Figure 1: The X-51 Waverider is a scramjet powered vehicle launched from an aircraft mother ship and brought to scramjet ignition speed and altitude by a mounted booster rocket. In a May 2013 test flight, it reached Mach 4.8 at about 20 km altitude over a period of 210 seconds.

Hypersonic Vehicles

Game Changers for Future Warfare?

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Introduction

Hypersonic technologies offer potential solutions and applications that could have a strong impact on doctrine and conduct of future military operations. Different applications are conceivable for hypersonic flight vehicles in order to enable new or advanced military capabilities. Most obvious is the rapid delivery of weapons. Serving the 'speed is life' tenet, high speed would allow for rapid regional or global strikes against time critical targets from standoff distances, while keeping the launch platform out of highly contested areas. As adversaries push out the boundaries of contested areas with advanced Anti-Access/Area-Denial (A2/AD) capabilities involving most modern Integrated Air Defence Systems (IADS), hypersonic flight counters the trend and allows greater standoff operations for first strike. In addition, the extreme speed of hypersonic penetrating systems makes kinetic intercept by the adversary very difficult.

This essay is based on a presentation given on behalf of the Applied Vehicle Technology (AVT) Panel at the 2016 NATO Science & Technology Symposium on 'The Future of Warfare', a collaborative venture between the NATO Science and Technology Organization (STO) and Allied Command Transformation (ACT).[1] The remainder of the article will be split into two parts. The first part will provide an introduction to hypersonic flight, the current achievements in related research, experiments, and the further science and technology challenges concerning hypersonic vehicle development. The second part will explore the feasibility, benefits, and timeline projection of potential future military applications, concluded by a summary and remaining considerations.

Part A – An Introduction to Hypersonic Flight

Research, Experiments, Science & Technology Challenges

Definition and Types

Hypersonic flight has no agreed upon scientific definition but is typically understood as flight within the atmosphere at speed of Mach 5 and beyond, which is five times the speed of sound. Generally, three different vehicle types may be considered for the hypersonic flight regime:

Boost glide vehicles. An unpowered hypersonic vehicle is carried to altitude (boosted) by a rocket, detaches in the vicinity of 100 km altitude, and subsequently glides on the top of the atmosphere at speeds of 8–10 Mach. This type is also known as hyper-glide vehicle (HGV).

Supersonic Combustion Ramjet (SCRJ) powered vehicles. These are variants of a ramjet (RJ) air-breathing jet engine in which combustion takes place in supersonic airflow throughout the entire engine. This allows the vehicle to operate at considerably high speeds, theoretically getting efficient at about Mach 5. Obviously, these vehicles need to fly lower in the atmosphere to ensure the oxygen supply for the engine.

Exo-atmospheric ballistic missiles. These are the classical rocket-powered exo-atmospheric ballistic missiles, which are not further discussed in this paper, even though they operate in the hypersonic speed regime.

History and Present Status of Research

Research in hypersonic flight has a long history[2] reaching back to the X-15 program, which aimed at preparation for space-flight. The X-15 experimental, manned vehicle with liquid rocket propulsion reached a speed record of Mach 6.7 at an altitude of 59 km in 1967. The Space Shuttle and other re-entry vehicles pass though the hypersonic regime when entering the atmosphere (80 km altitude) at Mach 20+ and decelerate during the dive. Numerous hypersonic research experiments follow a similar re-entry flightpath with interim pull-up/glide and manoeuvring phases.

The dream of an operational powered reusable hypersonic vehicle is not new. The US embarked on a major research project in the 1980s to develop a hypersonic, reusable single stage to orbit passenger 'airplane'. This program was called the 'National Aerospace Plane (NASP)'. In 1986, US President Ronald Reagan publicly talked about a plane that would fly from New York to Tokyo in two hours, increasing belief that hypersonic platforms were close to reality. NASP was cancelled in 1992 as the technology proved to be too difficult, but the scientific knowledge gained through ten years of research set the stage for the current generation of hypersonic vehicles. This theme of program termination after learning much about the basic science is recurring in hypersonic vehicle research, which has led to episodic advances in technology.

Research is typically conducted in cycles. The results of one research campaign are used to improve modelling as well as to define follow-on activities. Based on modelling, ground testing (both static and in wind tunnels) and live flight experiments, current research activities are investigating fundamental hypersonic phenomena, materials, components, and the technologies for flight control, navigation, instrumentation, and propulsion.

Hypersonic research is currently conducted by the USA, Russia, China, and Australia, and at a more modest scale by Japan, France, and Germany as well as to some extent by India.[3] The Technology Readiness Level (TRL) for hypersonic flight vehicles lies at or below 6 (i.e. prototype demonstration in a relevant environment).[4] However, the systems being developed and tested today are mature enough to let us believe they will be fielded in the foreseeable future.

Experimental Boost Glider Vehicles

Most of today's hypersonic research vehicles have no internal propulsion, i.e. they are boost gliders. Some of the more notable recent experimental vehicles include:

- **Advanced Hypersonic Weapon (AHW).** A boosted glide vehicle launched by the United States Army Space and Missile Defense Command in November 2011 from the Pacific Test Range. The AHW flew 3,700 km in 30 minutes (average speed Mach 6), striking a target at Kwajelin Atoll.
- **Chinese DF-ZH.** Open source information indicates that China tested a boost glide hypersonic delivery vehicle called the DF-ZH (original name WU-14), with speeds Mach 5 to Mach 10. It is assumed that the boost glide body can be mated with both intercontinental and theatre ballistic missiles. There have been at least seven flights of the DF-ZH.
- **Russian Unmanned Hyper Glide Vehicle.** In April 2016, the Russians conducted and announced a flight test of a new vehicle YU-71. Specific capabilities of this vehicle are not known.[5]

Experimental SCRJ Powered Vehicles

Other experiments focused on testing SCRJ powered vehicles, as by the following examples:[6]

- **HyShot II Experiment.** In July 2002, the Australians conducted a low cost experiment using a sounding rocket to carry an SCRJ powered vehicle (the 'HyShot II') to exo-atmosheric altitudes. It then separated, re-entered the atmosphere, and ignited at about Mach 7.6 to stay in powered flight for six seconds.
- **X-43 (Hyper-X Program).** The X-43 SCRJ powered vehicle was part of the US National Aeronautics and Space Administration (NASA)-led Hyper-X program. A winged booster rocket (the Pegasus) with the X-43 on top was drop launched from a Boeing B-52 and brought the stack to target speed and altitude. Once SCRJ ignition speed (Mach 4–5) was reached, the X-43 detached from the Pegasus and flew free using its own SCRJ propulsion. In a test conducted in November 2004, the X-43 accelerated to Mach 9.6 at up to 34 km altitude and reaching a burn time of roughly 12 seconds.
- **X-51 Waverider.** Built by Boeing for the United States Air Force (USAF), the X-51 Waverider was comparable in size to the X-43. It is also launched from a B-52 aircraft, but with a Minotaur booster rocket (see Figure 1). Designed for longer duration flight, it

reached Mach 4.8 at about 20 km altitude over a 210 second SCRJ powered flight segment, in May 2013).

In comparison, the Lockheed SR-71 Blackbird, which was the fastest operational USAF aircraft designed for high altitude reconnaissance operations, reached Mach 3.3 at 25 km altitude in the 1990s.

The HIFiRE Program

The Hypersonic International Flight Research and Experimentation (HIFiRE) Program was a US-Australian collaboration, which conducted a multi-flight campaign as typical for hypersonic research.[7,8] Lasting from 2009 to 2016, the program resulted in seven launches to examine different aspects of hypersonic flight to include flight dynamics and powered flight (see Figure 2). Experimental vehicles were rocket launched, lifted to high or even exo-atmospheric altitude and separated from the booster. Then they dove or glided down through the atmosphere with high speed, gathering data, performing manoeuvres and sometimes adding another SCRJ powered phase. Some vehicles had features for final recovery to allow post flight inspection.

The Sharp Edge Flight Experiment (SHEFEX) program conducted by the German Aerospace Center is another example for hypersonic flight investigations that followed a similar approach.[9]

Disasters and Failures

An example for the extreme environment at hypersonic speed is given by the Space Shuttle Columbia disaster in 2003. Here, the Thermal Protection System of the left wing was damaged at launch, allowing hot gas to penetrate during re-entry and to destroy the internal wing structure, leading to the tragic loss of crew and vehicle.[10,11]

Another catastrophic failure happened during a test of the Hypersonic Test Vehicle (HTV-2), as conducted by the Defense Advanced Research Projects Agency (DARPA) in 2011. HTV-2 was lost after only a few minutes of flight due to extreme heating on the leading edge, which resulted in irregularities in the vehicle skin surface. This test failure demonstrated some further hypersonic flight challenges. At hypersonic speeds, any imperfection results in a growing shock wave around the platform. When the vehicle skin eroded due to heat, the corresponding shock wave system disturbed the aerodynamic stability and forced the vehicle into irrecoverable failure.

While the failure rate of hypersonic vehicle tests is comparable to early aviation flight tests and fiascos, it is very important to note that the technical knowledge gained from these let-downs is immense. Failures, therefore, should not deter further development, especially since NATO nations have successfully flown both boost-glide and SCRJ systems in recent years.

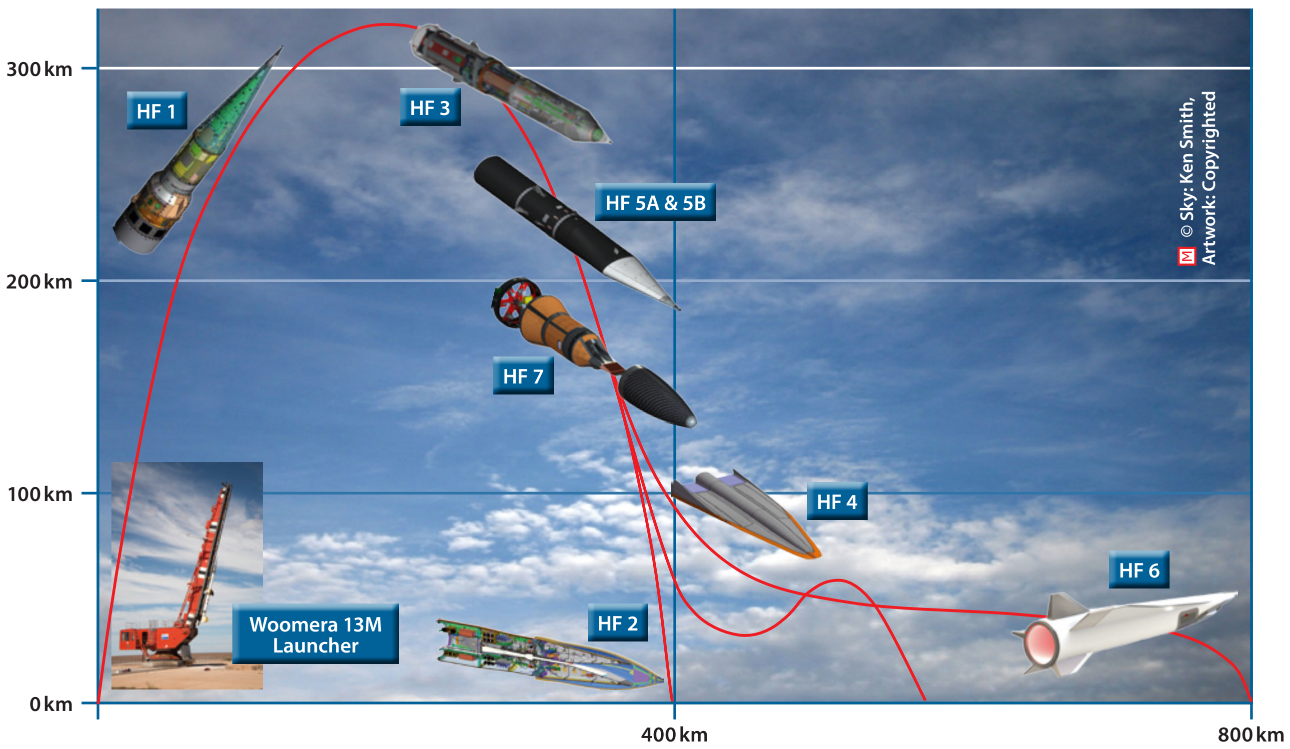


Figure 2: Hypersonic flight experiments – example: HIFiRE Program (USA, AUS).

Science & Technology Challenges

Many scientific and technological aspects (such as kinetic heating, force loading, etc.) are unique to hypersonic flight. There is yet too little knowledge available about such factors, which makes hypersonic vehicle design and development extremely challenging. After decades of hypersonic flight research, there are still many problems that need to be solved to get from hypersonic technology achievements to a truly operational hypersonic system.

In a very simplistic way, some challenges of hypersonic flight through the atmosphere are illustrated by a meteor. A meteor enters the atmosphere with a speed beyond 40 km/s (roughly Mach 12) and heats up depending of the thermal conductivity of its materials. The heated outer layers loose strength and may be fragmented by huge drag forces. This can be seen as a kind of cooling, since the most heated material is continuously removed. Depending on its size and composition, the meteor may be totally consumed during atmospheric entry, or it may reach the ground as a meteorite. As demonstrated by the meteor analogy, managing the excess thermal loading is clearly a principal challenge for hypersonic flight. Additional challenges come into play when thinking about the need to navigate and control the hypersonic vehicle.

Thermal and Aerodynamic Forces and Effects

Kinetic heating is a major effect that increases in severity with increasing speed. In brief, heating increases with both velocity and atmospheric density. Figure 3 shows the total temperature as a function of flight Mach number. Even when the recovery temperature acting on a flight vehicle will be somewhat lower, this gives an indication of the heat loads to be expected. The temperature limit with regard to strength for different structural materials is also indicated. High-performance steel and a typical Titanium-Alloy range from 800 Kelvin (K) to 950 K. Molybdenum-Alloys (e.g. Ti/Zr/Mo) are usable up to about 1,700 K, but they are brittle and have a much higher density. Ceramic materials like Carbon Fibre Reinforced Silicon Carbide Composites (C-SiC) can be used even beyond 1,800 K, but they feature a very low strain capability, which limits their application for load carrying structures. Consequently, conventional materials and designs are not applicable for hypersonic flight, while the current class of available advanced materials will limit high altitude (but not exo-atmospheric) flight to Mach 5–6.

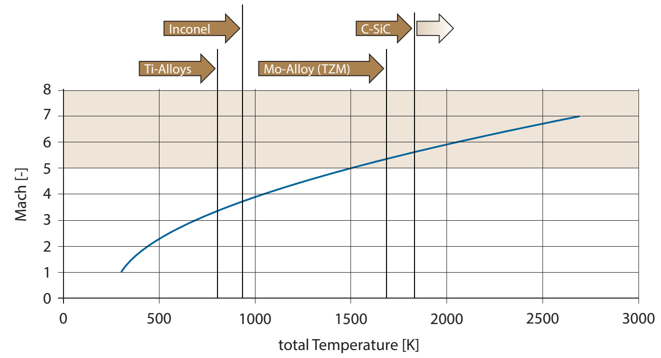


Figure 3: Total temperature depending on flight Mach number application limits of structural materials.

Massive aerodynamic forces at hypersonic flight lead to additional issues. Figure 4 shows the pressure behind a normal shock wave in metric tons per square metre to illustrate the forces acting on a vehicle. At 40 km altitude, a hypersonic vehicle has forces of the mass of a motor car per square metre. This increases to the mass of a truck on a square metre at 20 km altitude. The extreme aerodynamic forces and the extreme kinetic heating have highly transient patterns[12] due to

- shock pattern dominated flow (which caused e.g. the HTV-2 failure);
- complex boundary layer transition mechanisms;
- shock-shock and shock-boundary layer interactions;
- thermo-chemical effects.

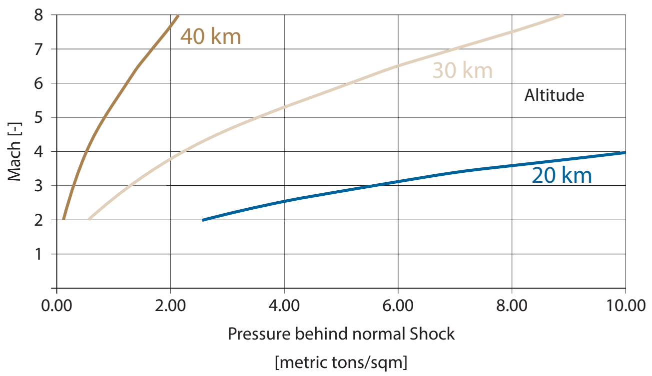


Figure 4: Pressure behind a normal shock vs. Mach number.

Each of these forces as well as the related effects must be understood and dealt with during design and test to develop an operational, repeatable system.

For the vehicle itself, which is typically configured as a wave rider as illustrated in Figure 5, the effects on structural integrity and endurance are among the main challenges.[13] The thermal management to keep structural material strength high enough to carry extreme and highly dynamic structural loads is a key issue. Thermal protection by insulation or ablation delays heat flow into the vehicle structure and offers a viable solution for limited flight duration. Cooling can improve endurance if the fuel of a powered vehicle can be used as cooling fluid or if a cooling fluid can be carried as payload (weight penalty). Of course, a flight duration limit is then induced by the total amount of cooling fluid available in the vehicle.

Besides structural integrity, thermal issues are aggravated by the fact that vehicle equipment, such as control effectors and actuators as well as instrumentation, sensors, and electronics, typically need to be kept at temperatures below about 100°C (370 K) for operation. To sum up, it is evident that structural integrity issues of hypersonic flight require technical solutions at the edge or beyond current state of the art.

Another important issue is flight control to keep the vehicle stable while coping with the highly dynamic lift and drag forces.[14]

Figure 5: HTV-2 was a crewless, experimental hypersonic glide vehicle developed as part of the DARPA Falcon Project. In the two flight tests in 2010/2011 the 'waverider' was carried inside the nose of a Minotaur IV Lite rocket to outer space for the craft to separate from the booster. Both tests were unsuccessful due to lost contact to the glider after a few minutes.

Challenges for Sustained Hypersonic Flight

Rocket propulsion for launch/acceleration and climb to operational altitude of a hypersonic vehicle is state of the art, albeit problems may arise with very low temperature for ignition and operation. This can occur for configurations which are air-launched from a

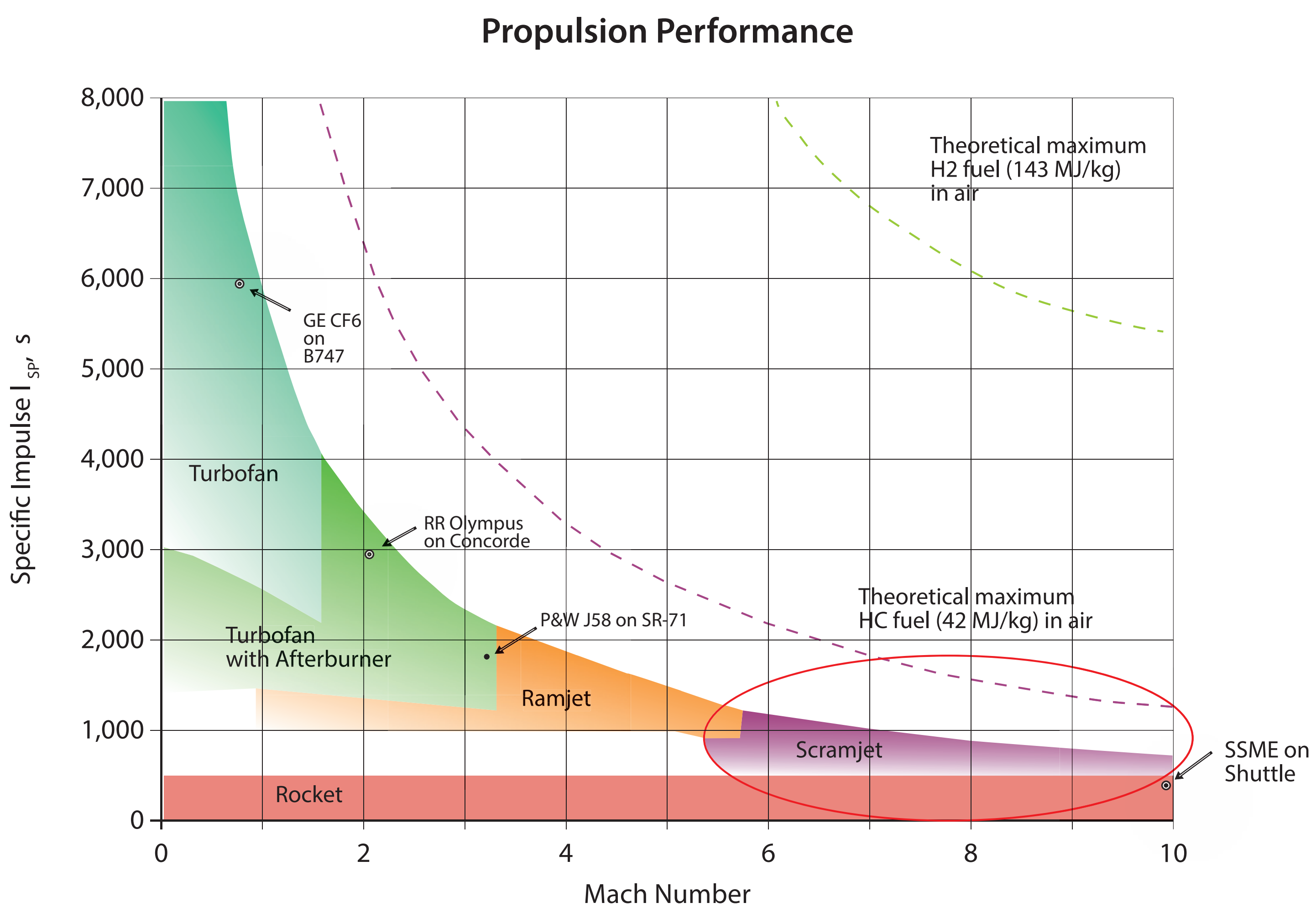


Figure 6: Performance of different propulsion systems vs. Mach numbers.

platform flying subsonic at high altitude for long duration.

Another issue is the propulsion for a sustained flight at hypersonic speed, which requires the use of SCRJs.[15,16] While SCRJs have been a research topic for more than fifty years, there are still considerable hurdles to overcome on the way to a reliable propulsion system, especially with regard to longer run times.

Major issues are the use of hydrocarbon storable fuel with regard to ignition, performance, and cooling and air intake performance as well as stability over a sufficient range of speeds/altitudes/angles of attack/sideslip operations.[17]

Figure 6 illustrates the achievable propulsion performance (i.e. the 'Specific Impulse') as a function of Mach number for different propulsion systems.[18] Extension of the operational regime of the propulsion system to lower Mach numbers will induce the need for combined cycle engine concepts like RJ/SCRJ or Turbo/RJ/SCRJ with even higher complexity.[19]

Vehicle and propulsion issues are highly interrelated and need aligned design concepts and of course, overarching requirements as mass and volume limitations, payload capacity, and affordability need to be considered when we assess the feasibility of a hypersonic flight vehicle.

Part B – Military Utility of Hypersonic Flight

Applications, Timelines, Considerations

Global Strike

The extreme speed of hypersonic systems could become a decisive military advantage when it comes to penetrating enemy defences from a safe stand-off distance. A hypersonic weapon systems could for example cover a distance of 1,000 km in about 10 minutes at Mach 5. For comparison, operational missiles today can fly

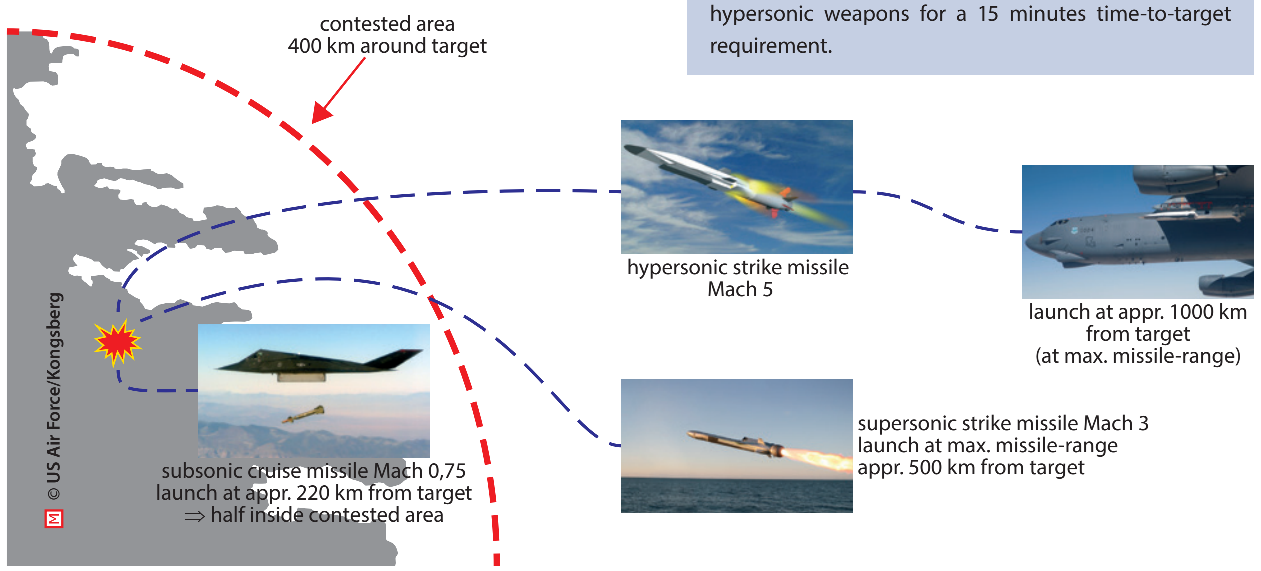
- 500 km at Mach 3 in about 9 minutes (e.g. ASMP-A; French supersonic cruise missile);
- 1,000 km at Mach 0.75 in about 67 minutes (e.g. Tomahawk; US subsonic cruise missile).

Figure 7 illustrates a comparison of the required launch distance for subsonic, supersonic, and hypersonic missile systems, given the objective to hit a target within 15 minutes after launch. An aerial launch platform of a subsonic Mach 0.75 missile would need to get as close as 220 km to the target before missile launch. This means entering deeply into the range ring of modern surface-to-air missiles (SAM) such as the Russian S-400 Triumf (SA-21 Growler), which covers up to 400 km. To launch a supersonic missile, one could keep a distance of up to 500 km, which is only a marginal advantage overcome by further advanced SAM systems in the foreseeable future. High risk to own high-value assets could only be avoided with hypersonic missile systems.

For a global strike range of typically 10,000 km, the flight Mach number of the hypersonic system must be considerably higher to reach the target within a certain limit of time. An Inter-Continental Ballistic Missile (ICBM) would reach 10,000 km in 30 minutes. A realistic goal for Hypersonic Vehicles is to reach Mach 10, which would keep the time-to-target below one hour.

The following sections will address some prospective hypersonic military applications to include the associated technological challenges as well as potential risks.

Figure 7: Launch distances for subsonic, supersonic and hypersonic weapons for a 15 minutes time-to-target requirement.



Hypersonic Manoeuvrable Glide Vehicle

Figure 8 shows the mission trajectory of a manoeuvrable glide vehicle. To date, the US, China, and Russia have successfully tested this concept. A boost-glide vehicle would be boosted to high altitude (100 km+), separate from the boost rocket, and perform an un-powered relatively flat glide phase with manoeuvres in the upper atmosphere at around Mach 8–10 before the final dive to the target. Such glider would be much more difficult to intercept than state-of-the-art, re-entry vehicles with a ballistic trajectory. The reason is simple and points to an advantage of non-ballistic trajectories. Current long range strike systems will be detected by ground based radar, which can spot approaching ballistic missiles with much more lead time. At boost-glide altitudes, a ground based system may not detect the vehicle until very late in the flight, making intercept much more difficult.

Boost-glide vehicles would carry conventional warheads to fulfil the global strike requirement. Therefore, the hypersonic glide vehicle would have to be bigger in size and mass than operational BM re-entry warheads. Extreme peak dynamic pressures and temperatures together with aggressive manoeuvres (to evade intercept) are the major challenges for the structural integrity of such vehicles. Typically, time-to-target would be less than one hour. The Circular Error Probable (CEP) will depend on issues like navigation (and communication) means and guidance/flight control precision. Such vehicles could also be used for medium range strike with ranges around 3,000 km+, if launched from a ship or submarine operating near the target region. In this case, there would be a strict volume constraint for the design, to ensure compatibility with existing launch equipment. Another most difficult technical challenge associated with boost-glide is that precise engagement of a target would likely require deceleration to about Mach 3 in the terminal phase. Even then achieving a precise hit will remain very difficult.

Hypersonic glide vehicles could be a lethal instrument for power projection, but for now, they would require limited range to avoid a nuclear escalation. Early warning systems would likely differentiate the depressed trajectory of such glide weapons from an ICBM's re-entry warhead. On the other hand, the early post-launch ballistic curve of long-range, hypersonic vehicles would probably have considerable similarity with a BM launch and could be detected as easily. If falsely interpreted, this could lead to an undesired and inappropriate reaction of the adversary.

Technically, the boost-glide vehicle is likely to be the first operational system, as the number of global successful tests of prototype systems outpaces any other hypersonic technology by far. An operational system is attainable by 2022–2025. Many research projects are aiming at this goal:[20]

- US: Falcon, HIFiRE, HSSW/TBG (High Speed Strike Weapon/Tactical Boost Glide);
- YU-71 (Russia);
- WU-14 (China).

Hypersonic Cruise Missile

Hypersonic cruise missiles may be used for tactical strike from standoff distances. Flying at Mach 4–6+ at altitudes of 20–30 km, flight time for up to 1,000 km is shorter or comparable to a ballistic missile. Most likely, hypersonic cruise missiles will be air launched from a mother ship (such as a B-52), resulting in a mass- and size-restricted vehicle. Figure 9 illustrates the mission with air launch, a boost and climb phase with an expendable rocket and the cruise to the target with SCRJ propulsion. Typically, the vehicle has to accelerate to about Mach 4–5 for SCRJ ignition. The vehicles will be difficult to detect at launch and to intercept during high altitude cruise and terminal dive.

For this mission, peak temperatures are lower than for the glide vehicle due to lower speed, but integrated heat loads will still be high depending on flight duration. Aerodynamic forces will be higher than for the glide vehicle because of the lower flight altitude, but manoeuvres during the cruise phase will be moderate.

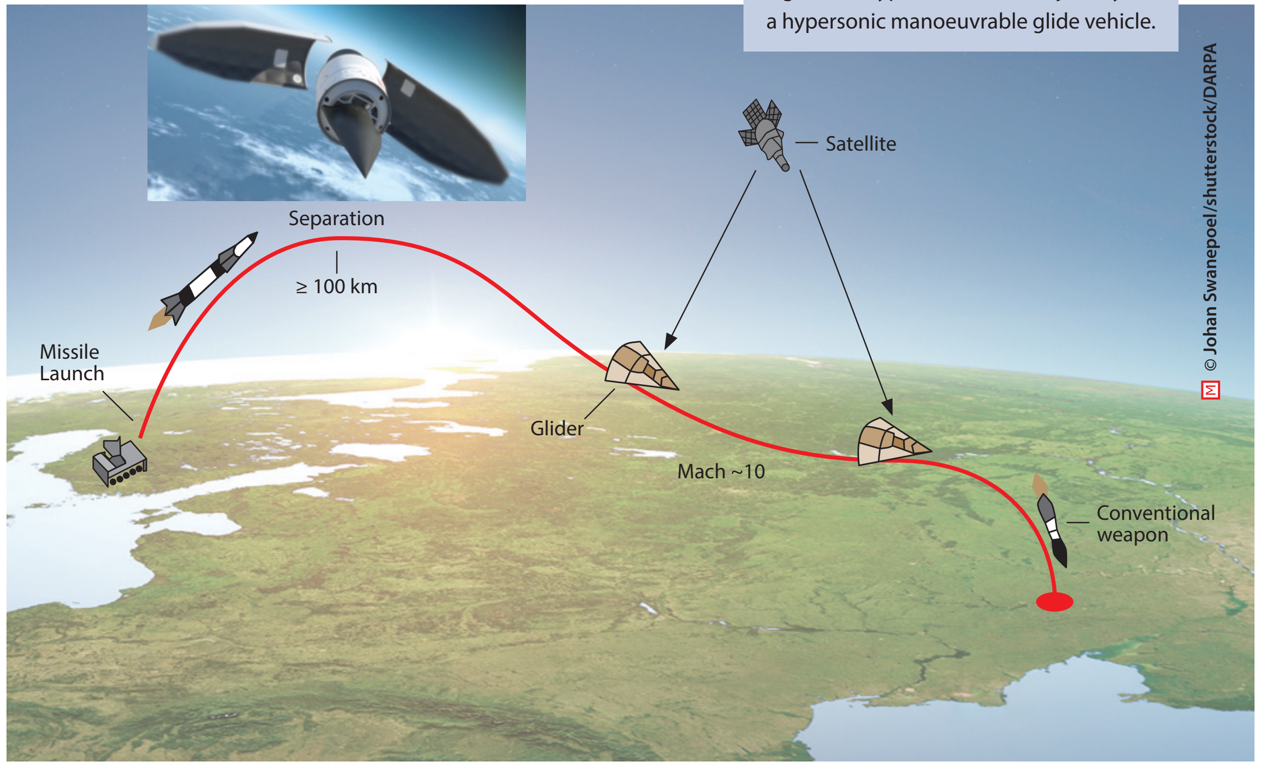


Figure 8: Typical mission trajectory of a hypersonic manoeuvrable glide vehicle.

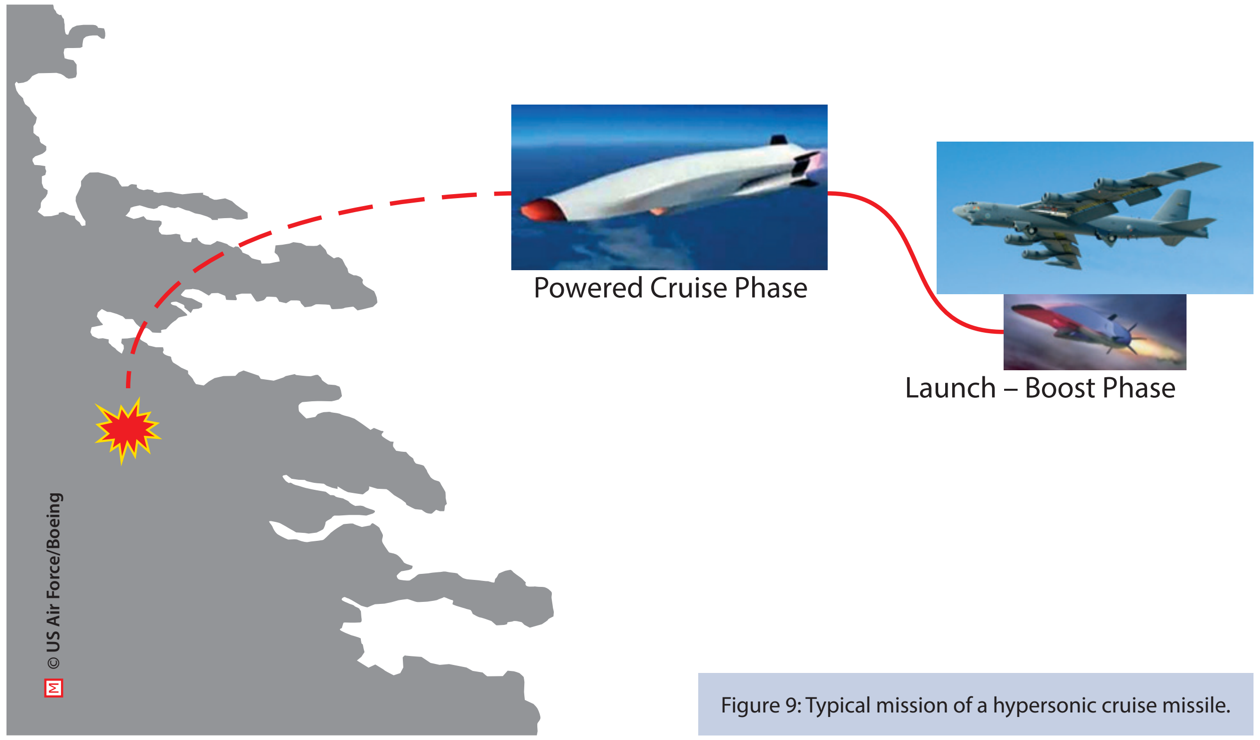


Figure 9: Typical mission of a hypersonic cruise missile.

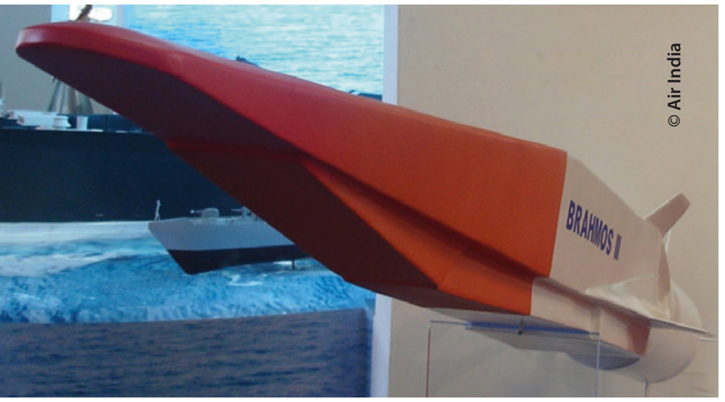
Long range (1,000 km+) implies vehicle and propulsion endurance in the stretch between 10 minutes up to an hour.

While a hypersonic cruise missile will have many positive attributes, several critical technologies are still in development and are uncertain. Widely unresolved issues relate to structural integrity, propulsion efficiency and endurance, as well as precision of flight control and navigation. The requirement for air carriage to the launch position restricts size and mass of the vehicle with impact on military payload and boost rocket mass. The result is a very complex and expensive vehicle.

Figure 10: Examples of hypersonic cruise missile concepts.

US X-51 – Hypersonic SCRJ powered experimental vehicle

Russian "Zircon" missile concept (Mockup)



Indian/russian Brahmos II concept (Mockup)

Research and concept development in this direction are carried out in the US, e.g. X-51, the High Speed Strike Weapon (HSSW), and the Hypersonic Air-breathing Weapon Concept (HAWC). Russia is reported to field a ship-based hypersonic missile (Zircon[21]; Mach 5–6, range ~250 km) within years and India is working with Russia on the Brahmos II hypersonic missile concept. Reporting indicates that China is also conducting research and development in SCRJ design with the aim to build a hypersonic cruise missile. Figure 10 shows pictures of some hypersonic cruise missile concepts.

Operational readiness of long-range, air-launched hypersonic cruise missiles is very unlikely within the next decade, because of the higher complexity of a powered vehicle in comparison to a glider, but should be attainable within 20 years.

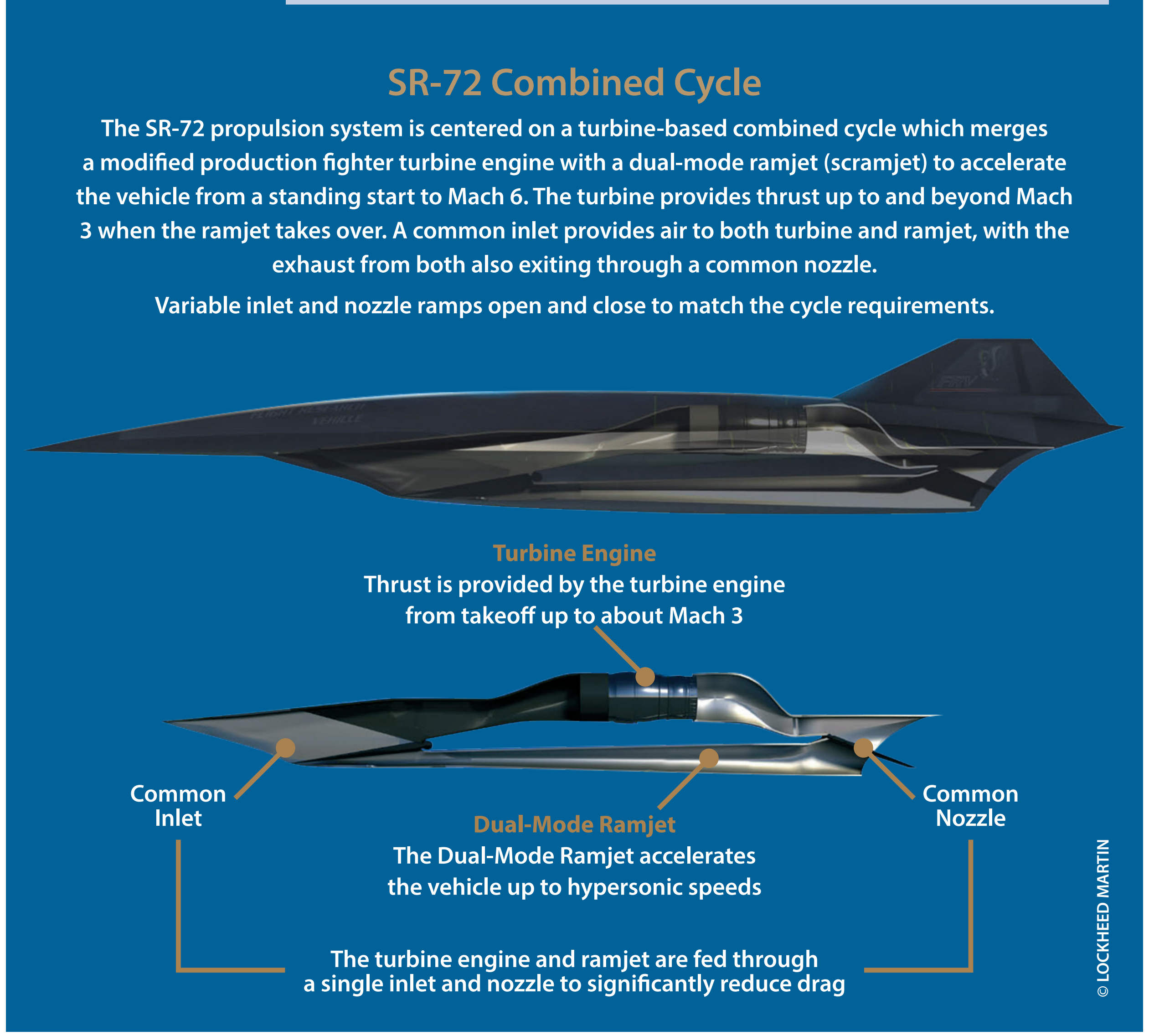
Hypersonic Vehicle for Intelligence, Surveillance, Reconnaissance (ISR)

Looking even more into the future, we can envisage a powered hypersonic vehicle for ISR missions and possibly weaponized for reconnaissance-strike action. This system will likely fly at Mach 5–7 and at altitudes greater than 25 km; it will perform ISR or tactical strike at ranges well beyond 1,000 km and return after its mission. It will be difficult to intercept due to speed and high operating altitude and will be able to perform its mission in areas highly contested by adversaries' enhanced A2/AD capabilities. Potentially, such a system could be more flexible than satellite reconnaissance.

Lockheed-Martin Skunk Works' work on a 'SR-72' (no official name) was first published by Aviation Week & Space Technology in November 2013.[22] It is an unmanned aircraft for ISR purposes, using a complex, combined cycle propulsion (TurboJet/RamJet/SCRJ) system to accelerate to Mach 6, while being able to take off and land like a conventional aircraft. Figure 11 shows the propulsion concept together with an artist's impression of the vehicle. This very ambitious concept is not the only way forward and not the most likely one.

An alternative would be a limited life, partially reusable or refurbishable vehicle with a propulsion similar to the hypersonic cruise missile. Take off/launch would be from the ground or less likely from an aircraft with a rocket booster. Hypersonic cruise would use SCRJ propulsion (or a combined RJ/SCRJ system), and landing or recovery would likely occur as a glider. Such a concept has a potential to offer lower operating costs than a fully expendable system or a fully reusable system like SR-72. All issues mentioned for the hypersonic cruise missile apply for this system, significantly increased by the complexity of a re-usable vehicle and an even longer flight duration (greater than one hour). Also, hypersonic speed and external aero-thermal effects may pose severe problems for ISR sensor performance (e.g. picture resolution) and data communication links.

Figure 11: Lockheed Martin's Concept of the SR-72 (fully re-usable hypersonic vehicle for ISR



While the US, Russia and China appear to work on such vehicles, little reliable information is available. Articles can be found depicting propulsion concepts similar to the SR-72.[23]

This operational capability may be reached in the mid-term by 2035+, but a stepwise approach may occur with vehicles flying up to Mach 4 with a more limited range by incorporating existing state-of-the-art technology. For the ISR mission, stealth is still a key factor to allow operation in strongly defended regions, and being feasible with current technology. The US is following this path with the X-47 and RQ-180 subsonic drones.

Hypersonic Endo-Atmospheric Interceptor Missile

Of course, hypersonic vehicles can also be applied for defensive actions. A powered hypersonic interceptor missile could be used against time sensitive and high value aerial targets (also for ballistic missile defence) and would have the potential to counter adversary hypersonic vehicle threats. The interceptor missile could be ground or air launched, boosted to the takeover Mach number for the SCRJ sustained propulsion and could cruise to the target at Mach numbers between 6 and 9. Typical range of such missiles will be hundreds of kilometres with an operational ceiling beyond 30 km.

Technology issues for such interceptor missiles would be similar to a hypersonic cruise missile, but severity is increased by the higher Mach number regime and the need for aggressive manoeuvres. On the other hand, structural issues are alleviated by lower integrated heat load due to the relative short flight duration less than five minutes). High precision guidance and flight control to hit the target will be another important challenge for these missiles.

A military capability may be achievable within the same timeframe as the hypersonic cruise missile, because the technical issues are similar. Again, a stepwise approach is likely, first using more mature technology for Mach 4–5 and conventional, ramjet propulsion with subsonic combustion system. Figure 12 shows an example with a German concept study for a ground-launched Mach 5 endo-atmospheric interceptor missile.[24]

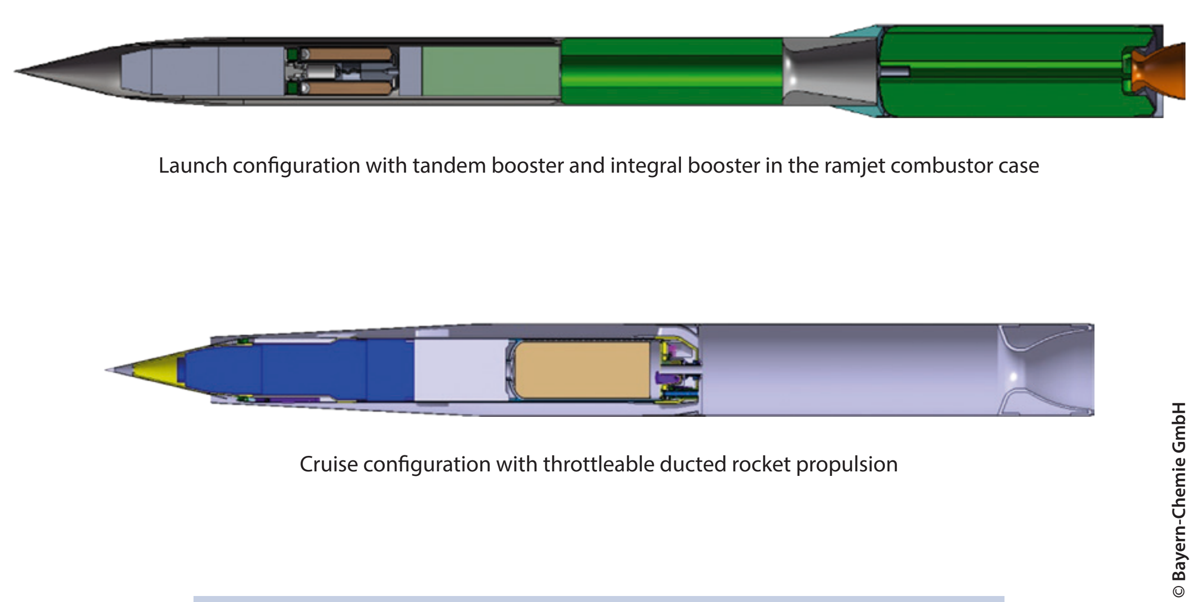


Figure 12: Concept for a ground launched endo-atmospheric interceptor (Mach 5)

Conclusion

The game-changing quality of hypersonic technologies has been recognized by the US[25] as well as by the Alliance. Without any doubt, hypersonic flight can offer important advantages for prompt strike over mid to long ranges into highly contested environments, for flexibility of ISR and for penetration of enemy air defence. Hypersonic systems can be applied to neutralize a singular urgent threat but potentially – if available in sufficient numbers – also to decapitate adversary command, control, communications, and information systems. Published concepts aim at conventional ordnance, but the implementation of nuclear warheads could be an option.

Most notably, the technological advantage is not only on the Alliance's side. Potential adversaries are striving for similar hypersonic flight capabilities. Russia has had a long history of hypersonic research and recently began cooperating with India in this field. China also appears to massively invest in hypersonic flight research. China owns the world's largest hypersonic wind tunnel (the JF-12) capable of producing speeds of up to Mach 9[26], while the NASA hypersonic wind tunnel reaches only up to Mach 7. There have been seven reported tests of the Chinese DF-ZH hypersonic glider over the past two years. However, the frequency of open source publications about China's basic and applied hypersonic research has significantly dropped in the recent past, indicating that the country has a growing military interest and tendency to consider the results as classified information.

Research and development for hypersonic flight is extremely complex and expensive, due to

- the variety of complex technical challenges;
- the limited capability of ground testing even in highly specialized costly facilities;
- the high effort for flight experiments.

The path to operational hypersonic systems will therefore take time, and an initial capability is to be expected no earlier than 10 to 20 years from now. Its development will demand continued investment through a series of hypersonic test campaigns due to the wide area of unresolved technical issues today. This will likely result in very complex and expensive hypersonic systems with limited ordnance payload, whose cost effectiveness will remain to be judged. A stepwise approach might therefore be the most feasible solution: Stay below the hypersonic regime first, allow near term development using evolved materials and technologies like ramjets, but make provisions for the longer term incorporation of hypersonic SCRJ capabilities.

Besides the financial and technical hurdles, the following operational and political issues should be considered:

- How to ensure operational procedures preceding hypersonic weapon use do not reduce its time advantage?
- How much 'autonomy' is acceptable for such a critical weapon system? It will need to fly highly automated to its pre-determined targets. Is there a need and feasibility for a final 'human' decision on target validity during the terminal phase (the man in the loop)?
- How big is the risk that the launch of a long range glider is detected by a potential adversary (who may not even be the target) and leads to misconception and catastrophic overreaction?
- Is there a risk, that such capable (conventional) weapon systems affect the balance of nuclear deterrence and lower the threshold for hostile actions?

So What?

Recent technological advance has brought us closer to fielding an operational hypersonic system, first boost-glide, then air-breathing cruise missile. While the West is advancing, so are Russia and China. The potential strategic and tactical applications of hypersonic flight are such that the West must remain involved in research and development so as to not be put at a capability disadvantage. In the past, funding of high speed/hypersonic research in NATO nations was not always purposeful and very discontinuous, which led to fluctuations in the TRL level and cost increase due to the inefficiency of a stop-and-go development process. This implies that decision makers must develop (based on clear political and military objectives) a long-term roadmap, which is strictly followed with sustained funding (nationally or cooperatively). Therefore, it could be very efficient to commonly fund the necessary fundamental research, as in the example of the US/AUS/DEU HIFiRE collaboration. Last but not least, overcoming commonplace hurdles of information sharing will be key to success for collaborative hypersonic weapons development.

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