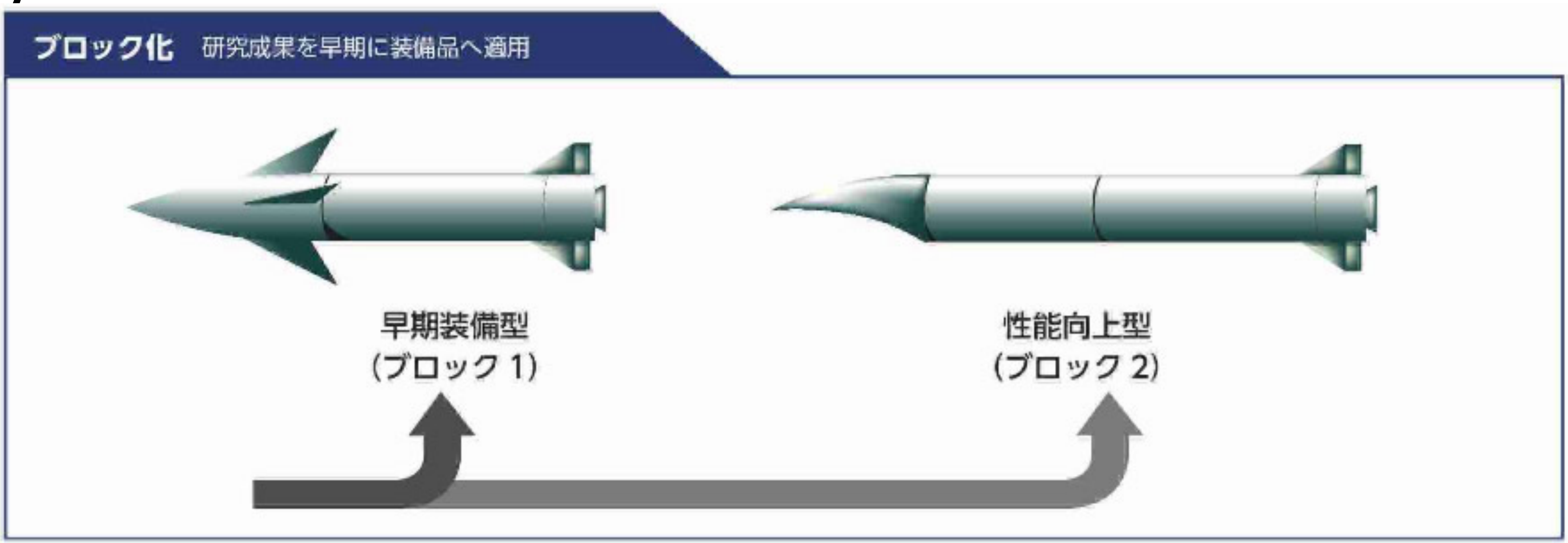


Germany operates three hypersonic wind tunnels and is capable of testing speeds of up to Mach 11.

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.



Joint Statement of the 2023 U.S. – Japan Security Consultative Committee ("2+2")
JAN. 11, 2023

Based on the progress of joint analysis on counter-hypersonic technology, the Ministers concurred to begin joint research on important elements including advanced materials and hypersonic testbeds. The Ministers also concurred to begin discussion on potential joint development of a future interceptor.

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 manoeuvering 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.

strategic implications

Strategic implications of hypersonic weapons

An arms race for hypersonic weapons presents many destabilizing aspects for the present (already precarious) global strategic balance, increasing the uncertainties and risks of escalation of military confrontation in case of conflict:

- **warhead ambiguity**
- **destination ambiguity**
- **origin ambiguity**
- **target ambiguity**
- **crisis instability**

Warhead ambiguity

the attacked country can erroneously misinterpret the launch of a vehicle with conventional weapons and conclude that the missile carries nuclear weapons instead, thus suggesting the need for a nuclear response.

However, even if a State did know that an HGV launched toward it was conventionally armed, it may still view such a weapon as strategic in nature, regardless of how it was perceived by the state firing the weapon, and decide that a strategic response was warranted.

Ambiguity of destination

hypersonic weapons, due to their high manoeuverability, can induce a country observing a HM launch to mistakenly conclude that it is the real target of the attack, while the HM vehicle is destined for another country.

Prompt, global attack capabilities could prove destabilizing, when nations might have incomplete information about the nature of an attack and too little time to gather more information and plan an appropriate response. Faced with these circumstances, a nation who was not an intended target might choose to respond quickly, rather than to wait for more information.

Origin ambiguity
in the case of non-detecting the launch of an HM, an attacked country may not know which is the attacking state and therefore react against the wrong opponent; the problem becomes acute in the case of proliferation of hypersonic weapons

Target ambiguity
a state can mistakenly believe that its nuclear forces are threatened, while the objective are conventional systems; the risk is all the greater given the increasing integration of nuclear and conventional command and control systems

Crisis instability

The real or perceived ability of HM to hold a country's nuclear or strategic conventional capabilities at risk creates pressures to use (or threaten to use) weapons out of concern that they lacked survivability.
HMs thus increase fears of a disarming attack, encouraging to devolve command and control of strategic forces to low-level officials and to disperse forces, in an alert posture during a crisis. These extremely destabilizing measures lower the threshold for military actions.

The speed of war:
faster weapons, shorter reaction times

The pace of technological change in hypersonic flight vehicles in conjunction with areas such

- robotics and uninhabited land, sea and air vehicles
- quantum cryptography and quantum computing
- artificial intelligence and autonomuos control
- nanosciences and material science
- space militarization
- directed energy

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

Faster weapons and faster C_4ISR systems (command, control, communication, computers, intelligence, surveillance and reconnaissance) will change the way military leaders operate on the battlefield as well as how they plan and execute missions. They 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.

The increasing speed of weapons and of the decision making cycle will challenge military professionals.

New technologies will enable even more sophisticated and disruptive "grey zone" operations

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 hypersonics 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 to 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.

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."

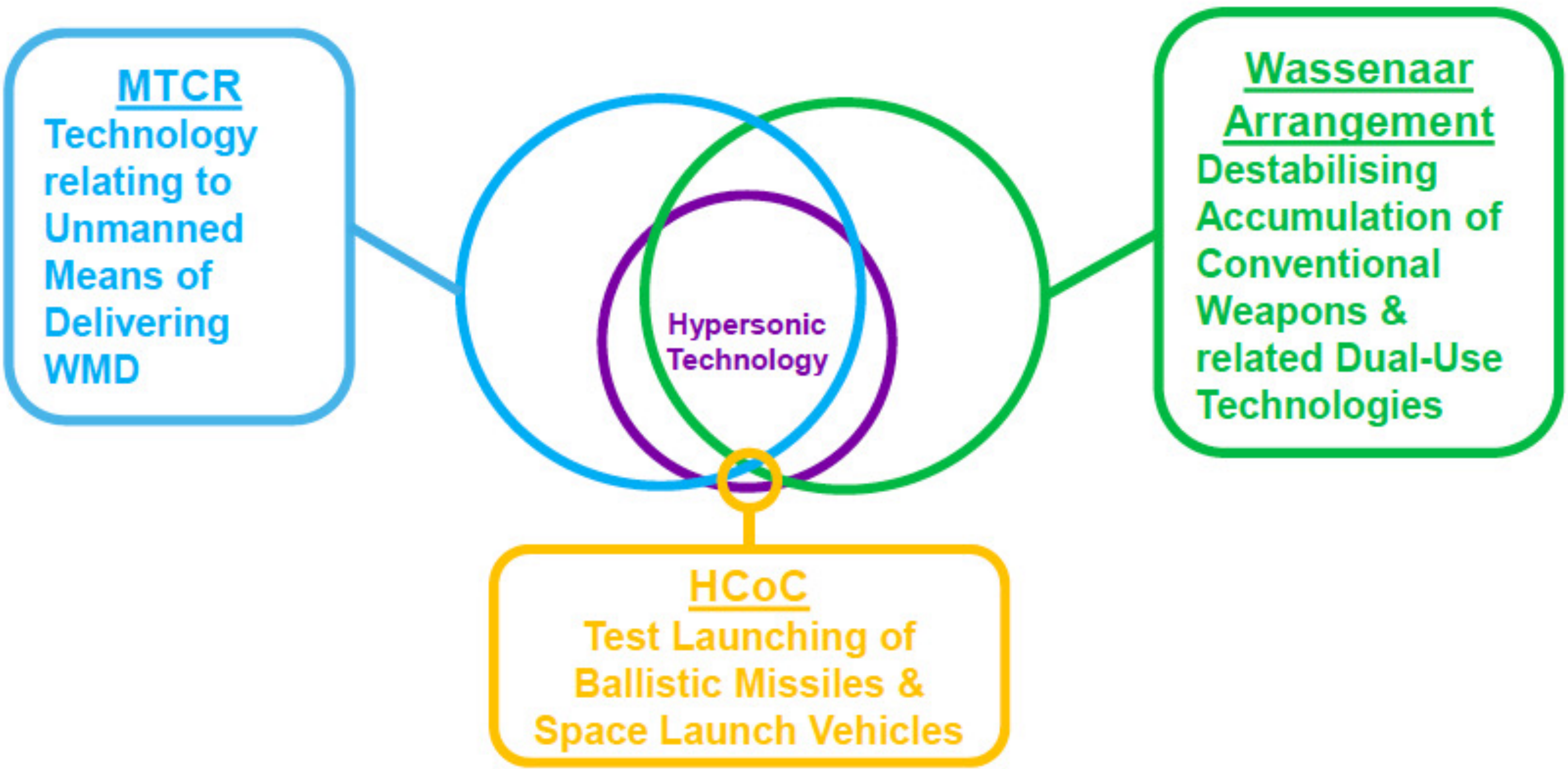
As a result, a party would have the opportunity to question the other party on whether the boost-glide systems should count under the treaty. But the second party would not have to delay the development, testing, and deployment of these systems while the discussions proceeded.

Non proliferation

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

Multilateral export control regimes are relevant

Multilateral Export Control Regimes (MECRs)



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

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)

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 MTCR participating governments have commit themselves politically to apply restrictions on the transfer of technology capable of being used for the delivery of weapons of mass destruction. These restrictions apply to complete rocket systems and unmanned air vehicle (UAV) systems; production facilities for such systems; and major subsystems including rocket stages, re-entry vehicles, rocket engines, guidance systems and warhead mechanisms.

The transfer of the most sensitive Category I items (with capabilities exceeding a 300km/500kg range/payload threshold) are subject to an unconditional ''strong presumption of denial''. 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)

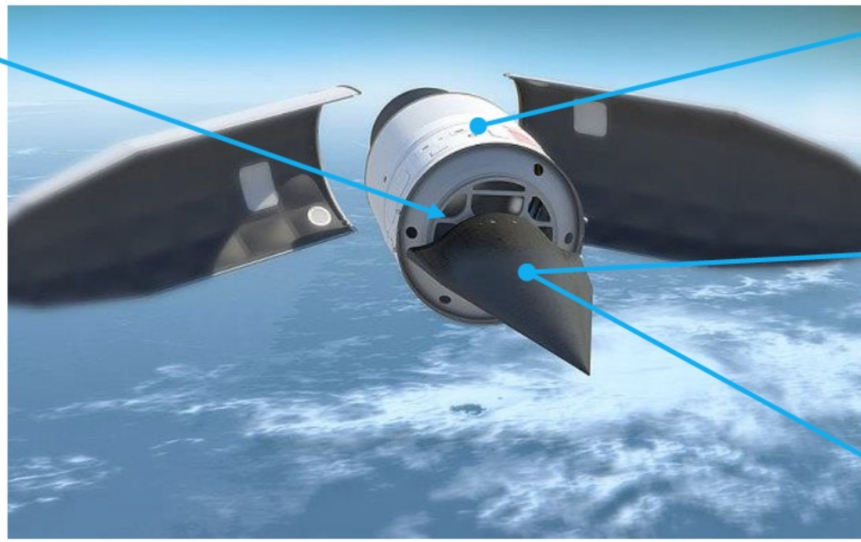


Image: Defense Advanced Research Projects Agency DARPA

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

Flight testing is crucial:

1. **Generate information unique to flight test environment that cannot be obtained on the ground**
2. **Use the data to anchor/validate models and to verify ground test data**
3. **Validate system performance in its operational environment and/or for system certification**
4. **Identify unanticipated problems**
5. **Reduce risk and demonstrate technology in flight**
6. **Provide political messaging**

the initial five are vital to the development and fielding of HVs, both civilian and military

Arms control for hypersonic weapons

Negotiates have been proposed for an international moratorium or ban on hypersonic weapon testing.
Analysts counter that a test ban would be infeasible, as no clear technical distinction can be made between hypersonic missiles and other conventional capabilities.
These analysts have instead proposed international transparency and confidence-building measures, such as exchanging weapons data; conducting joint technical studies; providing advance notices of tests; choosing separate, distinctive launch ocations for tests of hypersonic missiles; and placing restraints on sea-based tests.

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.

Impact on humanitarian principles

Hypersonics could reduce collateral damage

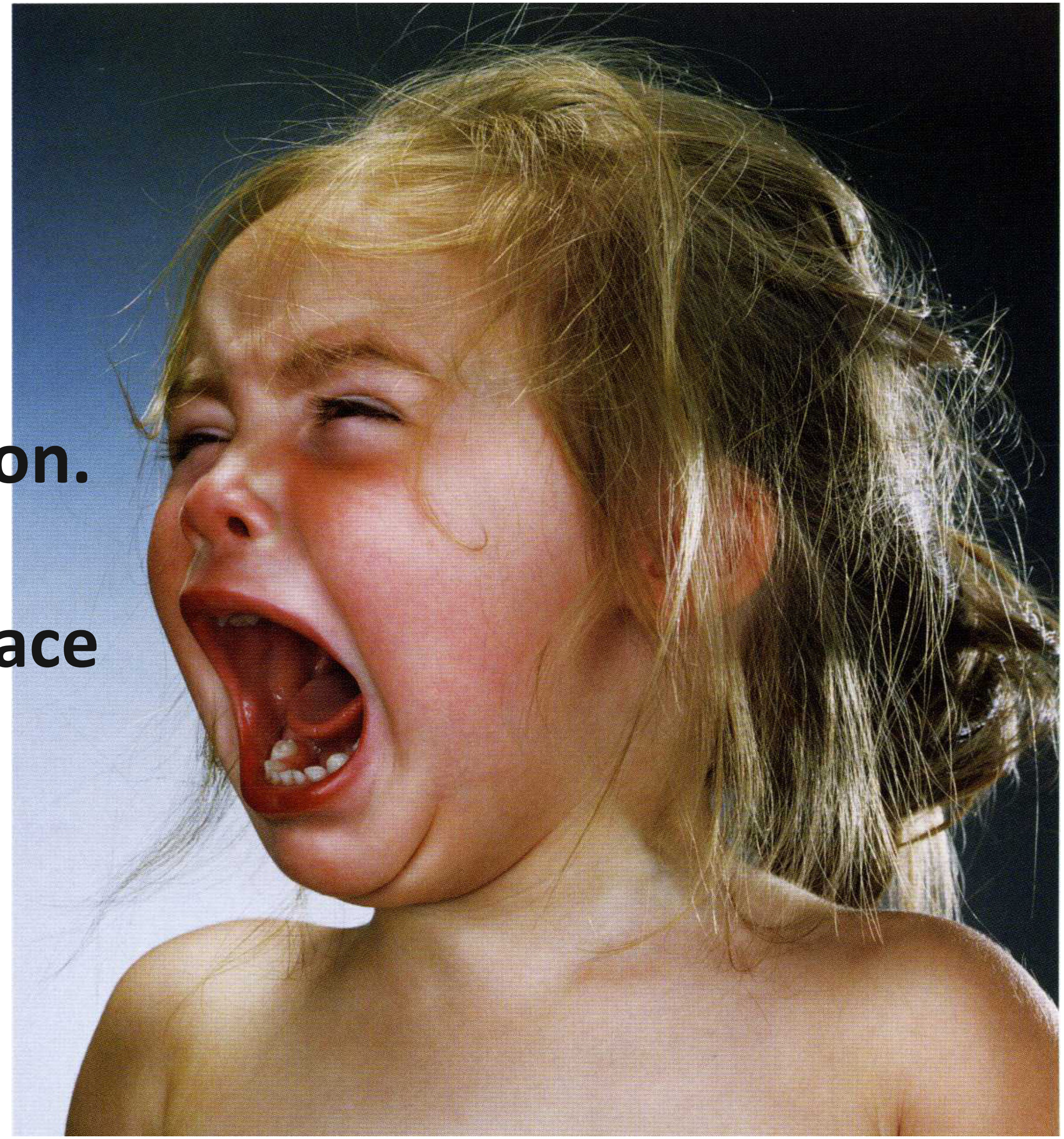
The accuracy of conventionally armed hypersonic weapon systems could enhance the precision of attacks, enabling belligerents to limit civilian casualties.

To the extent that a hypersonic weapon system constitutes a conventional alternative to a nuclear strike option, it could also allow for more proportionate uses of force.

Hypersonics could reduce meaningful human control in attacks

The anticipation of compressed decision making time could push leaders to rely on automated or semi-automated command and control of these systems. If the targeting and/or guidance of the weapon is delegated to automated or autonomous systems, human oversight and control could be reduced in such a way as to undermine compliance with the laws of war.

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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