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Coming ready or not

Hypersonic weapons

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On Vladimir Putin's 68th birthday in October 2020, Russia announced that it had launched a 3M22 Zircon hypersonic cruise missile from a ship in the White Sea, adding that the missile had hit a target in the Barents Sea. If we can take that claim at face value—we don't know what Western intelligence knows about the missile system or the test—that's a significant achievement. It's the latest in a line of Russia's claims about its new weapon systems. Putin previously claimed that the Zircon is capable of flying at nine times the speed of sound over a distance of 1,000 kilometres.

Not that the Russians have the field to themselves. While not at the stage of making claims about near-operational systems, many other countries also have active hypersonics R&D programs. China and India are developing hypersonic systems, and China is known to have tested several different systems. The US and its Western allies are playing catch-up to an extent. Perhaps because of the strengths of Western militaries in many other technology areas, R&D in hypersonics has been afforded relatively low priority until the past few years. But there are now several active development programs for hypersonic weapon systems. The US has been especially active of late and has budgeted for a substantial

Image source: lockheedmartin.com

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funding increase over the next few years. That includes an ongoing collaborative effort with Australia that's now almost two decades old. In December 2020, the Australian Government announced its support for the next series of trials, designed to test operational systems. Australia is well placed to play a role, having a cadre of subject-matter experts in the government, university and industry sectors.

This report aims to explain the technology behind hypersonic weapon systems and to examine their likely impact on war fighting and strategy. From recent articles, a casual reader could reasonably form the impression that hypersonic systems are a dramatic new development poised to revolutionise future warfare—the term 'game-changer' is something of a favourite in this area.

In fact, hypersonic weapons have been around for over 60 years in the form of intercontinental ballistic missiles (ICBMs), and numerous experimental systems were developed and tested in the 1960s before other solutions were adopted for practical reasons. But developments in materials science, computer simulation power and software guidance systems have allowed a new generation of operational hypersonic systems to emerge.

To put those new developments in context, it's important to understand what sets hypersonic systems apart from well-established weapon systems and what their unique characteristics mean for a range of military applications. Intra-theatre hypersonic strike weapons will further complicate missile defence efforts, which may have implications for the survivability of major platforms. And hypersonic systems with ranges from thousands of kilometres to global reach could be deeply destabilising of strategic balances by reducing the time available for measured assessment and response by existing command and control arrangements. But first we need to understand what hypersonic systems are.

What is 'hypersonic'?

At the risk of sounding like the opening lines of *The hitchhiker's guide to the galax*y, I'll say that 'hypersonic' refers to things that move really, really fast. In fact, it's not possible to be much more precise than that—there's a level of subjectivity as to where the hypersonic regime begins, unlike the sharp distinction between subsonic and supersonic marked by the 'sound barrier' (which is a transition between two different physics regimes, rather than a true barrier).

A helpful way to think about different speed regimes is in terms of the engineering problems that arise in moving from one to another. Moving from subsonic to supersonic largely involves solving the problems of maintaining the controllability of an aircraft or projectile and the efficiency of its aerodynamics during the transition. The challenges arise from the compressibility of the air that the object is moving through, which can be largely neglected at speeds well below that of sound, and from the generation of a shock wave when flow becomes supersonic. (The speed of sound is often referred to as 'Mach 1'. Twice the speed of sound is 'Mach 2', and so on.[1])

'Breaking the sound barrier' was a much-heralded achievement at the time but it was built on well-understood engineering principles. Supersonic ballistic projectiles were in widespread use long before the US Air Force achieved the first manned supersonic flight in 1948. The fuselage of the Bell X-1, the first aircraft to go supersonic, was modelled on a .50 calibre machine gun round, many millions of which had been fired during World War II. At a muzzle velocity of almost Mach 3, the .50 calibre bullet was proven to be stable at supersonic speeds. The next step was mastering controlled flight and manoeuvre at transonic speeds—the X-1 was an experimental aircraft designed for straight-line, high-speed flight—which was considerably more challenging and required extensive development effort. Nonetheless, those problems were solved in the 1940s and 50s and supersonic flight is now routine for both manned and unmanned systems.

However, as the speed of a moving object increases to multiples of the speed of sound, other engineering problems emerge, especially as the heat generated by the friction of air passing over external surfaces becomes significant. Such 'kinetic heating' can generate substantial heat build-up, and that heat needs to be dissipated. During the Cold War, both the US and the Soviet Union built aircraft capable of speeds up to Mach 3, made possible by the development of aerodynamic solutions and new materials that could endure high temperatures for extended periods. For example, the US SR-71 spy plane and the Russian MiG-25 (built to counter high-speed, high-altitude American aircraft) had structures that made extensive use of titanium and other heat-resistant metals, rather than the aluminium usually used in aircraft construction.

At speeds above Mach 5, engineering challenges increase beyond the capacity of those relatively straightforward solutions. At hypersonic speeds, heat management requires the use of novel materials, and airframe design requires the ability to simulate and test aerodynamic behaviour in a regime in which simplifying assumptions about flow behaviour that are valid at lower speeds no longer apply. At even higher speeds, from Mach 10 upwards, the generated heat is sufficient to ionise the surrounding air, creating a high-temperature plasma around the vehicle. That became a practical issue in the 1950s when engineers began to design re-entry vehicles for spacecraft and ballistic missiles. By the mid-1950s, many of the problems had been identified in theoretical calculations, and real-world solutions started to emerge. A 1958 paper by engineers with the US National Advisory Committee for Aeronautics (NACA, later NASA) contains many of the foundational concepts for hypersonics—termed 'hypervelocity' at the time—that are still being pursued today.[2]

Early solutions involved shaping air vehicles to reduce the build-up of heat, the application of ablative materials that would sacrificially burn off, or both. Those approaches were used in the first generation of ICBMs, in space programs and in the development of manned research aircraft.[3] The first ICBMs—and thus the first hypersonic weapon systems—were deployed operationally by the US and USSR in 1959. Later re-entry vehicles employed specialised insulating materials—the well-known ceramic tiles of the space shuttle, for example—instead of ablative coatings for protection.

Table 1 shows indicative speeds of the various aerodynamic regimes. For the purposes of this report, the hypersonic regime begins at speeds around five times the speed of sound (Mach 5), above which hypersonic aerodynamic challenges dominate design criteria. Re-entry is included as a separate case because plasma effects can very quickly result in the destruction of a vehicle unless special steps are taken.

Table 1: Aerodynamic regimes

Regime	Mach number	Major engineering problems
Subsonic	Below 0.8	• 'Compressibility' at the upper end of the speed range causes control surfaces to lose effectiveness.
Transonic	0.8 – 1.2	• Shock waves form at Mach 1, and new aerodynamic shapes and geometry are needed.
Supersonic	1.2 – 5.0	• The air intake of jet engines must be managed to keep the flow subsonic. • Friction heating becomes important at higher speeds.
Hypersonic	5 – 10	• Temperature management becomes critical. • Internal supersonic flow becomes a major consideration in the design of air-breathing engines.
Re-entry/hypervelocity	15+	• Temperatures from kinetic heating exceed normal material limits.

Hypersonic missions

NASA has built on its early work and has an ongoing involvement in the development of hypersonic systems. It categorises the mission set of prospective hypersonic vehicles into three broad categories:[4]

- re-entry from orbit (Mach 25)
- air-breathing cruise
- air-breathing accelerator—boost to orbit system.

The first two missions are relevant to discussions about hypersonic weapons and are the subject of much of the rest of this paper. Although the third mission also has defence and national security applications, an air-breathing hypersonic accelerator delivers the same end functionality as the rocket-based launchers already in widespread use, so only a short discussion is in order here.

As the name suggests, 'boost to orbit' involves using hypersonic vehicles as launch platforms to accelerate payloads to orbital velocity as an alternative to rocket launches. The principal advantage of that approach is that the hypersonic launch vehicle could be re-usable, being more easily retrieved and refuelled than a single-burn rocket stage, thus providing an orbital launch capability with lower costs and faster turnaround times between launches than single-use rocket systems.

Those capabilities could help make space-based systems more robust and repairable. As pointed out in ASPI's 2018 paper *Australia's future in space*,[5] several nations now have the ability to target orbiting satellites, and the ability to rapidly launch replacement space-based sensors and communication systems could help provide resilience against such attacks.

Future hypersonic orbital launch systems are likely to face competition from improved rocket launch systems. The private company SpaceX is developing rocket systems with re-usable major components and has already demonstrated the successful return and re-use of multiple rocket stages. Similarly, China's state-owned China Aerospace Science and Industry Corporation is developing a re-usable two-stage-to-orbit spaceplane. It's possible that both rocket and hypersonic approaches will have applications, depending on mission profiles and the associated economics.

Orbital re-entry systems

As I've noted, ICBMs were the first fielded hypersonic weapon systems. They allowed Cold War adversaries to strike deep into the other's territory, with a high degree of confidence that the incoming missiles couldn't be intercepted due to their very high re-entry speed. However, their mostly ballistic trajectories (some ICBM re-entry vehicles have the ability to manoeuvre, but the flight before the terminal phase follows a predictable ballistic curve) means that they travel well above the Earth's atmosphere before re-entering. The total flight time of around 30–40 minutes for a USSR or US missile shot, combined with the high trajectory, meant that incoming missiles could be seen and tracked in enough time for a retaliatory strike to be launched. Both sides kept air, submarine and siloed missiles on stand-by for rapid launch on detection of an incoming strike, and the high likelihood of 'mutually assured destruction' resulted in a stand-off in which neither side could hope to gain a decisive advantage from a pre-emptive strike.

The 1950s NACA/NASA research program included studies of a quite different approach in the form of glide vehicles that skip off the atmosphere one or more times before being brought back to earth, like a stone skipping across the surface of water.[6] NASA and the US Air Force studied many possible configurations of glide and skip systems in the 1950s and 60s before a combination of technical difficulties, cost and a higher priority on manned spaceflight saw the long-range strategic strike role consolidated in ballistic missiles and aircraft-delivered weapons. However, the idea has been revisited from time to time as new engineering techniques and materials have reduced the difficulty of implementation. As we'll see below, we're probably at the point of seeing a similar concept realised in the next few years.

The currently preferred model is a vehicle that's rocket-launched to outside the atmosphere before returning on an unpowered shallow-angle glide trajectory. The high speed and shallow glide angle allow ranges of thousands of kilometres to be achieved. The possible trajectories of hypersonic glide weapons offer some significant operational advantages. An incoming vehicle is less liable to be detected by ground-based radars early in its flight than a ballistic missile on a high lofted trajectory. Because the radar horizon of an object in flight depends on its height, a glide vehicle wouldn't be visible to airborne radar systems until it's much closer to the intended target than would be the case for a ballistic missile on a high lofted trajectory. For example, an ICBM, with a typical maximum altitude of around 1,500 kilometres, is detectable by ground-based radars at around 5,000 kilometres distance, while a hypersonic weapon at an altitude of 100 kilometres would become visible only in the last 1,300 kilometres of its flight, and thus allows significantly less warning time. The warning time problem might be mitigated if gliders are detectable by space-based surveillance systems or airborne radars, but they're likely to have lower detection signatures than rockets. (The Pentagon is developing a new space-based hypersonic and ballistic tracking space sensor system and is aiming for a first deployment in 2023.[7]) And they further complicate the surveillance problem relative to ballistic missiles because they have much more scope for manoeuvre and may approach the target from essentially any direction, thus making it more difficult to identify their intended target.

The reduced warning time means that there will be less time to identify the threat, compute its trajectory and execute an interception attempt than with existing missile systems. As discussed in more detail below, China, Russia and the US have all examined the possible benefits of hypersonic glide weapons as a way of being able to strike targets essentially anywhere on the globe with a response time measured in a few tens of minutes.[8]

Hypersonic cruise systems

Another important family of hypersonic systems comprises air-breathing cruise vehicles, which, like jet-powered aircraft, operate within the atmosphere. Sustaining hypersonic cruise at Mach 5 or above isn't possible with conventional turbojet engines and afterburners, which require the intake flow to be slowed to subsonic by appropriate shaping of the intake duct before air enters the combustion chamber, which is possible only up to around Mach 3. Ramjets, which use the vehicle's forward motion to compress air for combustion rather than a fan or turbine as in a jet engine, can work with subsonic combustion up to Mach 5. At higher speeds, only rockets or scramjets (supersonic ramjets) function effectively. Scramjets are the propulsion system of choice for many of today's hypersonic systems.

The advantage provided by an air-breathing engine over a rocket is that the vehicle doesn't have to carry the oxidant for combustion, thus reducing its launch weight, increasing its payload, or both. A hypersonic cruise vehicle will typically be carried aloft by either a rocket or a conventional aircraft and then be accelerated to hypersonic speed by a booster rocket before igniting a scramjet to continue its flight. Scramjets aren't a new concept; the hypersonic Bell X-15 manned rocket-powered aircraft flew with an experimental mock-up of a scramjet for research purposes in 1967, although that line of investigation didn't result in an operational system. The past 20 years has seen the development of reliable and efficient scramjets by researchers in several countries, including Australia. As we'll see in the next section, the fielding of hypersonic cruise weapons is likely to be possible as soon as the first half of the 2020s.

A significant line of research that could lead to truly practical hypersonic vehicles is the 'combined cycle' engine, in which either a turbine or a rocket is combined with a ramjet and scramjet, with all engines sharing the same flow path. Such an integrated configuration would reduce the number of separate propulsion systems required for independent hypersonic flight. NASA has been actively investigating combined cycle engines for at least 20 years.

Hypersonic weapon system developments

The leaders in military hypersonic technology development are China, Russia and the US. Australia also has active research lines in civil applications of hypersonics, as well as a long-established R&D relationship with the US. This section discusses the defence-centred programs of those countries,[9] but it's worth noting that there also are hypersonic weapon R&D programs in France, India, Japan and Germany.

Australia

Australia makes a significant contribution to US R&D and has a cadre of world-class researchers in the field of hypersonics. From 2007 to 2018, the collaboration between the two countries was formalised in the Hypersonic International Flight Research Experimentation (HIFiRE) program. A 2017 HIFiRE test saw a successful flight of a hypersonic glide vehicle designed for speeds in the range of Mach 6 to Mach 8. Previous tests had explored scramjet engine technologies.

There's an extensive history of hypersonics research in Australia, dating back to work with shock tunnels in the 1960s. The University of Queensland (UQ) has a long history of work in hypersonics and developed and flight-tested scramjet engines at speeds of up to Mach 9.5 under its HyShot program (1998–2006). That program evolved into the HIFire program, a collaborative venture between the UQ, the Defence Science and Technology Organisation (now DST Group) and Boeing. After HIFire finished in 2018, DST Group and UQ continued collaborative work on scramjets and alternative propulsion systems. As well, DST Group works with its American counterparts in classified weapons and countermeasures work. UQ is home to the Centre for Hypersonics, which has an active research program with contributions from researchers from Australian and international universities and from industry partners, including Boeing and BAE Systems. The centre's work is more broadly focused on materials, fuels for scramjets and other operational concept applications such as satellite delivery (the third of the NASA mission sets described above) and intelligence, surveillance and reconnaissance. An offshoot of the UQ work is a commercial start-up organisation called Hypersonix, which invests in research into scramjets, including fuels, materials and component manufacture, and is positioning itself as a future provider of hypersonic boost-to-orbit services.

Between Defence and the university groups, Australia has a number of hypersonic test facilities. The instrumented Woomera Test Range is ideally suited to the task due to its size and remoteness, and laboratory facilities include hypersonic wind tunnels capable of testing speeds of up to Mach 30. But, due to a shortage of long-term investment, some significant shortcomings are becoming apparent. The current wind tunnel facility that's available for hypersonics research in Australia is adequate for fundamental research activities but is starting to show its age, and its capacity isn't well suited to a large number of concurrent applied hypersonic R&D activities.

A relatively small investment of tens of millions of dollars now to refresh and upgrade our research facilities could pay off significantly in the future. Other nations seeking to develop and extend hypersonic technologies have invested heavily in hypersonic wind tunnels in recent years. For example, over the past four years, funding announced for hypersonic wind tunnel facility development at universities and other research institutions in the US has exceeded US$400 million, and more is likely to have been spent on classified projects. A *pro rata* figure for Australia (weighted by the size of the economy) would be around A$40 million; in fact, there have been no announcements of funding for any new Australian hypersonic wind tunnel facilities in that time. And most of our existing hypersonic facilities require an urgent injection of funding for upgrades to hardware and instrumentation, especially if we're to continue to collaborate with the US as it increases the priority of hypersonics R&D.

It might be the case that some or all of the required investment is already in train on the defence side, but it's hard to know because of the now routine lack of detail in Defence's public documents. The exact amount for hypersonic research isn't clear, although the Force Structure Plan that accompanied the 2020 Defence Strategic Update includes a reference to funding hypersonic research as part of a A$9.3 billion package to develop strike capabilities. The government's December 2020 announcement of the next generation of collaborative work under the (slightly laboured for the effect of the acronym) title Southern Cross Integrated Flight

Research Experiment (SCIFiRE) shed no light at all on the level of funding, again simply citing the much larger aggregated total for all missile and strike capability investment.[10] And it's worth observing that in some other areas of defence investment, such as shipbuilding and land vehicles, there's an active effort to build up local industry capabilities. The domestic R&D and nascent commercial activities in hypersonics would also benefit from funding for a technology refresh of their research facilities.

The new-found American focus is probably driven by China and Russia seemingly being on the cusp of introducing hypersonic weapon systems to service (see below). But, while the Pentagon has committed a substantial sum to R&D that supports current experimental activity, there's no procurement funding for hypersonic weapons in the Pentagon's five-year Future Year Defense Program, although that will presumably change in the next few years if developmental programs mature.

Given Australia's in-country capability in hypersonics, there's an opportunity here for a rapid integration of newly developed hypersonic weapons into the force structure. The Defence Strategic Update notes that Australia's 'plans also include the acquisition of … advanced air-to-air and strike capabilities with improved range, speed and survivability, potentially including hypersonic weapons'.[11] While the US is the source for many weapon systems in the ADF's inventory, Australia is well placed to either contribute to developmental programs with the US, as we have previously done in other technology areas with the Mk 48 Mod 7 CBASS heavyweight submarine-launched torpedo and the extended range JDAM guided air-to-ground weapon, or to develop our own systems. The former approach probably makes more sense for reasons of economy of scale and the need to integrate systems with the existing platforms and C4ISR systems,[12] many of which are sourced from the US. Australia isn't likely to want to acquire a global strike capability, but we're likely to be in the market for tactical hypersonic weapons to improve our strike capability, including anti-shipping weapons.

Intermediate-range hypersonic cruise weapons might also prove attractive as a way to reinstate the ADF's long-range strike capability previously provided by the F-111 bomber, though that would need careful consideration. The strategic need that drove the 1960s decision to acquire the F-111 was the assessed risk of aggression from Indonesia, which was to be countered by the ability to strike targets almost anywhere in the archipelago, including Jakarta. Today's threat spectrum is quite different, and, if we were to pursue strike capability as part of a deterrence posture against China, there would be a risk that we'll precipitate a response in kind, in which China forward-deploys systems to be able to quickly strike Australian targets.

Members of the AGM-183A Air-launched Rapid Response Weapon Instrumented Measurement Vehicle 2 test team make final preparations prior to a captive-carry test flight of the prototype hypersonic weapon at Edwards Air Force Base, California, 8 August 2020. (US Air Force photo by Kyle Brasier). Image courtesy: Edwards Air Force Base, online.

United States

The US has a considerable number of hypersonic system developments on the books. As well as possible highly classified ‘black’ projects, there are half a dozen known R&D programs, summarised in Table 2. Along with experimental programs overseen by the Defense Advanced Research Projects Agency (DARPA) of the US Defense Department, the US Navy has the lead on the development of a common glide vehicle, intended to be adapted for the other services.

Table 2: Major US military hypersonic development programs

Sponsor	System	Five-year development plan budget (US$)	Comments and planned timeline
Navy	Conventional prompt strike	$5.3 billion	Re-entry hypersonic glider vehicle, intended for multiservice roles. Submarine-launched version around 2028.
Army	Long-range hypersonic weapon	$3.3 billion	Army employment of the common glide vehicle being developed by the US Navy. Advanced prototypes by 2023 and acquisition from 2024.
Air Force	AGM-183 air-launched rapid response weapon	$581 million	Air-launched hypersonic glide vehicle prototype. Speed up to Mach 20 at a range of approximately 575 miles. Flight testing planned to conclude in 2022.
DARPA	Tactical boost glide	$117 million in 2021	In partnership with the US Air Force. A developmental path for future air-launched, tactical-range hypersonic boost glide systems
DARPA	Operational fires	$40 million in 2021	Intended to develop the tactical boost glide system (above) into a ground-launched weapon.
DARPA	Hypersonic air-breathing weapon concept	$7 million in 2021	A longer term program intended to lead to a tactical air-launched air-breathing hypersonic cruise missile small enough to be carried and fired by a wide range of platforms.

Source: Congressional Research Service, *Conventional prompt global strike and long-range ballistic missiles: background and issues*, report R45811, 2020, online.

The common glide vehicle is the most strategically significant of the developmental weapon systems, being at the centre of the ‘conventional prompt global strike’ (CPGS) program[13]—the operationalisation of the hypersonic glider re-entry vehicle concept discussed above. The aim of CPGS, as the name suggests, is to provide the US with the capability of delivering conventional weapons anywhere on Earth in a short timescale. It’s thus intended to augment existing conventional strike capabilities, allowing ephemeral targets such as mobile missile launchers—which have been very hard to target effectively in recent conflicts—to be engaged in very short time frames.

Other US developments include medium-range cruise missiles and short-range tactical weapons. While the US has an extensive selection of tactical strike weapons in its inventory, there’s something of a gap in its capabilities around ranges of several thousand kilometres due to developments of weapons in that class being restricted by the Intermediate-range Nuclear Forces (INF) Treaty. From the signing of the treaty in 1987 until its withdrawal in 2019 following claims of Russian noncompliance, the US was prohibited from developing ground-launched systems with ranges from 500 to 5,000 kilometres.[14] The current US Army long-range hypersonic weapon program wouldn’t have been compliant with the INF Treaty. According to a study by the Center for Strategic Budgetary Assessment, intermediate-range hypersonic glide or cruise weapons are competitive with intermediate-range ballistic missiles in both range and expected development cost and potentially offer better capability, being harder to detect and travelling on less predictable trajectories in the terminal phase.[15] As this paper was going to press, the Pentagon announced that it had awarded a contract of US$1.54 billion to Lockheed Martin for the development of an Intermediate Range Conventional Prompt Strike Weapon System.[16]

While not included in the NASA mission set classification or in the hypersonic programs compiled in Table 2, another class of hypersonic weapon system deserves inclusion here, as the US has already demonstrated the system's near-operational capability. Artillery projectiles have long been supersonic, and muzzle velocities of Mach 3 were achieved by World War II vintage guns. But new projectile designs allow either conventional guns (artillery pieces and deck guns on naval vessels) or advanced electromagnetic cannons ('rail guns') to fire rounds—including projectiles with guidance systems—at hypersonic muzzle velocities of up to Mach 7. Although the projectile would rapidly lose speed as it travels through the dense lower atmosphere, the initial speed greatly increases the hitting power, achievable range, or both. Such hypervelocity projectiles (HVPs) can be used in offensive fire missions or as a part of a defensive system against incoming ordnance or aircraft. The US Navy demonstrated the ability of existing ships' guns to fire HPVs in the 2018 RIMPAC exercise,[17] and both the US Navy and Army have used a guided HPV round to shoot down a simulated cruise missile.[18] A major advantage of using HVPs rather than dedicated hypersonic vehicles or advanced defensive missiles such as the SM2 or ESSM deployed on Australian warships is that they're much less expensive, costing less than US$100,000 per round compared to several million dollars each for the missiles.

China

China has two major incentives for developing hypersonic weapons. First, it has been alarmed by the deployment into its region of US anti-ballistic missile systems—though the US has repeatedly (and credibly) pointed out that such systems are intended to counter only a small number of North Korean missiles. (And there are good reasons to doubt their effectiveness against even that relatively modest threat.) Second, Chinese analysts have said that the US's development of prompt global strike systems and other hypersonic delivery systems places its own relatively small nuclear deterrent forces at risk of a decapitating strike, leaving US anti-ballistic missile systems capable against any remaining Chinese missiles. The development of hypersonic anti-shipping and strike weapons would also be consistent with China's long-established program of building anti-access/area-denial systems to blunt US power projection capabilities in its seaward approaches. There's no clear indication yet whether China will opt for nuclear-armed hypersonic delivery systems or limit itself to conventional warheads.

Chinese developments seem to be a blend of Russian-influenced technology and extensions of its own missile programs. The DF-17 medium-range ballistic missile, an addition to China's DF ballistic missile family, has been specifically designed to launch hypersonic gliders. It's also possible that the existing DF-21 and DF-26 anti-shipping ballistic missiles could be modified for use as launch platforms for hypersonic delivery systems. Over longer ranges, the DF-41 ICBM could be used to deliver weapons at hemispheric distances, including to the continental US or Australian territory.

Other Chinese hypersonic systems include the DF-ZF hypersonic glide vehicle (sometimes designated WU-14), which has been tested at least nine times since 2014 and might be nearing operational status. US defence officials have said that the DF-ZF has a range of approximately 2,000 kilometres and is capable of 'extreme manoeuvers' during flight (however, see the discussion below about hypersonic manoeuvrability). The DF-ZF is designed to be carried aloft by the road-mobile DF-17 medium-range ballistic missile.

There's also Starry Sky-2 (or Xing Kong-2), which is an air-breathing hypersonic missile prototype. China claims that a 2018 test saw the vehicle reach top speeds of Mach 6 and execute a series of in-flight manoeuvres before landing. The status of this system isn't clear, but it's probably still years from operational service.

Like the US and Russia, China has also prototyped electromagnetic rail guns on at least one of its warships. The program has been running since at least 2011, when reports of its development first surfaced.

Russia

Russian developments in hypersonic technologies also date back to the Cold War space race and the development of ICBMs. There was a flurry of activity in the 1980s, although that didn’t lead to operational systems. Current Russian developments were, according to Moscow, spurred on by the development and deployment of anti-ballistic missile systems by the US, and by the latter’s withdrawal from the Anti-Ballistic Missile Treaty in 2001. President Putin has stated that hypersonic systems are seen as insurance against US anti-missile developments negating Russia’s nuclear deterrent in the future.

US intelligence reportedly thinks the Tsirkon cruise missile could be operational by 2023. Other Russian hypersonic systems in advanced stages of development include a manoeuvrable air-launched ballistic missile and a space-based glide re-entry vehicle, both of which are nuclear capable. The Kinzhal ballistic missile is claimed by Russian sources to have a maximum speed of Mach 10 and a range of up to nearly 2,000 kilometres, although those performance parameters are questioned by foreign experts. There are photos of the Kinzhal being carried by a MiG-31 interceptor jet, itself a Mach 3 capable platform, which would take the weapon to height and launch it at high speed.

The Avangard glide vehicle is launched into space atop an ICBM launch rocket and has been tested at least three times, with one known failure. As with the US CPGS concept, the Avangard is intended to be manoeuvred to impact essentially anywhere and is capable of being fitted with onboard defensive countermeasures and a nuclear warhead.

The implications of hypersonic weapon systems

As with all major developments in weapons technology, the appearance of hypersonic weapons in national inventories is going to bring new opportunities and challenges at the tactical and operational levels. And there are also potential strategic ramifications because the hypersonic systems described in the previous section significantly overlap with strategic nuclear weapon delivery systems. This section explores some of the issues that are likely to arise.

Tactical implications

We begin with a discussion of relatively short-range intra-theatre weapon systems. ‘Relatively’ is apposite here, because we’re talking about weapons that can be launched hundreds of kilometres from their intended targets. With the exception of cannon-fired hypervelocity projectiles as discussed in the previous section (which are only hypersonic on launch), the technology doesn’t lend itself to much smaller ranges because hypersonic speeds are only possible at altitudes of tens of kilometres or more due to kinetic heating in the dense atmosphere near sea level. That makes them eminently suited for intermediate or strategic range weapons but limits the prospect for short-range tactical guided hypersonic systems.

As well, hypersonic weapons are likely to be most effective against static or slowly moving targets, for which targeting is relatively easy and little terminal manoeuvre is required. The popular defence press is fond of describing hypersonic weapons as ‘fast and manoeuvrable’. But simple physics means that manoeuvrability and speed aren’t compatible attributes—increasing one necessarily leads to a decrease in the other. Course corrections during hypersonic flight are possible, but they won’t happen rapidly or over short distances. A straightforward calculation gives some representative numbers. Table 3 shows the time taken by representative subsonic and hypersonic missiles to change course by 10° and the distance the missile would travel in that time. Because of simplifications made in the calculation, the quoted figures overestimate the manoeuvrability of hypersonic weapons, but the relativities illustrate the cost to manoeuvrability of high speeds.[19] It’s clear from these results that hypersonic missiles won’t be able to manoeuvre anywhere near as tightly as slower weapons, limiting their applicability against rapidly manoeuvring targets.

Table 3: Indicative turning radii for missiles at various speeds and g-forces

20 g capable missile	**300 m/s = Mach 0.88**	**3,000 m/s = Mach 8.8**
Time to change course by 10°	0.25 sec	2.5 sec
Distance travelled in that time	75 m	7.5 km
30 g capable missile	**300 m/s = Mach 0.88**	**3,000 m/s = Mach 8.8**
Time to change course by 10°	0.16 sec	1.6 sec
Distance travelled in that time	50 m	5.0 km

The above considerations mean that ‘tactical’ hypersonic weapons are most likely to manifest as stand-off strike weapons that quickly close the distance to the target. The likely flight profile is a launch from hundreds of kilometres from the intended target, a boost to high altitude for hypersonic cruise, and a descent to low altitude (and necessarily lower speeds) for the terminal engagement phase.

Precise targeting of static targets would be no more difficult than with ballistic missiles—a problem solved long ago. For engagements against slowly moving targets such as surface vessels, they will offer a similar threat to defensive systems as China’s DF-21 and DF-26 manoeuvring anti-ship ballistic missiles, with the added complication that hypersonic cruise weapons may be able to be fired from mobile platforms rather than requiring land-based launchers, and thus can arrive on target from essentially any direction. And, like the Chinese anti-ship ballistic missiles, even relatively low levels of manoeuvrability when compared to subsonic strike weapons could be adequate. In the time it takes a Mach 8 weapon to travel 100 kilometres, a surface target travelling at 20 knots travels only 430 metres. (To put that in perspective, a US Navy Nimitz-class aircraft carrier is 317 metres long.) Provided that the weapon had been programmed with accurate target coordinates on launch, only a small correction in direction during the terminal phase would be required to retain a lock on the target.

It isn’t possible to say with any certainty that hypersonic strike weapons will change the attack/defence balance, or that ship-borne defences won’t be able to evolve to meet the challenge. Two possible responses to the threat, both already under development, are hypervelocity projectiles and directed energy weapons. As we saw in the previous section, the US has already demonstrated the use of rail guns and deck cannons to fire hypersonic rounds. And directed energy weapons have a huge advantage in speed even against hypersonic systems, being able to engage targets at the speed of light. But it isn’t clear that they would prove effective against incoming hypersonic weapons that are likely to be pretty solid in construction and lack the ‘soft spots’ required for laser penetration or disruption. And directed energy weapons can only operate in a line-of-sight mode, and thus the response time will be limited to when the incoming weapon appears over the horizon.

Hypersonic weapons potentially constitute a significant challenge to ship-borne missile defence systems such as the Aegis combat system / Standard Missile combination found on US Navy and allied vessels, including Australia’s surface combatants. The added complications caused by manoeuvring hypersonic cruise weapons exacerbates the challenge already posed by ballistic missile systems and the large Mach 3 capable anti-shipping weapons already fielded by China, India and Russia. (In contradistinction, Western nations have relied on relatively small subsonic ‘smart’ weapons backed by advanced electronic warfare capabilities for anti-shipping strike.) Hypersonic strike will make an already fraught surface environment even more dangerous for surface combatants.

Strategic conventional and nuclear power balances

The Russian and Chinese interest in long-range hypersonic systems is probably due to a combination of tactical and strategic factors. Tactical hypersonic weapons potentially provide a means to blunt the power projection capabilities of the US, particularly in countering the reach and striking power of its nuclear aircraft carrier battle groups.

Strategically, long-range hypersonic weapons can provide global (or at least hemispheric) strike capabilities. Since the collapse of the Soviet Union, the US has consistently demonstrated its ability to strike targets in the Middle East, Africa and Europe with either land- or sea-launched cruise missiles or weapons launched by aircraft. The fleets of surface vessels, submarines and long- and short-range strike aircraft needed to sustain that capability require a huge initial capital investment and ongoing sustainment funding that only the US defence budget can support (and, even then, US fleet sizes have been falling for many years). If long-range hypersonic systems can provide similar strike capabilities without the huge costs of the platforms needed to deliver conventional strike by traditional means, it’s possible that China, India and Russia could leapfrog into near-peer status with the US for strike capability, at much lower cost. Of course, strike is only one mission set for the US Navy and Air Force, and its ships, in particular, conduct many other missions. Hypersonic systems won’t provide the same suite of capabilities as is currently enabled by conventional platforms.

As we have seen, several nations are currently working towards being able to deploy hypersonic weapons with global range. Given current progress and a number of successful experimental flights, for the purpose of strategic analysis it’s prudent to assume that the technology will mature sufficiently for that to happen. There are several related reasons to think that this particular weapon evolution could have strategic implications: the blurring of lines between global delivery systems for conventional and nuclear weapons, the reduced decision-making time afforded by an incoming hypersonic glide system and the weaponisation of space.

As explained above, Chinese and Russian strategic hypersonic systems are being designed as dual warhead capable. That raises the problem of a target nation being able to reliably distinguish between an incoming conventional strike and a potential nuclear strike. Of course, that isn’t unique to hypersonic skip/glide weapons, applying as it does to essentially any strike weapon delivered by a nation with nuclear weapons in its inventory. When both sides have nuclear weapons, deterrence depends on an expectation of a prompt and destructive response to any attempt to use those weapons pre-emptively. That’s why concerns have been raised about Chinese anti-ship ballistic missiles; there’s a risk that a conventional ballistic missile strike against US surface assets or bases in the Pacific theatre could lead the US command system to assume the worst and respond accordingly. Ultimately, decisions about the nature of an incoming strike will revolve around what can be discerned about the physical properties of the detected contact. If they’re consistent with the signature of a nuclear weapon delivery system, then a nuclear response is likely to be considered. US naval strategist Norman Friedman described the risks very simply: ‘nuclear-armed nations shouldn’t throw ballistic missiles at each other’. Further reducing the warning time can only heighten those risks.

Nuclear warhead capable hypersonic cruise weapons with intermediate ranges (500–5,000 kilometres) also raise strategic stability issues. Again, they aren’t new problems, although the technology exacerbates some of them. During the Cold War, moves by both blocs to position short- and intermediate-range nuclear weapon delivery systems near the borders of the other proved to be destabilising. Such ballistic missile systems were at the heart of the Cuban missile crisis, when the US was alarmed at the prospect of Soviet weapons being only short flight times from major US population centres and military bases. The Soviet Union was similarly concerned about NATO missiles located in Turkey, near its own borders. The crisis was resolved when the US agreed to remove its missiles from Turkey in response to the Soviet Union’s withdrawal of its missile systems from Cuba. Similarly, the negotiation of the INF Treaty followed a period of deployment of American and Russian intermediate-range nuclear ballistic missiles in Europe. Hypersonic cruise weapons on much flatter trajectories again telescope decision-making time frames.

Placing prompt global strike weapons in orbit for later use would be the first weaponisation of space—which would be a significant and negative development. Placing nuclear weapons in orbit would violate the 1967 Outer Space Treaty. Even conventional weapons in orbit would have a deleterious effect on stability and, in any case, the dual warhead capability of some hypersonic systems would make it hard to tell the difference. There are two possible (and not mutually exclusive) negative consequences.

First, the development of ground-based countermeasures to orbiting weapons puts at risk the continued safe use of near-Earth orbital space. Intercepting manoeuvring hypersonic weapons on re-entry will be prodigiously difficult, being technically harder than intercepting ballistic missiles, and current ballistic missile defence systems offer questionable enough protection against small numbers of unsophisticated weapons and almost none against sophisticated missiles. In practice, countering prompt global strike systems isn't likely to be feasible in the terminal phase. The only reliable counter-strategy will be to pre-emptively target them while they're in predictable orbits. That might be done via capabilities similar to the antisatellite systems that have been developed by the US, China, India and Russia, tests of which have produced worrying amounts of debris.[20]

Second, the US 2019 Missile Defense Review alluded to a possible future space-based segment for the detection and tracking of hypersonic weapons, perhaps complemented by space-based non-nuclear interceptors. If the US were to do that, China and Russia could use that as a justification to expand and accelerate their own counter-space capabilities, probably leading to an escalating arms race in space.

For all of those reasons, the US Congressional Research Service review asks whether there's a 'a need for risk-mitigation measures, such as expanding *New START* [the new strategic arms reduction treaty], negotiating new multilateral arms control agreements, or undertaking transparency and confidence-building activities'. Some analysts argue that hypersonic systems would simply become part of the existing deterrence calculus and that, for example, 'it is really a stretch to try to imagine any regime in the world that would be so suicidal that it would even think threatening to use—not to mention to actually use—hypersonic weapons against the United States … would end well'.[21] Others argue that the novel aspects of hypersonic systems mean that new understandings and agreements need to be forged to reduce the risk of inadvertent escalation. That seems the correct position; deterrence works best when everybody knows what the stakes are and the implications of new weapon systems.

Conclusions

After a long gestation, hypersonic technology has now matured to the point where multiple new weapon systems are likely to be fielded by several major powers in the next few years. 'Tactical' hypersonic weapons (actually stand-off strike weapons) will challenge existing ship-borne missile defence systems even more than ballistic missiles—potentially to the point of rendering defences largely ineffective. A new class of intermediate-range weapons in the form of hypersonic cruise missiles, some of which will be nuclear weapon capable, could proliferate, with concomitant risks to strategic stability. On current trends, by the end of the decade there might be several countries with the capability of orbiting prompt strike systems that can deliver a prompt strike anywhere on the world's surface, with significantly less warning time than is currently the case with long-range ballistic missiles.

Given our existing in-country expertise in Defence and the university and industry sectors, there's considerable scope for Australia to play a role in the development of hypersonic systems for both the defence and wider commercial fields. However, our research infrastructure is ageing and an investment in modernisation and an expansion of capacity are required, both inside government defence science and in the wider R&D community.

Future hypersonic weapons could enhance the ADF's strike capability, including the reacquisition of a long-range strike capability not seen since the retirement of the F-111 bomber over a decade ago. The potential downside to these developments is that the very substantial investment being made by the government in building warships with missile defence systems designed to deal with previous weapon generation threats could be substantially devalued by emerging hypersonic threats.

In one sense, hypersonics isn't a transformative technology in the same way as aircraft or nuclear weapons were in the past. Those technologies introduced new military mission sets and brought dramatically new elements into the strategic calculus. Instead, hypersonics looks to be a new technology that applies to existing missions. Nonetheless, hypersonic systems could significantly diminish the effectiveness of well-established weapons and destabilise existing conventional and nuclear balances.

Notes

1 Speed expressed as a Mach number refers to the *local* speed of sound, which depends on the temperature and pressure of the atmosphere surrounding the object. At sea level, Mach 1 corresponds to about 1,225 km/hr, while in the thinner atmosphere at an altitude of 30 km Mach 1 is approximately 1,080 km/hr. (More data is online.)

2 Alfred J Eggers Jr, H Julian Allen, Stanford E Niece, *A comparative analysis of the performance of long-range hypervelocity vehicles*, National Advisory Committee for Aeronautics, 1 January 1958, online.

3 The manned North American X-15 was an aircraft operated by NASA that achieved speeds of up to Mach 6.7 in a series of nearly 200 flights between 1959 and 1968. For very high speed tests, the X-15 was coated in an ablative finish.

4 See the NASA webpage on 'Hypersonic missions', online.

5 Malcolm Davis, *Australia's future in space*, ASPI, Canberra, 22 February 2018, online.

6 For a recent popular level discussion, see 'Gliding missiles that fly faster than Mach 5 are coming', *The Economist*, 6 April 2019, online.

7 'Hypersonic and Ballistic Tracking Space Sensor (HBTSS)', Missile Defense Advocacy Alliance, 2 July 2020, online.

8 A good discussion of these issues, including some dissenting views, can be found in Matthew Gault's 'New Russian missiles squeeze response time', *Scientific American*, 27 March 2019, online.

9 The subsections on the US, China and Russia draw on a useful recent review of the development status of hypersonic systems by the US Congressional Research Service, *Hypersonic weapons: background and issues for Congress*, Washington DC, 14 February 2020, online.

10 Linda Reynolds, 'Australia collaborates with the US to develop and test high speed long-range hypersonic weapons', media release, 20 December 2020, online.

11 Department of Defence, *2020 Defence Strategic Update*, Australian Government, Canberra, June 2020, online.

12 C4ISR = command, control, communications, computing, intelligence, surveillance and reconnaissance.

13 Congressional Research Service, *Conventional prompt global strike and long-range ballistic missiles: background and issues*.

14 For a summary of the INF Treaty and its implications for US missile systems, see *The Intermediate-Range Nuclear Forces (INF) Treaty at a glance*, Arms Control Association, Washington DC, online.

15 Jacob Cohn, Timothy A Walton, Adam Leman, Toshi Yoshihara, *Leveling the playing field: reintroducing US theater-range missiles in a post-INF world*, Center for Strategic and Budgetary Assessments, Washington DC, 19 May 2019, online.

16 'Lockheed wins US Navy's $1.54B conventional prompt strike weapon deal', *Defenseworld.net*, 12 March 2021, online.

17 Sam LaGrone, 'Navy quietly fires 20 hyper velocity projectiles through destroyer's deckgun', *USNI News*, 18 January 2019, online.

18 Ryan Morgan, 'Army and Navy cannons shoot down drone "cruise missiles"', *American Military News*, 9 September 2020, online.

19 The calculation assumes that a constant acceleration (g-force) and constant speed turn are possible. In practice, manoeuvring vehicles lose speed rapidly in high-g turns. As well, there's the engineering challenge of providing a very high speed weapon with control surfaces capable of providing the lateral acceleration required for aggressive manoeuvre.

20 'Space debris from anti-satellite weapons', Union of Concerned Scientists, 3 December 2007, online.

21 Jyri Raitasalo, 'Hypersonic weapons are no game-changer', *The National Interest*, 5 January 2019, online.

Acronyms and abbreviations

ADF	Australian Defence Force
CPGS	conventional prompt global strike
DARPA	Defense Advanced Research Projects Agency (US)
HVP	hypervelocity projectile
ICBM	intercontinental ballistic missile
INF Treaty	Intermediate-range Nuclear Forces Treaty
NATO	North Atlantic Treaty Organization
R&D	research and development
UQ	University of Queensland

About the author

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Coming ready or not
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