ROYAL AUSTRALIAN AIR FORCE

AIR POWER DEVELOPMENT CENTRE

Beyond the Planned Air Force Series

01 HYPERSONIC AIR POWER

EXECUTIVE SUMMARY

Beyond the Planned Air Force (BPAF) introduces a series of topics that extend Air Force's perspective beyond the objective force envisaged in the Defence White Paper 2016 and the Defence Integrated Investment Plan. Building upon the culture of innovation engendered by Plan JERICHO, BPAF challenges readers to identify and explore how technological, societal, and environmental disruptors and drivers may shape how Air Force provides air power for Australia. Hypersonics is one such technology that is highlighted in BPAF as a popular research theme, in university and military research around the globe, and for potential applications by commercial and military interests in air and space environments.

The future operationalising of hypersonic air vehicles is expected to trigger a change in the technology available to military forces, without significantly changing the longstanding understanding of the fundamental roles for air power. A hypersonic strike aircraft could significantly benefit Air Force's capability of reaching a distant target inside the time period needed by an adversary to detect and respond with current air defence systems. A hypersonic ISR drone could enter and exit enemy territory, sending back imagery without being detected by enemy sensors in time to react. Weapons travelling at hypersonic speeds would present serious complications for enemy defences with only seconds available to respond against the incoming attack. A high-flying hypersonic air vehicle could have sufficient kinetic energy to launch a small mission payload into low earth orbit.

This paper compiles technical and non-technical information in all its complexity, beginning with appreciating hypersonic air power historically and considering its future opportunities. This paper also promotes the scientific and engineering prerequisites, challenges, and limitations that will shape and influence the technology and its effective employment and future operations. The APDC BPAF Team has sought to reduce the complexity of the reading material to make the paper useful to diverse readership; however, hypersonic air power is complex and cannot be over–simplified without sacrificing the knowledge that needs to be factored into future Air Force concepts and designs. While reading BPAF may be challenging, preparing Air Force for a disruptive future requires all members to extend themselves beyond their current comfort zones.

INTRODUCTION

Hypersonic technology has enjoyed a growing level of media interest thanks largely to the success of a number of test flights in Australia,[1] the USA,[2] and China,[3] and claims of the imminent weaponisation of hypersonic vehicles.[4] For the uninitiated reader, the widespread and potentially loose use of the term *hypersonic* in the popular press can cause confuse as to what exactly is the technology being developed and the significance of recent advances. Without an informed appreciation of hypersonic technology and its influence on future operations, airmen will be unprepared to adapt and evolve to the potential disruptive effect that operationalising hypersonic technology will have on developing, managing, and employing air power. This paper addresses this knowledge gap by explaining to readers the basics of hypersonics, and exploring its potential impact on air power. The understanding gained will help ensure that the Australian Defence Force (ADF) is prepared to adapt if and when hypersonic systems become operationally viable

The first step is to define what *hypersonic* means. It refers to speeds from Mach 5 (≈ 3,000 knots) to approximately Mach 25 (≈ 16,000 knots). With such a broad range of speeds falling within this definition comes a correspondingly large array of capabilities and systems that fall within the scope of hypersonic technology: from air-to-air missiles launched from a fighter flying through the atmosphere at Mach 6, to space vehicles re-entering the atmosphere at Mach 25. Making sense of the potential effect of such a diversity of systems on the future of air power is challenging. One approach is to identify what characteristics of hypersonic systems stimulate military interest.

Speed defines hypersonics and partially explains the military interest in the possibilities of the technology. Reducing time between the launch of a vehicle and arriving at its intended destination or target enables the compression of a hypersonic-equipped force's decision-cycles, particularly the time between decision to act and the time that the effect is realised. This compression can provide a force with a potentially decisive advantage.

But speed is not the only advantage. Hypersonic systems can also survive against modern and foreseeable future air and missile defence systems, which are not designed to counter manoeuvrable threats travelling at these high speeds. To paraphrase Stanley Baldwin, it appears that, for the foreseeable future, the hypersonic vehicle may always get through. By combining speed and survivability, hypersonic technology can disrupt contemporary air and space power.

While an indefensible weapons system appearing in the region or in an operational theatre causes concern, many technological, design, and strategic issues need to be overcome before hypersonic systems become a realistic military option. The scientific and aerospace engineering communities in the USA, China, Russia, India, Japan, Korea, Europe, and Australia are all engaged in hypersonic research programs to realise a viable hypersonic capability.[5] Though the technological and engineering obstacles are considerable, international investment contributes to the potential of hypersonic flight becoming operationally viable in the next decade or two.

With research and experimentation continuing apace, force designers and policy makers cannot afford to wait before starting to frame responses to emerging hypersonic systems. Concurrently, over–reacting to potentially inflated assessments of such a potential capability would be wasteful and counterproductive. Balancing

1 'Hypersonic flight on the horizon', *UQ News*, 19 May 2016, https://www.uq.edu.au/news/article/2016/05/hypersonic-flight-horizon accessed on 4 October 2017.

2 'X-51A makes longest scramjet flight', *NASA*, 28 May 2010, https://www.nasa.gov/topics/aeronautics/features/X-51A.html accessed on 4 October 2017.

3 Franz-Stefan Gady, 'China tests new hypersonic weapon', *The Diplomat*, 26 November 2015, http://thediplomat.com/2015/11/china-tests-new-hypersonic-weapon accessed 4 October 2017.

4 L. Todd Wood, 'Russia tests Zircon hypersonic missile system, which it says makes U.S. defences obsolete', *The Washington Times*, 03 June 2017, http://www.washingtontimes.com/news/2017/jun/3/russia-tests-hypersonic-missile-which-it-says-make accessed 4 October 2017.

5 Hans-Ludwig Besser, et al., 'Hypersonic vehicles: Game changers for future warfare?' *JAPCC Journal*, no. 24, Spring/Summer 2017, https://www.japcc.org/hypersonic-vehicles accessed 4 October 2017.

unfounded optimism and ill-considered denial about the future of hypersonics is therefore necessary to ensure that decision makers are prepared to adapt future force designs if disruption occurs as predicted. This paper assists in finding that balance by describing the hypersonic challenge and the potential impact of the technology on the future of air power.

Anticipating how experimental hypersonic systems will influence the development and application air power is difficult given the current levels of technical immaturity and uncertainty of the future operating environment. Present assertions about how a future battlespace featuring hypersonic systems is characterised can only be regarded as informed speculation. To ensure that the opinions contained in the pages that follow are valuable, this paper explains the science of hypersonics, considers how it will shape operational system design, and assesses these findings using air power theory and its doctrine.

Therefore, the paper comprises five chapters that analyse hypersonic air power from historic, technological, design, doctrinal, and strategic perspectives. Each chapter has been written so they can be read either sequentially, or as their interest dictates. The chapters that follow are:

- **Chapter 2: The history of hypersonics**: briefly overviews the stops and starts that have defined the interest in, and development of, hypersonic systems from the 1930s to the emerging capabilities of today.
- **Chapter 3: The science and technology of hypersonics**: briefly examines the science and technology of hypersonics to assist the non-technical reader to understand the technical aspects underlying the challenges and opportunities of hypersonics.
- **Chapter 4: System designs for hypersonic air and space power**: examines the practical scientific, technological designs of hypersonics for air and space mission.
- **Chapter 5: A doctrinal view of hypersonics**: examines hypersonics through the lens of doctrine by exploring the potential impact of the technology on the core and enabling air power roles.
- **Chapter 6: Strategic risks of hypersonics**: overviews some of the strategic considerations that may guide Australia's decision-making in developing and/or acquiring hypersonic technology.

Before beginning the history of hypersonics, it is important to emphasise that this paper provides an airman's perspective on the implications of hypersonic technology. The intention is to inform, not to advocate. Each chapter provides decision-makers at all levels of command, capability development, or policy formulation, with knowledge that should be factored into any discussions or debates on developing or acquiring hypersonic systems by Australia, its allies, or other states. Accordingly, statements made in the pages that follow should not be read as advocating any position for the RAAF, the Australian Defence Force, or the Australian Government in relation to hypersonics, other than the need to understand its potential to enhance air power capabilities and its disruptive effect.

THE HISTORY OF HYPERSONICS

Hypersonic technology has attracted an increasing level of media interest over the past few years, partly because of recent successful hypersonic tests in the USA (X-51A), China (WU-14/DF-ZF), Russia (Zircon) and even Australia (Hyshot/HiFiRE). Despite the apparent novelty of hypersonic systems featuring in the popular press, scientists and engineers have been challenged by the technology of hypersonic flight for over six decades. Interest in travelling in excess of five times the speed of sound has a long history that pre-dates World War II, and hypersonic travel has been a routine part of human space travel since the 1960s.

Understanding the history of research and development in hypersonic flight is important to appreciating current interest in, and the operational future of, this potentially disruptive technology. This chapter thus provides a brief history of hypersonic technology to contextualise recent achievements.

Beginnings of hypersonic flight

Scientists were discussing the possibilities of hypersonic flight early in the history of air power. In 1933, Austrian scientist, Eugen Sänger, wrote about a rocket flying at Mach 10 at 300,000 feet.[6] Over the following decade, German scientists would make great strides in achieving hypersonic flight as they developed Germany's rocket program during World War II. The *Aggregat* missile program (from which designs for the V-1 and V-2 rockets were derived) saw rockets that approached but did not achieve Mach 5. Nevertheless, Germany's efforts to develop rocket-powered weapons during World War II laid the foundations for the post-war development of hypersonic systems.

Post-war competition between the emerging superpowers drove interest and investment in developing Intercontinental Ballistic Missiles (ICBM) and manned space programs. As any object re-entering the Earth's atmosphere, whether it be a rocket-propelled nuclear warhead, or a manned space capsule re-entering the Earth's atmosphere at speeds approaching Mach 25, hypersonic research and technology was critical to both US and Soviet programs. German scientists who had worked on the *Aggregat* program became integral to post-war space and missile programs, as they drew on their wartime experience to address the technical challenges that the programs faced. German wartime expertise proved invaluable to the advances achieved on both side of the iron curtain.

In the USA, scientists and engineers set about modifying captured V-2s from the standard single-stage configuration into a multi-staged rocket. The first such rocket was created by mounting a "WAC (Without Attitude Control) Corporal" sounding-rocket on top of a V-2.[7] This new rocket, the RTV-G-4 "Bumper", ushered in the hypersonic age by achieving the world's first acknowledged hypersonic flight at the US Army's White Sands Proving Grounds (now Missile Range) in New Mexico in February 1949.

Hypersonics in the jet age

The United States' early post-war achievements in hypersonic flight motivated the advances critical to the success in its space program and in developing ICBM technology. Another avenue of research pursued as part of US efforts to push the envelope of aircraft performance was to develop manned hypersonic aircraft. One of the first major steps forward in this area was NASA's X-15 rocket plane. In 1959, the X-15 became the first manned hypersonic aircraft when, in October 1967, reaching Mach 6.7 at 100,000 feet, and setting an unofficial world speed record.

In addition to rocket-powered aircraft, also being researched was what is now known as 'boost-glide' systems. In late 1959, the US Government awarded Boeing a contract to develop the X-20 Dyna-Soar,[8] the first attempt at developing a reusable space vehicle. Boeing envisaged the X-20 being launched into orbit on the tip of a

6 T. A. Heppenheimer, *Facing the Heat Barrier: A History of Hypersonics*, Washington, DC, NASA History Division, 2007, p. 8.

7 'WAC Corporal Missile', *Boeing*, http://www.boeing.com/history/products/wac-corporal-missile.page accessed 4 October 2017.

8 'X-20 Dyna-Soar Space Vehicle', *Boeing*, http://www.boeing.com/history/products/x-20-dyna-soar.page accessed 5 October 2017.

Titan III rocket, to then glide back into the atmosphere at hypersonic speeds under pilot control.[9] This ability to manoeuvre during the de-orbital phase rather than follow a pre-determined re-entry trajectory is what distinguishes 'boost-glide' from the de-orbital technologies associated with the Mercury, Gemini, and Apollo programs. While the initial X-20 flight was planned to occur in 1965, the US Government elected to divert funding for the project to the Gemini program, so that the X-20 program was cancelled in December 1963.

Following this cancellation, US research into hypersonic flight was diverted to ballistic hypersonic re-entry for NASA's first manned space programs (eg Mercury, Gemini, and Apollo) and then the space shuttle. Ronald Reagan's election in 1980 saw, albeit briefly, interest in hypersonic capabilities re-emerge, as did corresponding research into its enabling technology. Reagan's vision of America's hypersonic future was eloquently expressed in his 1986 State of the Union address when he stated that the United States was:

> "…going forward with research on a new 'Orient Express' that could, by the end of the next decade, take off from Dulles Airport, accelerate up to 25 times the speed of sound, attaining low Earth orbit or flying to Tokyo within 2 hours."[10]

Reagan's 'Orient Express' vision became the X-30 National Aero-Space Plane (NASP). Despite Reagan's portrayal of the NASP in a civilian role, the Department of Defense had a military application for the aircraft. In 1985, then commander of US Air Force Systems Command described the potential military utility of the NASP as:

> "...the speed of response of an ICBM and the flexibility and reliability of a bomber, packaged together in a plane that can scramble, get into orbit, and change orbit so [that] the Soviets can't get a reading accurate enough to shoot at it."[11]

Despite grand visions, the NASP, like the X-20, never flew and the project was cancelled in 1995. Ironically, the demise of the NASP program marked a turning point in hypersonic research with NASA's introduction of the Hyper-X program.

Hyper-X and beyond

NASA's Hyper-X program, launched in 1996, succeeded the NASP and aimed, in the words of the scientists involved in the program, 'to move hypersonic, air-breathing vehicle technology from the laboratory environment to the flight environment'.[12] Hyper-X focused on developing an air-breathing hypersonic propulsion system referred to as a supersonic combustion ramjet (scramjet). The eight-year US$230 million program would eventually produce the X-43.[13] In November 2004, an X-43A achieved speeds approaching Mach 10 at 110,000 feet.[14] Its success was a step-change in the evolution of hypersonic systems; transitioning from rockets to air-breathing engines brought hypersonic systems out of the space domain and into the air domain. The technology developed because the X-43 program laid the foundation for the Boeing X-51 Waverider.

The X-51, a collaborative effort between Boeing, the United States Air Force Research Laboratory (AFRL) and the Defence Advanced Research Projects Agency (DARPA), represented the first major reinvestment in actual hypersonic flight hardware by the USAF since the X-15 project in the 1960s, and the X-20 and NASA space

9 Heppenheimer, *Facing the Heat Barrier*, p.126.

10 Ronald Reagan, President of the United States, 'Address before a Joint Session of Congress on the State of the Union', Washington, DC, 4 February 1986, http://www.presidency.ucsb.edu/ws/?pid=36646 accessed 5 October 2017.

11 Quoted in Rebecca Grant, 'Is the spaceplane dead?' *Air Force Magazine*, November 2001, http://www.airforcemag.com/MagazineArchive/Pages/2001/November%202001/1101spaceplane.aspx accessed 5 October 2017.

12 Delma C. Freeman, Jr., et al, 'The NASA Hyper-X Program,' Presented at 48th International Astronautical Congress, 6-10 October 1997, Turin, Italy, p.1.

13 'NASA Armstrong Fact Sheet: Hyper-X Program', *NASA*, 1 March 2014, https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-040-DFRC.html accessed 5 October 2017.

14 'NASA's X-43A Scramjet breaks speed record', *NASA*, 16 November 2004, https://www.nasa.gov/missions/research/x43_schedule.html accessed 5 October 2017.

shuttle.[15] While the X-43 was designed for maximum speed, the X-51 aimed to achieve sustained hypersonic flight. When the X-43 reached Mach 9.6 in November 2004, the scramjet burned for just 10 seconds. Although the X-51 did not reach the same speeds as the X-43, reaching only a maximum speed of Mach 5.1, it achieved sustained scramjet propelled hypersonic flight time for four minutes.[16] From an air power perspective, a more useful metric of the success of this May 2013 test was that X-51 travelled in excess of 230 nautical miles (approximately 425 km) in just over six minutes.

The X-51 program is now complete, and the USAF is looking to extend the technologies developed in the X-51 in developing a high speed strike weapon (HSSW).[17] AFRL predicts an operational reusable hypersonic ISR platform could be in service by 2030, and 'a no-kidding', reusable, persistent, penetrating hypersonic vehicle that could be manned or unmanned in service from 2040.[18]

Hypersonics in the international arena

The USA has not been alone in developing hypersonic technology. A number of states including China, Russia, and even Australia, are investing to varying degrees in the science and technology of hypersonics.

Chinese efforts in developing hypersonic weapons have attracted media attention since the first flight of the DZ-ZF (previously known as the WU-14) hypersonic glide vehicle in 2014.[19] Although little definitive open source information is available on the DZ-ZF, the informed speculation about the potential utility of this currently experimental platform indicates that China may be ahead of other states in developing a viable hypersonic weapons system. In particular, the apparent ability of the DF-ZF to conduct 'extreme manoeuvres' at speeds between Mach 5 and 10 would enable it to overcome currently available area and point defence systems.[20] The DF-ZF would thus complement the Chinese DF-21 'carrier killer', an important component of China's anti-access/area-denial strategy.

In January 2016, a researcher from China's National Security Policy Committee described China's need for high-speed weapons systems: 'only by matching the real-time information with the zero-time firepower can one achieve the operational result of destruction upon detection.'[21] Connecting the improvements in the timeliness of information with the need to improve the timeliness of strike has become an important aspect of developing hypersonic weapons systems, and will be discussed in later chapters of this paper.

Chinese interest in hypersonic weapons extends beyond 'boost-glide' technology. As with the USA, Chinese researchers are also experimenting with hypersonic missiles. In November 2016, the People's Liberation Army-

15 Sharon Evans, 'Accelerating hypersonics development', *U.S. Air Force News*, 9 May 2017, http://www.af.mil/News/Article-Display/Article/1177338/accelerating-hypersonics-development accessed 5 October 2017.

16 Guy Norris, 'X-51A's record-breaking hypersonic milestone', *Aviation Week*, 3 May 2013, http://aviationweek.com/blog/x-51as-record-breaking-hypersonic-milestone accessed 5 October 2017.

17 arina Malenic, 'USAF using X-51 lessons learned to weaponise hypersonic vehicles', *IHS Jane's Defence Weekly*, 18 May 2015, http://www.janes.com/article/51472/usaf-using-x-51-lessons-learned-to-weaponise-hypersonic-vehicles accessed 5 October 2017.

18 John A. Tirpak, 'Beyond the hyper', *Air Force Magazine*, 22 January 2015, http://www.airforcemag.com/DRArchive/Pages/2015/January%202015/January%2022%202015/Beyond-the-Hyper.aspx accessed 5 October 2017.

19 Bradley Perrett, Bill Sweetman and Michale Fabey, 'U.S. Navy sees Chinese HGV as part of wider threat: China demonstrates a hypersonic glider', *Aviation Week*, 27 January 2014, http://aviationweek.com/awin/us-navy-sees-chinese-hgv-part-wider-threat accessed 5 October 2017.

20 Franz-Stefan Gady, 'Will this Chinese weapon be able to sink an aircraft carrier? The PLA's anti-access/area denial arsenal is slowly but steadily expanding', *The Diplomat*, 13 June 2015, https://thediplomat.com/2015/06/will-this-chinese-weapon-be-able-to-sink-an-aircraft-carrier accessed 5 October 2017.

21 Bill Gertz, 'China successfully tests hypersonic missile: Seventh test of new DF-ZF glider tracked over northern China', *The Washington Free Beacon*, 27 April 2016, http://freebeacon.com/national-security/china-successfully-tests-hypersonic-missile accessed 5 October 2017.

Air Force is reported to have test fired a very long range air-to-air missile from a J-16 fighter.[22] The six metre long missile is reported to have achieved a range in excess of 250 nautical miles (approximately 460 km), travelling at speeds up to Mach 6. Such a weapon would provide Chinese aircraft with a significant advantage in the battle for control of the air against potential adversaries.

Russian investment in hypersonic weaponry is following a similar path to that of the Chinese. In February 2015 and April 2016, Russia tested its Yu-71 hypersonic glide vehicle using an SS-19 ICBM as a launch vehicle to accelerate a glide vehicle to hypersonic speed.[23] As with China, Russia has also identified the potential benefits of hypersonic missiles in military strike capabilities, in the Russian case, to enhance the effectiveness of their anti-ship missiles. The 3M22 Zircon is a hypersonic anti–ship cruise missile anticipated to enter into operational service on the Russian Navy's Kirov–class guided missile cruisers in 2018.[24] The potential psychological and strategic effect of these weapons has already been noted in public discussion. Following the successful test firing of the *Zircon* in March 2017, the British press reported that the 'Royal Navy's new aircraft carriers cannot stop Russia's new hypersonic Zircon missiles'.[25] Claims that the Royal Navy's new flagships may be obsolete before they enter operational service highlight the concerns over the disruptive potential of hypersonic weapon systems.

Australian interest in hypersonics has focussed primarily on the experimental aspects of the technology. Researchers at the University of Queensland (UQ) began investigating hypersonic systems in the late 1980s. Building on these early efforts, UQ has become a leading institution in advancing hypersonic technology. The flagship program has been the Hyshot/HIFiRE (Hypersonic International Flight Research Experimentation) series.[26] HIFiRE is an international collaboration involving Australian and US research agencies: UQ, Australia's Defence Science and Technology Group (DTSG), and the US Air Force Research Laboratory) with a goal to explore hypersonic glide and scramjet technologies.

To date, Australia's DTSG and the US Air Force Research Laboratory have been cooperating to conduct experimental flights in Australian under the HIFiRE Program: a Mach 8 hypersonic glider (HIFiRE 4) successfully flew in July 2017, and a Mach 8 scramjet (HIFiRE 7) successfully flew in March 2015. A third test of a Mach 8 scramjet powered glider (HIFiRE 8) is planned for testing in 2019. These experimental test flights are important in developing an Australian understanding of the potential of hypersonic technology for roles such as operationally responsive and low-cost space launch. This is the main focus of hypersonic research being conducted at Australian universities, including the University of New South Wales and UQ.

An electromagnetic sidenote

While the preceding overview of the history of hypersonic research and technology focused primarily on rocket and scramjet propelled systems, they are not the only propulsion methods available to accelerate objects to hypersonic speeds. Another option verging on achieving operational viability is to use electromagnetic accelerators, such as those used in railguns.

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22 Jeffery Lin and P. W. Singer, 'China is testing a new long-range, air-to-air missile that could thwart U.S. plans for air warfare', *Australian Popular Science*, 23 November 2016, http://www.popsci.com.au/tech/military/china-is-testing-a-new-longrange-airtoair-missile-that-could-thwart-us-plans-for-air-warfare,442329 accessed 4 October 2016.

23 Bill Gertz, 'Russia tested hypersonic glide vehicle in February: Moscow follows Chines in seeking maneuverable high-speed missiles', *The Washington Free Beacon*, 25 June 2015, http://freebeacon.com/national-security/russia-tested-hypersonic-glide-vehicle-in-february accessed 5 October 2017; Bill Gertz, 'Russia tests hypersonic glide vehicle on missile: High-speed weapon to match U.S. prompt strike weapons', *The Washington Free Beacon*, 22 April 2016, http://freebeacon.com/national-security/russia-tests-hypersonic-glide-vehicle accessed 5 October 2017.

24 L. Todd Wood, 'Russia tests Zircon hypersonic missile system, which it says makes U.S. defences obsolete', *The Washington Times*, 3 June 2017, http://www.washingtontimes.com/news/2017/jun/3/russia-tests-hypersonic-missile-which-it-says-make accessed 5 October 2017.

25 Caroline Mortimer, 'Royal Navy's new aircraft carriers connate stop Russia's new hypersonic Zircon missiles', *The Independent*, 27 March 2017, http://www.independent.co.uk/news/uk/home-news/royal-navy-new-queen-elizabeth-class-aircraft-carriers-not-stop-russia-zircon-missiles-hypersonic-a7651781.html accessed 5 October 2017.

26 'HIFiRE Program', *University of Queensland Centre for Hypersonics*

The use of electromagnetic accelerators for launching projectiles was first conceptualised and patented in the USA by French scientist, Fauchon-Villeplee, in 1922.[27] In 1944, German scientists also proposed an electromagnetic propulsion system, which could possibly have been employed in the air defence role. However, it was not operationally fielded in time for service during the war.[28] The first modern example was the Canberra railgun, so named as it was developed in Australia by Sir Mark Oliphant at the Australian National University. It began operation in 1962, laying the foundation for modern developments in railgun technology. The Canberra railgun also highlighted one of the main limitations of the electromagnetic propulsion: the large amount of energy needed to launch a projectile at hypersonic speeds. Its success depended on a 500 megajoule, homopolar generator that powered the system; an impressive achievement for the time.

Railgun development and testing, by both industry and government, continued in the USA in the decades that followed, and these efforts are achieving results. In 2005, the US Office of Naval Research (ONR) initiated the electromagnetic railgun innovative naval prototype which aims to operationalise railgun technology in the US Navy. Testing of the US Navy's first railgun occurred in 2012.[29] Operationalising this capability is progressing, most notably in its deployment onboard the *Zumwalt*-class destroyers. This new class of guided missile destroyer was the first to field an electromagnetic railgun, the advanced gun system (AGS), as its primary armament. The AGS, and in particular its specialised load-out of long-range land-attack projectiles (LRLAP), faced a number of issues, not least being the US$800,000 price tag per LRLAP round.[30]

The US Navy and industry remain undeterred in developing hypersonic railgun technology. BAE Systems continues to work with ONR on the development of a hyper-velocity projectile for future US Navy platforms. General Atomics has also invested in the technology, announcing in May 2017 that it had successfully test fired hypersonic guided projectiles from its Blitzer railgun system.[31] Based on its success, hypersonic railgun technology will likely be the first hypersonic weapon system to be used.

Current Military Research Themes in Hypersonics

Despite the advances and breakthroughs of hypersonic research and development since the first hypersonic flight in 1949, much remains to be achieved before hypersonic systems can be considered an operationally viable capability. What follows are seven examples of research and development being pursued internationally. This list indicates the technologies that may define the hypersonic systems which may be fielded in the battlespace of the future.

Surface-to-surface intercontinental non-nuclear ballistic missiles: The USA has investigated the possibility of using non-nuclear ICBMs for a conventional prompt global strike (CPGS) capability.[32] This capability allows countries currently possessing ICBMs to use precision-guided hypersonic vehicles with conventional warheads as an affordable and accessible alternative to nuclear weapons. Though such vehicles are technically feasible, concerns have been raised about the strategic wisdom of equipping nuclear–capable missiles with non-

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27 A. L. O. Fauchon-Villeplee, 'Electric apparatus for propelling projectiles', U.S. Patent No. 1421435, 4 July 1922 https://patentimages.storage.googleapis.com/d7/e2/f6/063514cc85a525/US1421435.pdf accessed 9 October 2017.

28 Richard A. Marshall, 'Railguns', Presented at 9th U.S. National Congress of Applied Mechanics, 21-25 June 1982, Cornell University, Ithaca, NY, https://repositories.lib.utexas.edu/bitstream/handle/2152/33217/PN_077_Marshall.pdf accessed 9 October 2017.

29 Grace Jean, 'With a bang, Navy begins tests on electromagnetic railgun prototype launcher' *Office of Naval Research*, 28 February 2012, https://www.onr.navy.mil/en/Media-Center/Press-Releases/2012/Electromagnetic-Railgun-BAE-Prototype-Launcher accessed 9 October 2012.

30 Geoff Fein, 'USN considers options for replacing Zumwalt's LRLAP projectile, *Jane's 360*, 29 December 2016, http://www.janes.com/article/66566/usn-considers-options-for-replacing-zumwalt-s-lrlap-projectile accessed 9 October 2017.

31 'General Atomics successfully tests railgun hypersonic projectiles', *General Atomics*, 10 May 2017, http://www.ga.com/general-atomics-successfully-tests-railgun-hypersonic-projectiles accessed 9 October 2017.

32 Megan Eckstein, 'Navy conducts flight test to support conventional prompt strike from Ohio-class SSGNs', *USNI News*, 3 November 2017, https://news.usni.org/2017/11/03/navy-conducts-flight-test-support-conventional-prompt-strike-ohio-class-boomers accessed 9 November 2017.

nuclear warheads because of the possibility of unnecessary nuclear escalation resulting from misinterpreting a CPGS launch.[33]

Surface-to-surface boost and hypersonic glide vehicles. Russia and China have both successfully tested boost-glide systems with ranges of 1500 + nautical miles (approximately 2780 km).[34] While these systems are comparable to ballistic missiles in their initial launch phase, on re-entry into the atmosphere, they employ a controlled manoeuvering glide descent to extend the range of the system. The USA has also explored the boost-glide concept, ultimately unsuccessfully, through the DARPA Falcon HTV-2.[35]

Hypersonic strike missiles. Although hypersonic missile systems such as the Russian *Zircon* are reportedly on the verge of entering operational service, a number of factors, described in next chapter covering the science and technology of hypersonics, would first need to be overcome before a truly hypersonic strike missile could be operationally fielded.

Hypersonic interceptor missiles. Hypersonic interceptor missile technology compares in some respects to that of hypersonic strike missiles. However, because of the shorter time of flight, and the need for higher precision and manoeuvrability to hit the intended point target, interceptor missiles have additional technological hurdles to overcome before they can be considered operationally viable.

Hypersonic ISR. The USA is currently investigating the development of a remote piloted system flying at Mach 5 to 7 at altitudes greater than 25 km. Lockheed Martin's advanced development programs, more commonly referred to as "Skunk Works," is developing such a system using the designation SR-72.[36]

Hypersonic air mobility. Military and commercial research into hypersonic transport roles has also been funded with various degrees of interest. The most likely form of hypersonic air mobility to reach operational service will be the delivery of payloads into orbit.

Electromagnetic railguns. Owing to difficulties associated with power and size constraints, railguns are still at the advanced research stage. However, success in operational testing of these systems by the US Navy and General Atomics indicates that using electromagnetic railguns to launch hypersonic projectiles may soon reach operational readiness.

33 James M. Acton, 'Prompt Global Strike: American and foreign developments', *Carnegie Endowment for International Peace*, 8 December 2015, http://carnegieendowment.org/2015/12/08/prompt-global-strike-american-and-foreign-developments-pub-62212 accessed 9 October 2017.

34 Gertz, 'Russia tested hypersonic glide vehicle in February'; James M. Acton, 'China's advanced weapons', *Carnegie Endowment for International Peace*, 23 February 2017, http://carnegieendowment.org/2017/02/23/china-s-advanced-weapons-pub-68095 accessed 9 October 2017.

35 Mary Plummer and Ned Potter, 'Falcon HTV-2 hypersonic plane loses control in Mach 20 test', *ABC News*, 11 August 2011, http://abcnews.go.com/Technology/hypersonic-flight-darpa-launches-htv-plane-test-loses-contact/story?id=14280849 accessed 9 October 2017.

36 'Meet the SR-72', *Lockheed Martin*, 1 November 2013, http://www.lockheedmartin.com/us/news/features/2015/sr-72.html accessed 9 October 2017.

HYPERSONIC SCIENCE AND TECHNOLOGY

To anticipate the potential future impact of a technology, one must first understand its science. Unfortunately, much of the recent media hype about hypersonic systems has focused more on what a hypersonic future may mean than the scientific and engineering challenges that remain to be met. This has the potential to create a gap in the knowledge of operators and decision-makers who do not possess the relevant technical background in hypersonics or its related fields. This chapter addresses this potential gap by describing the science and technology that underpins the development of hypersonic systems.

While seeking to understand the science and technology of hypersonics can be daunting, understanding the reality of hypersonics, rather than accepting the visionary statements on their potential, is necessary to ensure Australian force designers and operators are prepared to adapt to emerging operational hypersonic systems. Accordingly, this working paper has been written so that it is accessible to the broadest possible audience. Some of the topics described are complex and may prove challenging for readers with little exposure to some of the science. Where possible, these complex topics have been simplified as far as practicable to enable the non-technical reader to understand more readily. To provide further detail on some of the more complex topics, *Science notes* are included throughout the text to elaborate or provide examples of the concepts.

What is 'hypersonic'?

A key theme in the history of aviation has been the quest to design vehicles to achieve ever higher speeds. However, as airspeed increases, aerodynamic challenges become more complex for both the system designer and the vehicle operator. To simplify and standardise the nature of these challenges, four speed regions are used to define a vehicle's airspeed with reference to the speed of sound, or Mach number. *Subsonic* refers to objects travelling below the speed of sound (<Mach 1). *Supersonic* refers to objects travelling greater than the speed of sound (>Mach 1). Overlaying these two speed regions is the *transonic region*, which covers the transition from *subsonic* to *supersonic* speed between Mach 0.8 to 1.2. This region is characterised by rapid changes in aerodynamic drag and the development of localised supersonic shock waves on the air vehicle. These effects cause different flight control considerations between subsonic and supersonic airspeeds. The term *hypersonic* is used to refer to speeds in the high supersonic range, more specifically speeds greater than five times the speed of sound (>Mach 5). Figure 3-1 displays the true airspeed of an object travelling at various Mach numbers at various altitudes.

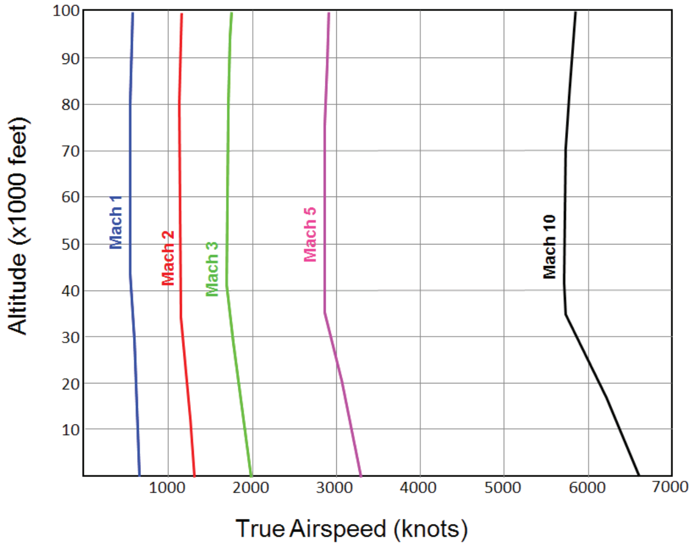

Figure 3-1. True airspeed and Mach numbers variations with altitude[37]

37 Graph provided by Defence Science and Technology Group.

Science Note

A vehicle's Mach number compares the vehicle's air speed relative to the speed of sound as a standard approach in aerodynamics to enable vehicle performance to be expressed in terms of changes in flight dynamics and characteristics resulting from movement through the atmosphere. The actual speed of sound in a gas, and its corresponding Mach number, depends on temperature. For air in Earth's atmosphere, the speed of sound varies as the temperature of the air decreases with increasing altitude.

Between Mach 0.8 to 5.0, the compressibility of air is the primary consideration driving air vehicle and propulsion system design. Beyond Mach 5, aerodynamic heating dominates air compressibility as the more important design driver. This is the principle difference between the characteristics of hypersonic and supersonic vehicles.

As airspeed increases into the hypersonic region, the energy imparted into the surrounding air, by the movement of the platform, generates temperatures so high that the vehicle disrupts the chemistry of the air. At low hypersonic speeds (between Mach 5 to 10), the molecular bonds of the air molecules (predominantly oxygen and nitrogen) increase their vibration, thereby increasing temperature. As temperatures exceed 2200°C, the atoms in the oxygen molecules begin to dissociate and become highly chemically reactive; at temperatures above 3,700°C, nitrogen dissociates; and, at higher than 8700°C atoms start to ionise and lose their electrons to form a plasma sheath about the vehicle. This ionisation effect and the plasma sheath that forms are observed when space vehicles re-enter Earth's atmosphere at speeds of about Mach 25 at altitudes where air density is substantial enough to cause aerodynamic heating. This dissociation of molecules begins in the high hypersonic range (between Mach 10 and 25). Figure 3-2 compares Mach number with the stagnation temperature of the vehicle.

Science Note

The skin temperatures associated with hypersonic vehicles are primarily driven by the *stagnation temperature*. This is the temperature of air at the *stagnation point*: the point on the surface of an air vehicle where the speed of the fluid, in this case the air, is zero relative to the vehicle moving through it. In aerodynamic terms, this occurs at 'a point near the leading edge or nose of a body placed in an airstream at which the airflow divides to go on either side of the body'.

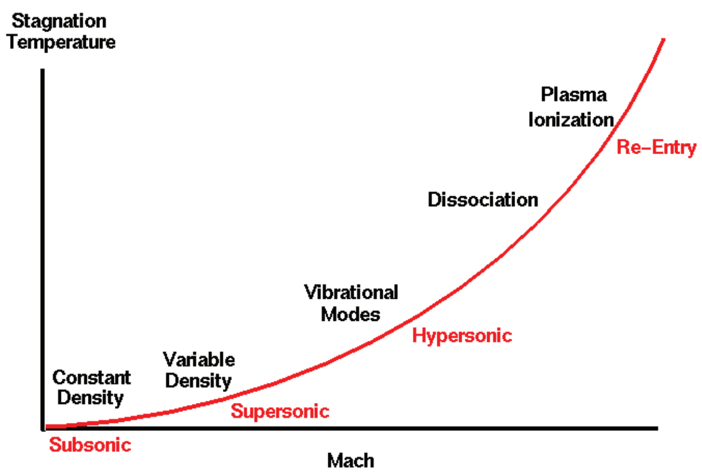

Figure 3-2. Velocity-altitude map showing the flight conditions at which vibrational xcitation and chemical reactivity affect the gas atoms in the airflow[38]

38 'Real Gas', *NASA*, 12 June 2014, https://www.grc.nasa.gov/www/BGH/realgas.html accessed on 13 November 2017

The stagnation temperature increases in proportion to Mach-squared (M^2), as illustrated in Figure 3-3. For example, if the Mach-number is doubled, the stagnation temperature increases fourfold. A secondary heating effect downstream of the stagnation point is caused by the airflow friction over the airframe surface.

Shock waves will form over the vehicle's surface that can offer some mitigation to the extreme heating caused by the aerodynamically heated airflow as these shock waves can shield the vehicle from the hottest regions of the hypersonic airflow. Shock waves are formed in the hypersonic flow in front of, and detached from, the vehicle. The detached shock wave is exploited by vehicle designers because it moves the region of highest temperature away from the vehicle body. This phenomenon explains why blunt shapes are used and sharp leading edges are avoided in designs for both hypersonic vehicle noses and the leading edges of fins and wings.

This protection by shock waves is most effective for high-drag earth re-entry space vehicles that are shaped with a large radius of curvature; vehicles such as low-drag guided missiles that need to be configured with sharp leading edges have less thermal protection from shockwave heating effects.

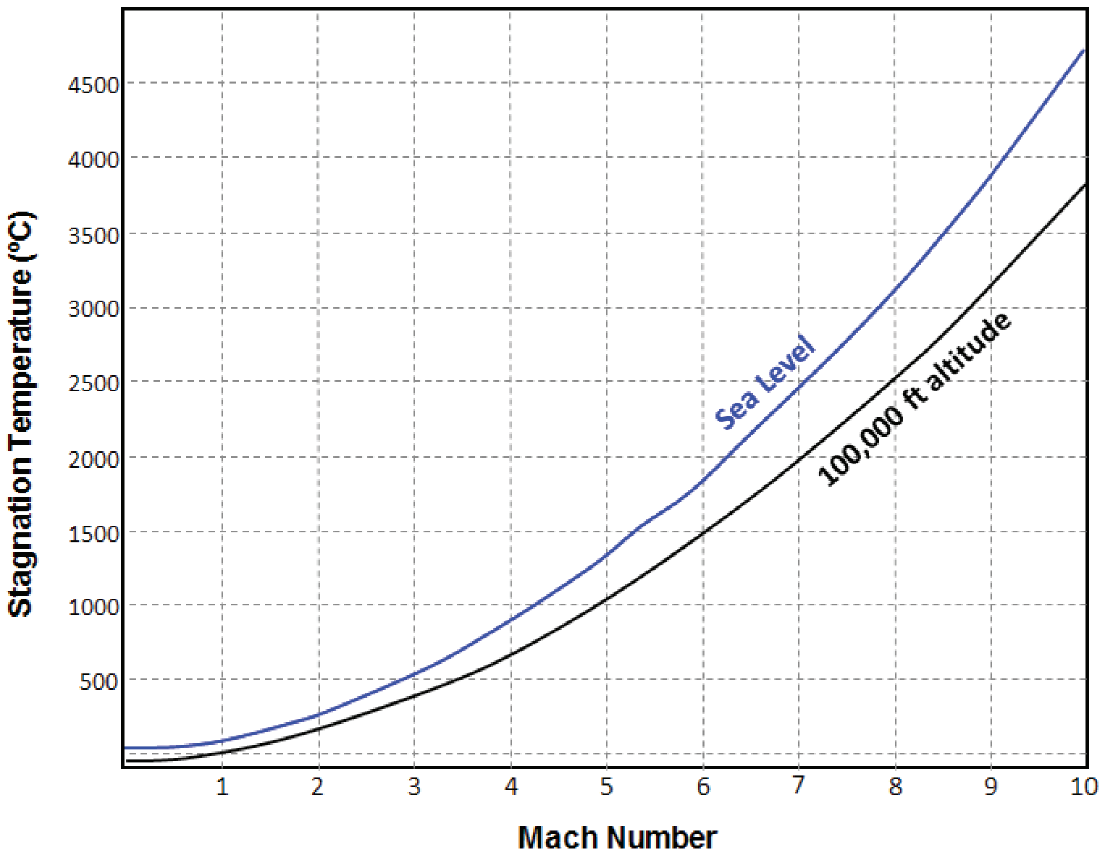

Figure 3-3. Stagnation temperatures versus Mach number[39]

Aerodynamic effects of a hypersonic airflow on the airframe will lead to variations in the primary causes of surface heating. The extreme temperature associated with hypersonic speeds is not necessarily uniformly distributed across the various parts of the airframe because of different heating and cooling rates for different aircraft parts and structural materials. The temperature at any particular point on the airframe will be determined by heat transfer occurring between the air and the airframe, thermal conductivity of the material, and the duration of flight at hypersonic speeds. Figure 3-4 illustrates notional temperature variations that can

39 Graph provided by Defence Science and Technology Group.

be expected at various parts of a hypersonic airframe travelling at different Mach speeds at an altitude of 80,000 feet.

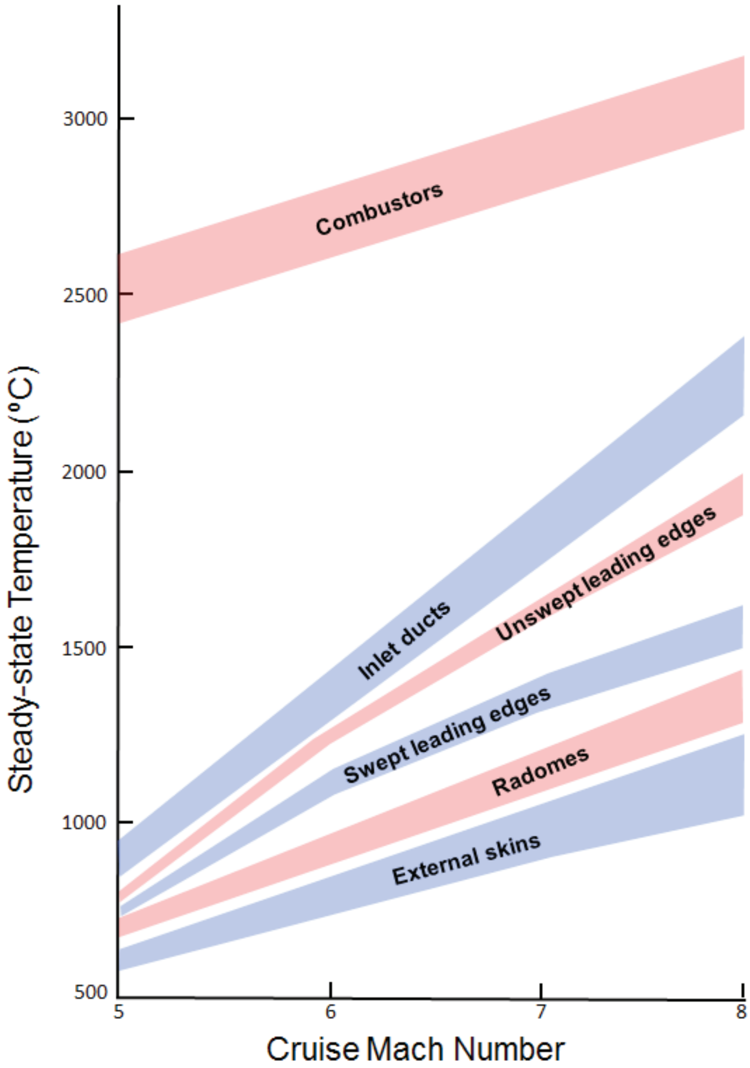

Figure 3-4. Steady-state temperature versus cruise Mach number for critical components at an 80,000-ft altitude[40]

The extreme temperatures associated with hypersonic flight present significant challenges in the design and operationalisation of hypersonic vehicles and their internal systems. Extreme aerodynamic heating requires these vehicles to be manufactured with alloys made of expensive rare metals such as nickel and titanium, or specialised heat-resistant ceramics. Thermal management considerations will also significantly influence the design layout of the internal systems of a hypersonic vehicle, as a means to assure the protection of the vehicle's less heat resilient components, such as the human occupant or temperature sensitive payloads, such as electronics, and to maximise efficiency. For example, through an on-board fuel distribution system designed to use cool fuel to reduce the temperature of hot aircraft structures before it is injected into the propulsion engine.

The impact of ionisation at high hypersonic speeds (Mach 10 to 25) poses another challenge for designers. At the temperatures associated with high hypersonic speeds, the air molecules surrounding the aircraft are

40 Adapted by Defence Science and Technology Group from David M. Van Wie, Stephen M. D'Alessio and Michael E. White, 'Hypersonic airbreathing propulsion', *John Hopkins APL Technical Digest*, vol, 26, no. 4, 2005, p.435, http://techdigest.jhuapl.edu/techdigest/TD/td2604/VanWie.pdf accessed 9 October 2017.

energetic enough to dissociate atoms from air molecules. At higher temperatures, ionisation occurs and electrons are separated from atoms. The atmosphere around the vehicle is then described as becoming ionised and, at the upper end of the high hypersonic range, a *plasma sheath* of ionised gas will be created. The electrically charged plasma that sheaths the vehicle travelling at high hypersonic speeds can prevent a reliable exchange of electromagnetic signals, including the communication of data and control signals with the receivers on board the vehicle.

The hypersonic air environment and thermal management

Extreme temperatures associated with hypersonic speeds mean that thermal energy management is critical to hypersonic vehicle design; the most important characteristic of hypersonic flight is the need to manage heat. All systems on, or in, a hypersonic vehicle must contend, to varying degrees, with the challenge of aerodynamic heating of the airframe. The failure of adequate thermal management was graphically demonstrated in the 2003 *Columbia* disaster NASA Space Shuttle. The Space Shuttle *Columbia* disintegrated upon earth re-entry at about 200 000 feet while travelling at about Mach 20 because of damage in its thermal protection.

Aerodynamic heating primarily challenges the material properties of the airframe and its ability to maintain strength and stiffness. Figure 3-5 depicts different types of materials that are typically employed in airframe designs to enable the vehicle to survive and function at different temperatures.

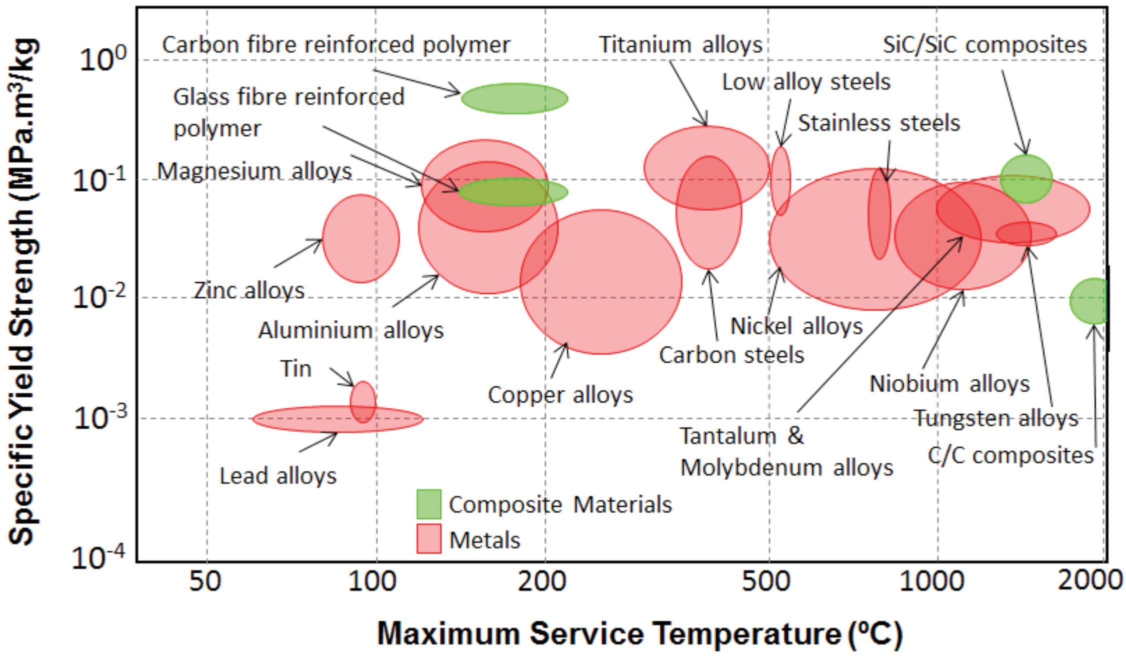

Figure 3-5. Airframe materials and their nominal service temperatures[41]

Titanium alloys are employed for airframes designed to fly at speeds up to approximately Mach 4. The airframe of the Lockheed SR-71 Blackbird, for example, was built using a metal alloy containing about 85 per cent titanium, enabling the aircraft to sustain speeds above Mach 3, thus enduring airframe temperatures ranging between 315 and 480°C. Flight speeds at higher Mach-numbers require airframes to use even more exotic rare metals, composites, and/or ceramics to withstand even higher surface temperatures.

41 Adapted by Defence Science and Technology Group from Scott D. Kasen, 'Thermal management at hypersonic leading edges', PhD Thesis, University of Virginia, 2013, p.13, http://www.virginia.edu/ms/research/wadley/Thesis/skasen.pdf accessed 9 October 2017

There are many ways to address problems arising from extreme airframe heating, all of which involve using appropriate materials based on their suitability to maintain mechanical and material properties across a wide temperature range, owing to their thermal conductivity and heat capacity. Heat can be managed by employing both passive and active thermal protection systems, with some of these design options described below:[42]

- **A Heat sink** describes a passive protection design option in which a high thermal conductivity and heat capacity material is positioned on the airframe to conduct heat away from a hot region of the airframe to a cooler region. The problem with this technique is that longer flight durations require more material to be present to act as the heat sink, and thus affect aircraft weight. As an example, the X-43, a NASA hypersonic research aircraft, carried 900 lbs of tungsten in its forward structure for the dual purposes of ballast for vehicle stability and to control vehicle thermal energy as a heat sink.
- **Thermal Insulation** describes a passive protection approach that uses an insulating material to reduce external heating in certain areas of the airframe. For example, a vehicle may be designed to protect an internal component from heat by adding a low thermal conductivity ceramic, or by separating the component from the external skin by an insulating layer of gas. This approach dumps heat via radiation before it is conducted through to vulnerable regions of the airframe. A practical example of this approach was used on the space shuttle: reusable surface insulation tiles insulated the orbiter body but higher level of thermal protection was needed in the wing leading edges and nose cone.
- **Ablative Coating**: 'Ablation' is 'the melting or wearing away of some expendable part of a space vehicle upon re-entry into the earth's atmosphere'.[43] In essence, an ablative coating is material designed to disintegrate slowly, or burn and separate from the vehicle to remove heat. Single-use ablative coatings are used to carry energy away from the airframe and ablate during flight through chemical change or evaporation. This approach is best suited to single-use vehicles (eg re-entering space capsules and missiles).
- **'Hot Structures'** refers to material structures that can be heated to very high temperatures but still maintain their mechanical properties to continue functioning. These materials have properties, such as a high thermal emissivity (or high emissivity coating), that efficiently radiate energy back into the environment. The Space Shuttle used reinforced carbon/carbon-composite material with high thermal emissivity on the surfaces of its nose and leading edges to cope with aerodynamic heating on Earth re-entry.
- **A Heat Convection Pipe**: High thermal conductance piping can be integrated into the hottest skin areas of the airframe and use a passing fluid to convectively transfer heat away from the aerodynamically heated external skin surface. The heated fluid then transfers the heat to a cooler region of the vehicle for radiating back into the environment or to be stored internally.

Hypersonic propulsion system design options

A range of mechanical options, as opposed to freefall Earth re-entry, can be used to achieve hypersonic speeds. These include:

- Rocket boosters employed for level flight, and ballistic/orbital/re-entry trajectories for boost and glide vehicles;
- Electromagnetic acceleration (eg an electromagnetic rail gun);
- An air-breathing engine (eg SCRamjet); and
- Hybrid designs that integrate one or more of the abovementioned designs into a single system.

The specific impulse (effectively a measure of propulsive efficiency for the mass of fuel that needs to be carried) of the various designs for jet/rocket propulsion systems for a range of Mach-numbers is shown in Figure 3-7. Different propulsion system designs are optimised for different speed ranges when operating within the atmosphere and consuming the oxygen that is readily available in air.

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42 Kasen, 'Thermal management at hypersonic leading edges', pp.22-24.

43 *acquarie Dictionary*, Second Edition, Macquarie Library, Macquarie Park, 1991, p.4.

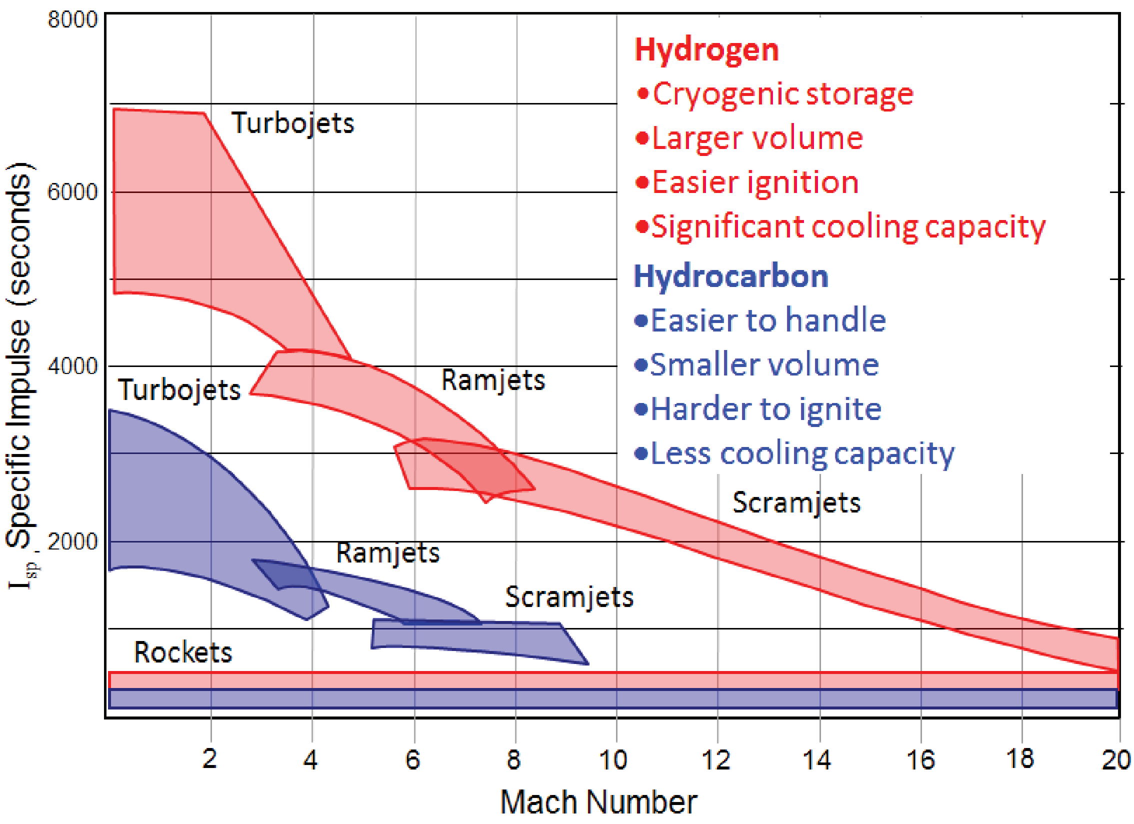

Figure 3-7. Comparison of Specific Impulse for different propulsion methods and fuels[44]

Rockets

Rockets are the simplest form of propulsion system and are a typical approach for achieving hypersonic speeds; the first manned hypersonic aircraft, the X-15, for example, was rocket propelled. Spacelift vehicles using staged rockets to accelerate a payload into space is another means of achieving hypersonic flight, as an orbital or sub-orbital vehicle achieves hypersonic speeds on re-entering the Earth's atmosphere. Vehicles that achieve hypersonic re-entry include the Space Shuttle, X-37B, and hypersonic boost-glide test vehicles such as the DARPA HTV-2, China's DZ-ZF, and the Australian managed HyShot, HyCAUSE, and HIFiRE programs.

Compared with other hypersonic propulsion systems, rockets are relatively simple to develop and operate, making them an attractive option for hypersonic research and development. An additional advantage of rockets is that they are designed to carry the required fuel and oxidiser internally, thus enabling propulsion in the low oxygen density environments of the upper atmosphere and in space. However, for operations within the atmosphere, where oxygen is abundantly available for use in combustion, the efficiency of the propulsion system design can be improved if it can negate the need to carry an oxidant store and associated plumbing.

44 Ming Tang and Caesar Mamplata, 'Two steps instead of a giant leap: an approach for air breathing hypersonic flight', Presented at 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 11-14 April 2011, San Francisco, CA, p.5, http://enu.kz/repository/2011/AIAA-2011-2237.pdf accessed 9 October 2017.

Air-breathing engines

Hypersonic vehicles designed for endo-atmospheric operations, those that do not leave the Earth's atmosphere, can achieve greater thrust efficiency by using air-breathing engines that consume the oxygen in the air as an oxidant. In such engines, hypersonic propulsion is created by forcing air from the atmosphere into a combustor, which mixes the atmospheric oxygen with on-board fuel. Removing the requirements for on-board oxidant storage and distribution system can make the vehicle lighter and faster. Additionally, because having fewer component parts reduces the risk of component-induced failure, system reliability is improved.

In traditional air-breathing engine designs, air is first compressed into a combustion chamber where fuel is then added and burnt; the heated and expanded gases are then expelled through a rear exhaust nozzle generating rearward thrust that, in keeping with the laws of Newtonian physics, propels the vehicle forward.

In turbine engine designs, air is compressed by a rotating compressor stages at the front of the engine, thus enabling the production of thrust at zero forward speed. At speeds above approximately Mach 3.5, turbine engines become problematic because the compressor and turbine blades cannot operate normally at the high temperatures caused by aerodynamic heating. At speeds higher than Mach 3.0, a mechanical compressor is not required because the forward motion of the vehicle can provide sufficient energy to compress the air (ram air) as it flows into the combustion chamber. This is the principle of operation used by ramjets and scramjets (supersonic combustion ramjets). Because ramjets and scramjets do not require rotating machinery for compressors and turbines, these engines are mechanically less complex and lighter than turbojets.

In ramjets, the airflow is slowed to subsonic speeds leading into the combustion chamber. Designs for slowing airflow are relatively straightforward; the process was first demonstrated to achieve Mach 2.0 flight in 1945. Slowing ram air to subsonic speeds is inefficient at speeds above Mach 5.0. This fact drove the development of scramjets, an engine design in which supersonic airflow is slowed and compressed upon entering the engine for combustion but is still travelling at supersonic speed. Providing a stable environment for ignition and combustion of fuel at supersonic speeds in the combustion chamber poses a considerable challenge to developing operational scramjet technology.

Hybrid engines

While the top speed of a traditional jet-turbine engine designs peaks at about Mach 2.5 (up to Mach 3.5 for SR-71 when operating in partial turbo-ramjet mode), hypersonic scramjet engines cannot provide effective thrust below Mach 5.0. This speed gap means that air-breathing hypersonic vehicles require a hybrid design that combines multiple propulsion systems, such as a launcher vehicle, rocket booster, or ramjet/scramjet, to accelerate the vehicle from zero speed to its normal hypersonic operating speed. Under consideration is a hybrid ducted rocket design that fills the empty air chambers of a ramjet with a solid fuel rocket propellant. Once the rocket propellant is fully expended, the air chambers are vacated, allowing the accelerated air to flow through the engine that now functions as a ramjet.

Fuels

In addition to the combustion mixture challenges in hypersonic propulsion engines, the heat required in the combustion chamber to generate thrust for hypersonic speeds can exceed 2700°C. Engine systems must therefore be designed with high temperature resistant materials and active cooling, including using specific fuels to cool the engine and surfaces of the vehicle. Distributed liquid hydrogen is one example of an efficient method of combustion chamber cooling. However, liquid hydrogen requires cryogenic storage and handling systems that present considerable on-board design and logistics support challenges. Whereas hydrocarbon fuels are more readily available in aviation and do not present the same logistical design challenges, they are far less efficient as cooling fluids, and become a performance limitation in designing scramjet engines. Regarding engine design, hydrocarbon fuels are less efficient and require physically longer engines to allow time to ignite and combust the supersonic air/fuel mixture travelling within the combustion chamber

Developing and chemically treating hydrocarbon fuels to improve their utility as coolants is an active area of research into improving the performance of hydrocarbon powered scramjets. Pyrophoric fuels, those that spontaneously ignite in air, such as silane, also have potential uses in scramjets, particularly to help with ignition. These volatile fuels present additional handling/toxicity challenges to designs that are safe and survivable.

The similarity between ramjet and scramjet designs is exploited in a concept known as the dual combustion ramjet. Its design aims to use hydrocarbon fuels over a wider range of Mach numbers by designing a ramjet and scramjet into a single hybrid engine. In a dual combustion ramjet, the subsonic ramjet combustion chamber provides thrust at lower Mach speeds; at higher Mach speeds, the supersonic output from the ramjet is then ignited in a supersonic combustion chamber to further increase the thrust to a higher supersonic airflow.

Engine integration

The traditional axisymmetric aircraft engine configuration was popular during the initial years of hypersonic test flying because it simplified research and observation. Some systems used the same combustion chamber for different modes of operation, like the turbojet or the ramjet, to cover the different speed ranges. However, such configurations are proving unsuitable for designing operational hypersonic engines. As a result, researchers have shifted to designing a rectangular airframe-integrated engine, whereby the airframe shape becomes an integral part of the engine structure.

Air-breathing hypersonic vehicles require tightly integrated airframe and propulsion systems to manage drag and heating. At super- and hypersonic speeds, some of the energy generated by the aircraft's speed through the atmosphere goes into compressing the air, thus changing the density of the local air. This compressibility effect alters the amount of resulting force acting on the airframe. The force becomes increasingly prominent as speed increases; above the speed of sound, small disturbances in the airflow are transmitted to other locations. Severe structural stresses, supersonic shockwaves, aerodynamic heating effects, and the sensitivity of controls to steer the airflow through the inlets and combustion chamber, all require that the hypersonic engine be carefully and tightly integrated within the design of the hypersonic air vehicle.

Design trade-offs

The physics of hypersonics give rise to a design trade-off that must be managed by engineers and systems designers to optimise a hypersonic system for an operational purpose. Balancing the thermal management, speed, operational profile and cost of exotic materials needs of hypersonic systems will be a complicated but necessary trade-off analysis challenge for operational systems designers.

Regarding thermal management, the temperature of the hypersonic vehicle and the air surrounding it increase by $Mach^2$; the rate of aerodynamic heat transfer between the air and the vehicle increase in proportion to $Mach^3$. However, both temperature and rate of heat transfer decreases as air density reduces at higher altitudes. This relationship favours hypersonic systems operating at higher altitudes, as lower temperatures reduce the need for expensive heat resistant materials. A similar relationship holds in relation to speed.

Hypersonic propulsion systems must overcome the aerodynamic drag forces acting on an air vehicle that increase with M^2, but are proportional to increases in air density. This relationship means that less engine thrust is required to overcome drag forces for a vehicle operating at higher altitudes. Further, the structural dynamic pressure loads that an airframe structure needs to withstand are also reduced at higher altitudes. This relationship tends to favour the operation of hypersonic systems at higher altitudes. However, at higher altitudes, the vehicle must fly faster to ensure a sufficient mass flow rate of oxygen through the engine.

While temperature and speed considerations drive researchers to conduct hypersonic flights at higher altitudes, operating them at this altitude requires a trade-off in engine design. As altitude increases, oxygen available for combustion decreases and creates difficulties for the operation of air-breathing engines.

This trade-off is depicted graphically in Figure 3-8 that illustrates the Mach number/altitude corridor where air-breathing engines are expected to be operable. At higher altitudes, less oxygen is available for an air-breathing engine; this provides the upper boundary of the corridor where there is insufficient ambient oxygen for fuel/air mixtures to generate propulsive thrust. The lower boundary reflects where dynamic pressure and heating effects will lead to adverse thermal and structural limitations. This corridor indicates the speed to altitude ratios that will be used by operational hypersonic vehicles and weapons.

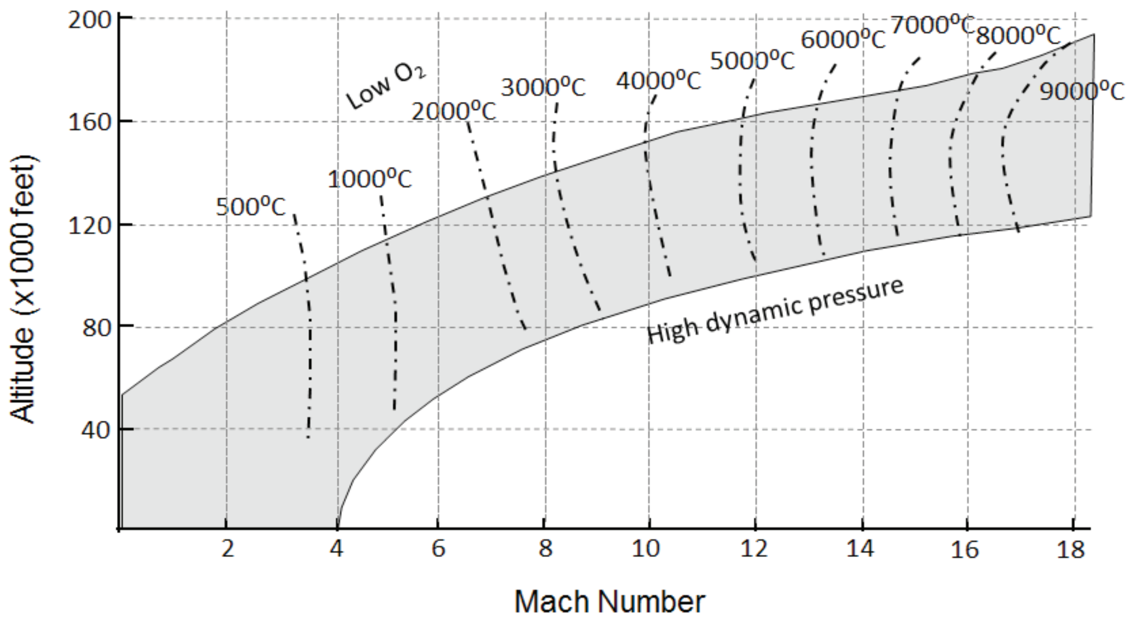

Figure 3-8. Mach number/altitude corridor for air-breathing engines[45]

Vehicle shape

A final design consideration for hypersonic systems is vehicle shape that differs between exo–atmospheric systems and those intended to be operated within the atmosphere.

Exo-atmospheric hypersonic vehicles, those that leave the atmosphere, can achieve higher speeds and longer ranges than endo-atmospheric air-breathing vehicles because of very low aerodynamic drag in the upper atmosphere and in space. Boost-glide vehicles typically use an exo-atmospheric profile, exiting the atmosphere on the tip of a rocket; these systems re-enter the atmosphere at very high Mach-numbers and perform a controlled glide towards the landing site. A crucial design consideration for exo-atmospheric vehicles is the lift that they develop, which can be problematic during re-entry because of the possibility of 'skipping off' the edge of the Earth's atmosphere. This problem can be overcome by rotating the vehicle's orientation to an angle that changes the shape of the vehicle relative to its line of trajectory. A vehicle shape that creates more drag and reduces the aerodynamic lift is important for controlling atmospheric re-entry speeds and aerodynamic heating.

For endo-atmospheric systems, including boost-glide systems after they re-enter the atmosphere, aerodynamic lift can be generated by a purpose designed lifting body. A lifting body is an airframe design that uses the main body of the air vehicle to generate aerodynamic lift using wave-riding principles, rather than add-on aerodynamic wings. This design is based on the principle that because lift increases with the square of the speed, hypersonic vehicles do not require as large a wing area as their slower counterparts. The single use X-51 'Waverider' exemplifies this type of design. Whereas re-usable hypersonic vehicle designs, such as the X-15, Space Shuttle, and X-37, also incorporate this design feature, wings need to be attached to these vehicles to generate sufficient lift and flight control effects at low subsonic speeds when being recovered by a conventional landing on a runway.

45 Adapted by Defence Science and Technology Group from Ronald S. Fry, 'A century of ramjet propulsion technology evolution', *Journal of Propulsion and Power*, vol 20, no. 1, 2004, pp.27-58.

Science Note

Waverider hypersonic vehicle is an integrated-by-design wing, aircraft, and propulsion system. It relies on its shaped lifting body exploiting compression lift that is generated behind the shock wave created by its hypersonic flight through air.

Hypersonic vehicle terminal manoeuvring and guidance

When considering hypersonic weapons, physical limits and targeting needs add additional design considerations. Weapons may need to decelerate to slower speeds to update navigation and/or targeting information, and to enable aerodynamic flight controls to rapidly execute error corrections to the flight trajectory. Limitations in current sensor and guidance systems indicate that, to ensure precision guidance and manoeuvrability in the terminal guidance phase, hypersonic weapons would need to slow to low supersonic or even subsonic speeds to assure weapon accuracy against static or moving targets. Even if issues with sensor and guidance at hypersonic speed were resolved in the near future, the physics of hypersonic speeds at the low altitudes that create heat issues for a terminal effector will add challenges that would need to be factored into hypersonic weapons design.

Figure 3-8 illustrates possible flight profiles for equivalent weight air-breathing Mach 6 and Mach 8 missiles. This graph highlights some of the trade-offs that would need to occur in hypersonic weapon design. In this case, the Mach 8 missile has a smaller range because of the increase in aerodynamic drag and the reduction in fuel mass that can be carried because its structural weight needs to be increased to manage increased aerodynamic heating. The graph also highlights that the terminal phase is envisaged to be in the low supersonic speed range.

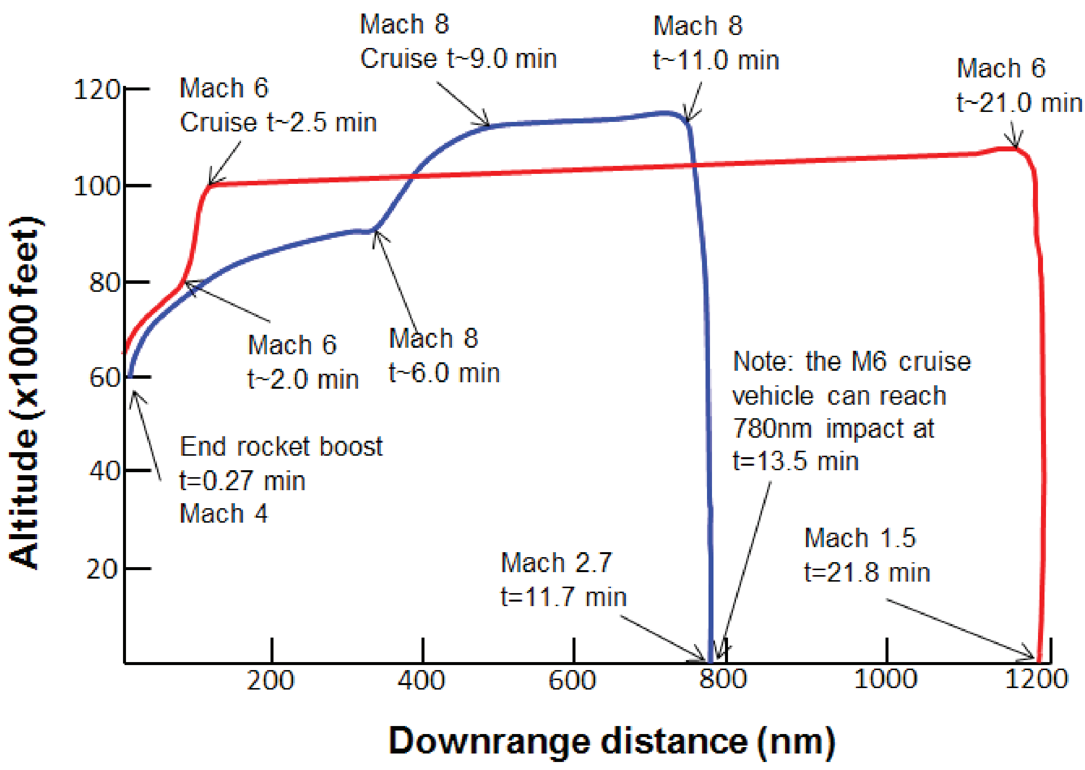

Figure 3-8. Profile of distance flown versus time, for missiles travelling at Mach 6 and Mach 8[46]

46 *Review and Evaluation of the Air Force Hypersonic Technology Program*, National Academies Press, Washington, D.C., 1998, p.6.

While the considerations described above are not insurmountable, the following issues will need to be addressed before hypersonic systems can be considered operational viable:

- Structural integrity challenges, especially for aerodynamic flight control surfaces and their ability to be effective in different speed ranges across subsonic, transonic, supersonic and hypersonic airflows.
- Beyond about Mach 3.5, at sea level, heating can weaken the material and structure of kinetic warheads, weakening their penetration effectiveness against hardened targets.
- Radio frequency and electro-optic/infra-red seekers may suffer attenuation effects caused by the plasma sheath at high hypersonic speeds beyond about Mach 10.
- Antenna functionality for weapons communications and data links for network-enabled weapons may be 'blacked out' at high hypersonic speeds.

International research continues on operationalising hypersonic technology for military and civilian purposes. To date, the most successful technology demonstrations have been boost-glide vehicles, and this type of system is likely to be the first concepts to realise hypersonic air vehicles, with some hypersonic boost-glide missile systems estimated to be operationalised from about 2022 to 2025.[47] Despite optimistic estimates, a number of scientific and engineering challenges must first be resolved before operational hypersonic systems can be realised.

The tactical, operational, and strategic benefits accruing from the speed and survivability of hypersonic systems will be significant. However, the opportunity and/or threat posed by a hypersonic system will vary based on the type of technology it employs. In developing an Australian response to potential hypersonic systems, whether that result from acquiring systems for the Australian Defence Force or from how we respond to other countries acquiring them, Australian force designers, engineers, and operators must ensure that they understand the hypersonic challenge rather than succumb to the allure of technological optimism.

47 Besser, et al., 'Hypersonic vehicles: Game changers for future warfare?'

SYSTEM DESIGN FOR HYPERSONIC AIR AND SPACE POWER

Transitioning experimental hypersonic vehicle designs into operational viable and useful systems will require a numbers of design trade-off decisions that will influence how the systems perform in the battlespace. In this chapter, the design implications and trade-offs for hypersonic systems to become operational in the future battlespace are considered from both a micro- and macro-system perceptive: the microsystem view refers to the design implications for an individual discrete hypersonic air vehicle accessing the battlespace, while the macro-system view is used to review the potential design implications for ISR sensors, situational awareness, and decision-making.

Microsystem view: system and mission trade-off analyses for hypersonic air vehicles

The complexity of the future battlespace will shape and influence different designs for hypersonic systems to perform differently in different roles. Trade-off analyses are necessary to prioritise the degree to which mission requirements can or should be prioritised over design constraints, and vice versa, when seeking to determine a single design solution or a family of related design solutions. The importance of trade-off analysis is to understand the impact of reducing one quality, aspect, or amount of a capability in return for gaining another quality, aspect or amount. Future combat systems are likely to continue to be increasingly complex because they involve many interdependent functions or qualities; accordingly, choosing to improve one quality in the design may force a reduction in another different but linked quality. The roles and designs for future hypersonic vehicles in the future battlespace will likely involve complex trade-off analyses.

Aerodynamic heating presents the most formidable problem for designers of hypersonic engines and vehicles, and will therefore be crucial in any trade-off analysis. Generally, there are three common design features related to aerodynamic heating that are interlinked when considering trade-offs in optimising the designs for a vehicle and its mission trajectory:

1. **Air Speed**. Because lift and drag depend on the square of their speed, hypersonic vehicles do not require a large wing area. The amount of heat generated depends directly on the speed of the vehicle so that the rate of heat generation increases with increasing speed. Near the stagnation point, the heat generated by direct compression of the air will dominate. On the sides of the vehicle, it is the airflow that converts speed into heat, that is transferred to the air vehicle's skin surface.
2. **Heat Capacity of Structural Materials**. The rate of heat transfer experienced by the vehicle at any point in it is trajectory varies directly with the cube of its speed at that point. Higher speeds incur higher temperatures that degrade the elastic properties and stiffness of the material used in the vehicle skin and structure. This degradation causes deformation and buckling which alters the airflow, and reduces structural integrity and further increasing drag and air friction effects.
3. **Air Density at Operating Altitude**. Thermal energy and the rate of heat transfer to the air vehicle surface increase with increasing air density; vehicle skin surface heating rates are thus most severe at hypersonic speeds at lower altitudes. Hypersonic vehicles are typically designed to operate at high altitudes where the air density may be so low that the air can be considered to not exist as a continuum. While the lower density air at higher altitudes reduces air friction and drag effects, it provides less oxidant for air-breathing engines.

Table 5-1 depicts a simplified example of a trade-off analysis for considering a notional tactical hypersonic air vehicle. The analysis illustrates how prioritising one mission can adversely affect other aspects of the vehicle design or mission profile. The trade-off analysis also shows how the balance can change as the mission design priority is changed and reviewed again.

Air Mission Design Priority	Interdependent Design Drivers for Notional Hypersonic System		
	Vehicle Speed	Vehicle Material & Structural Integrity	Vehicle Operating Altitude
Speed	*(Priority need)* Propulsion engines (rocket and air-breathing) can provide the necessary energy for an air vehicle to accelerate to, and/or maintain, hypersonic speed.	Sustained aerodynamic heating effects will demand the use of expensive heat resistant alloys and ceramics and airframe designs to reduce drag.	High altitudes will reduce airframe drag and aerodynamic heating but provide less oxidant for air-breathing engines.
Survivability	The required hypersonic speed, and duration, in air will be constrained by the effects of aerodynamic heating on the vehicle materials and structural integrity.	*(Priority need)* Expensive heat resistant alloys and ceramics, and low-drag airframe designs, can enable a vehicle to perform hypersonic air missions at higher speeds and lower altitudes (ie higher density air).	The required speed, design, and propulsion engine requirements will be constrained by the air density altitude.
Range	The density of the moving air needed for correct engine functioning, and air vehicle survivability against aerodynamic heating, may constrain the operating altitude and, therefore, the mission speed.	The choice of vehicle material will limit the mission profile, driven by the aerodynamic effects (thermal, pressure, vibration, etc) and the transitions through outer space for suborbital trajectories, based on the survivability of the material and structure to the broad range and types of environmental effects.	*(Priority need)* The lower density of air at higher altitudes can reduce the adverse effects of drag and aerodynamic heating, and increase the trajectory range.

Table 5-1. Example trade-off analysis for a notional hypersonic air vehicle.

While this notional design example is limited to only three factors, what follows lists six more possible factors:

1. **Hypersonic propulsion systems**. Currently, conventional designs for hypersonic engines range from liquid propellant rockets to air-breathing engines designed specifically for subsonic, supersonic or hypersonic flight, and engine designs that are hybrid mixes with rockets or multiple air-breathing engine designs. The fuels and the engine designs will necessitate complex testing and support systems and infrastructure.
2. **Speed versus agility in flight manoeuvring**. The laws of physics governing aerodynamic structures, material strengths, and flight within the atmosphere all work to limit the manoeuvrability and agility of an object travelling at hypersonic speed. The kinematics of a hypersonic guided vehicle in steady flight is good for long range strategic strike missions against a fixed target but may be inadequate for engaging an agile and manoeuvring air or surface target. An air defence system that fired hypersonic hittiles,[48] like a hypersonic version of the Phalanx close-in weapon system, might provide a viable option for an air defence system.

48 A hittile is a "hit-to-kill" projectile that is not configured with a warhead but, instead, uses its mass and speed to impact the target and cause damage with its kinetic energy.

3. **Hypersonic Vehicle Mid-Course and Terminal Navigation Accuracy: "Guidance onto location in space (GOLIS)**."[49] The plasma sheath that is formed when travelling at high hypersonic speeds will directly affect traditional designs for sensors and external communications that navigate and guide a weapon to provide position references for navigation corrections. As a closed system, internalised by the plasma sheath formed around the exterior, the vehicle will rely on an inertial reference system for mid-course and terminal guidance to navigate to a pre-planned position. The physics of hypersonic flight will limit the vehicle's in-flight manoeuvrability and its agility to evade unplanned obstacles and threats at short ranges. Air vehicles travelling at high hypersonic speeds will be limited to perform flight path corrections or mission updates only after decelerating to slower speeds.

4. **Mid-Course Trajectory Range/Altitude/Trajectory versus On-board Energy Store**. The principles of hypersonic propulsion are scalable, thus enabling different sized designs for different missions ranging from: first, tactical air-launched hypersonic missile/hittile, large passenger or payload carrying hypersonic aircraft; and second, spacelift vehicles that leave the atmosphere and temporarily exit into space for inserting space payloads into Earth orbit. The available on-board energy will also shape the feasible flight trajectory across a range of possible flight paths for different missions, as described below:

    a. Accelerated ballistic projectiles (ie unguided hittiles) will fly a near-flat ballistic path over a short line-of-sight trajectory to the target, where the gravity drop over the flight path is negligible and thus allows close-in, tactical artillery engagement distances.

    b. Unmanned aerodynamic combat vehicles may use air-breathing engines to fly a straight line as the quickest and short trajectory to the mission location because doing so efficiently and effectively assures that the engine functions at hypersonic speeds.

    c. A boost and glide trajectory might be employed to cover a long distance to the mission area by using a rocket or air-breathing engine to cover the horizontal range while climbing in height to exit the atmosphere, and re-entering it with a very steep angle terminal dive at high hypersonic speed.

    d. A future controllable flight vehicle using a hybrid engine could serve as a large transport aircraft, that is, as a standalone system that can accelerate from zero speed and safely transition to hypersonic speed and back again. The aircraft would manoeuvre at slower speeds during the subsonic phases (eg take-off and landing) and with only minor flight corrections during the long-straight-line transition at hypersonic speed.

5. **Hypersonic Impact as a Damage Mechanism for Strike Missions**. The momentum and kinetic energy of a body travelling at hypersonic speed can negate the requirement for configuring a hypersonic missile with an explosive warhead. Typically, such missiles and hypersonic projectiles, configured without an explosive warhead, are referred to as hittiles because the vehicle itself becomes a weapon when its kinetic energy is transferred to the target on impact. For example, the energy delivered at the target by a small 20 kg hittile travelling at Mach 6 may compare to the energy of an exploding Mk-84 2,000 lbs (900kg) general purpose bomb.

6. **Precision, fuze actuation, and collateral damage assessment**. Any weapon travelling at hypersonic speed in its terminal phase will need a very accurate, low-error tolerance, and a high-speed fuzing mechanism that will initiate the on-board warhead and accurately deliver the damage effect to the target. A problem for early designs for anti-ballistic missile warheads lay in designing the sensor-fuze-warhead train to function in adequate time for the expanding exploding warhead to impact upon the incoming threat missile. The warhead must be initiated with an appropriate lead-time to maximise the delivery of the effect at the target, while it is itself travelling at hypersonic speed, thus necessitating a longer range capability warhead sensor. The range error probable (REP) associated with a hypersonic

49 GOLIS defines a precision guidance technique to steer a weapon to a specific location in space, using an independent position reference system that links the weapon and the target, and is independent of the target motion or characteristics.

impact is likely to be very long for low impact angles along the direction of the flight path, thus suggesting that high-impact angles and a vertical trajectory may be preferred to maximise accuracy and reduce collateral damage.

Macro-system view: Adapting decision-making capabilities

Contemporary decision models, and headquarters organisations and systems have evolved to manage and respond to events in the battlespace occurring at subsonic and supersonic speeds. The step-change to hypersonic capabilities will compress the timelines for operational decisions and responses, thus motivating a similar step-change in the designs for systems used to support battlespace situational awareness and decision-making. From a force-level design perspective, developing operational hypersonic systems will demand improvements in the capability of a force to sense, comprehend, and act to ensure it retains a decision edge over a potential adversary. From this macro-system perspective, improvements will need to be made in the ISR and C2 systems to ensure that the force is optimised to capitalise on the opportunity offered or to mitigate the threat posed by hypersonic capabilities.

While the next chapter details aspects of these requirements, it is worthwhile to close this section on the system design considerations for the hypersonics in the battlespace by considering the design of future ISR and C2 systems.

Irrespective of whether a force has its own hypersonic systems or is facing an adversary that possesses them, the compression of the timeframe between decision to act and the effect generated will prioritise timely information to support effective decision-making. Increasing responsiveness and reducing latency will be the principal design considerations for ISR in response to operationalising hypersonic systems. For the force seeking to employ hypersonic systems, timely intelligence will be key to fully capitalising on the speed advantage created by using such a system. Forces facing a hypersonic threat, on the other hand, will depend on their ability to get 'left of launch' acting before the vehicle is launched to counter the threat. After the vehicle is launched, the force's response options will be limited to reducing the effectiveness of the system through protective defence measures. These measures will need to be supported by an ISR system that can detect a hypersonic launch event, track the vehicle during its transit, assess intended targets, and transmit warnings in sufficient time to enable the defensive measures to be enacted.

In both cases, what is required is a pervasive sensor network that enables quality and relevant information to be collected, processed, exploited, and disseminated to decision makers. By itself, the statement of this need adds little to the discussion about design, as it reflects an ideal ISR system irrespective of the capability being discussed. What differs in the case of hypersonics are the consequences that any latency or inefficiency in a force's ISR system will have in a hypersonic-enabled battlespace. Delays of only a few minutes at any stage of the ISR process, from collection through to a decision being made on the information, can make a decisive difference when facing a hypersonic threat.

While the force-level qualities of an ISR system adapted to respond to emerging hypersonics will not be unique to this technology, it is worth noting three qualities that warrant specific focus from future force designers.

1. **Expansive in scope**: The range of hypersonic systems will be regional, if not global, in scale, involving adversaries located on opposite sides of the globe, thereby requiring the reach of a force's ISR system to be correspondingly expanded. Furthermore, the need to get 'left of launch' will expand the array of data that will interest a force, and extend the time-scales that need to be considered.
2. **Multi-domain by design**: Sensor networks across air, sea, space, land, and cyber must be integrated by design. Current approaches that favour domain-specific analysis of collected data will be too slow and inefficient. Information from all domains will need to be fused and analysed in near-real time to support responsive decision making.
3. **AI-enabled**: While applying artificial intelligence to the military continues to attract negative publicity, the speeds required to respond to hypersonic systems will exceed the capability of the human to collect, process, exploit the data necessary to support operational-level decision-making.

> Accordingly, future ISR systems will need to be more autonomous by design to respond to hypersonic threats; decision systems will need to leverage AI capabilities for air-defence systems to be effective. Human-machine integration will be an important design to consider for future ISR systems.

ISR systems that exhibit the qualities described above will be of little use if the force's decision-making systems are not similarly responsive. From the strategic to the tactical level, C2 systems must be designed to support timely and good decisions. Although this is always needed for any force whether hypersonic systems are present or otherwise, it is one that will be more significant when such systems are operationally fielded.

The characteristics of hypersonic systems, as will be elaborated on in the following two chapters, favour keeping the responsibility for controlling these systems at the highest levels of an organisation. Unfortunately, increasing the levels of command through which the flow of information and decisions must flow will delay command decision-making. With the need to act 'left of launch' as the only approach currently assessed to be effective in countering hypersonic threats, such delays are not conducive to effective operations. Accordingly, the design and development of C2 systems must include options to ensure that protocols, procedures, and technology can ensure that strategic decision makers gain timely access to the information necessary to inform their decisions, and that such decisions can execute a viable response.

Such C2 systems already exist for states that possess nuclear weapons. Although nuclear and conventional hypersonic weapons differ in the scale of potential destruction, the speed and survivability of hypersonic systems makes them potentially decisive. Similarly, for forces facing a hypersonic threat, the need to get 'left of launch' may only be achieved by conducting a pre-emptive or preventative strike. The strategic consequences of such a decision necessitate close governmental control of operations related to hypersonic systems. For nuclear weapons states, the systems that manage strategic weapons already exist and could be adapt to the emergence of hypersonic systems. For non-nuclear states, C2 systems will need to be developed so that responsibilities for hypersonic/counter-hypersonic operations are appropriately delegated. This will ensure that decision making and execution of operational responses will be appropriate for hypersonic threats.

At the operational and tactical level, the main C2 design consideration will be to ensure that operations across the domains are seamlessly managed. The speed, range, and flight profile (potential crossing space and air domains) of hypersonic systems demand near-seamless coordination so that hypersonic capabilities are de-conflicted and integrated into broader operations. Accordingly, an operational C2 architecture, centred on the concept of multi-domain operations, is being discussed within the US Air Force, UK Ministry of Defence, and the Royal Australian Air Force.

Hypersonic system design will invariably require making trade-offs that ensure the systems developed and acquired can meet mission needs. These trade-offs occur at the individual and force-level systems and will require that the designers involved balance future hypersonic technology risks against affordable operational needs and viable force options.

A DOCTRINAL VIEW OF HYPERSONICS

Doctrine provides a useful lens through which to examine the potential disruptive effect that hypersonic technology will have on the continuing development and employment of air and space power. In articulating the wisdom gained through over a century of operational trial and error, doctrine represents how airmen understand their profession of arms. More importantly, doctrine guides airmen's approach to developing and employing new technology by providing an established framework with which to assess how hypersonic technology can be used in a future battlespace. Doctrine also enables an easier appreciation of how disruptive that technology may be for airmen; a slight change in the way air operations are conducted would be less disruptive than a fundamental shift in one of the core air power roles, for example.

This chapter explores the potential impact of hypersonic technology by examining the technology using the four core (control of the air, strike, ISR, and air mobility) and three enabling (command and control, force protection, and force generation and sustainment) air power roles defined in the RAAF's *Air Power Manual*.[50] This chapter provides a philosophical and conceptual understanding of how the speed and survivability of hypersonic systems may shape and influence future air power.

Control of the Air

> *The ability to conduct operations in the air, land and maritime domains without effective interference from adversary air power and air defence capabilities.*
>
> Air Power Manual, 6th edn, p 50

Hypersonic technology will not fundamentally change the core air power role of control of the air. Irrespective of the speed advantage that hypersonic systems will have over current systems, the need to gain and maintain control in the air domain to enable friendly operations without effective interference will endure. Although control of air will remain unchanged, the missions that will be conducted in its pursuit will potentially be quite different in a battlespace in which hypersonics may be employed. One of the primary disruptive effects will be to blur the distinction between offensive and defensive counter-air missions.

For much of air power's history, control of the air has been gained and maintained through actively engaging an adversary's air power and counter-air capabilities. Offensive counter air (OCA) missions, those aimed at destroying or degrading an adversary's air power as close to their bases as possible, have been important to the battle for control of the air since the days of the Red Baron's Flying Circus during World War I. However, if operations can be conducted effectively without needing to first degrade an adversary's counter-air capability through OCA, then this could reduce the resource demands on the low-density high-demand fighter, strike, and electronic warfare assets central to OCA missions, without reducing friendly force survivability. This ability will benefit hypersonic vehicles significantly.

Hypersonic air vehicles will have a survivability advantage over current and near future air defence systems. Accordingly, hypersonic strike, ISR, and air mobility systems are likely to be capable of penetrating and transitioning through contested and denied battlespaces without needing first to gain air superiority; they will have *de facto* air superiority by virtue of their speed. This is not a situation without precedent. The advent of low-observable technologies that underpin modern stealth capabilities have led to an adaptation in the conduct of air campaigns: the employment of the F-117 during the 1991 Gulf War is the most notable example of *de facto* air superiority being achieved without needing OCA. Hypersonic technology will not negate the need for OCA into the future, as not all platforms with enjoy the hypersonic advantage. However, the need to fight for control of the air through OCA missions will evolve when survivable hypersonic systems arrive into a force's order of battle.

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50 Royal Australian Air Force, Australian Air Publication 1000–D—*The Air Power Manual*, Sixth Edition, Air Power Development Centre, Canberra, 2013. [AAP 1000–D—*The Air Power Manual*]

The main shift in the pursuit of control of the air in a hypersonic age will relate to the defensive aspects of the role: those missions aimed at defending friendly forces and assets from an adversary's air power. These types of mission fall under the title of defensive counter air (DCA), which includes active or passive mission sets. Passive DCA considerations are addressed below in the section covering the force protection role.

Active DCA refers to actions designed to 'inflict attrition on or deter the adversary and neutralise the effectiveness of adversary air activity.'[51] Integrated air and missile defence (IAMD) systems and combat air patrols (CAP) fall within this definition; both will be affected by the advent of hypersonic systems. To understand how, it is necessary to distinguish between hypersonic vehicles and their non-hypersonic launch platform or fixed facility.

Against hypersonic vehicles, contemporary and currently foreseeable active DCA measures will be ineffective: the future hypersonic vehicle is likely to penetrate and survive contemporary air defence systems. This limits the utility of point-defence components of an IAMD system or CAP operating near or above friendly territory. This is what distinguishes the threat posed by long-range cruise missiles from that posed by potential hypersonic systems. As hypersonic systems are currently only vulnerable before their launch, the only effective defence against a hypersonic system is to destroy it left of launch.

This need means that defensive measures must be capable of engaging airborne launch platforms at the maximum range of any potential hypersonic ordnance they may carry. Using the example of a notional Mach 8 hypersonic weapon described in Chapter 3, this would require a DCA capability able to engage and destroy an adversary's air attack at least 800 nautical miles (approximately 1500 km) away from defended friendly assets. In some circumstances, this may require the defensive air power umbrella to reach deep into the territory of a neighbour and/or adversary, thus blurring the traditional geographic distinction between OCA and DCA missions. Even if the umbrella were not to extend into enemy territory, the engagement ranges at which defensive systems would need to reach to be useful may preclude their effective use against a hypersonic attack.

Developing a long-range, air defence system that provides a range comparable to that of hypersonic weapons is not currently technologically foreseeable. Pushing defensive CAP missions out to the ranges required to ensure that airborne hypersonic launch platforms are intercepted before they can launch is currently the only viable solution to the active DCA challenge. To be effective, such an approach would require fighters and airborne early warning and surveillance aircraft to operate at extended ranges across a potentially large front; this in turn would require significant air-to-air refuelling support. Any attempt to employ counter-hypersonic CAP will be resource-intensive and expensive, and likely to be prohibitive for smaller air forces such as the RAAF.

Active DCA is not a viable option for a small force to protect its vital areas against a hypersonic-equipped adversary. Whereas DCA will remain a valid and important mission set against non-hypersonic systems, removing the option for a defensive posture against the most dangerous course of action open to a hypersonic adversary has ramifications. When faced with a hypersonic threat, airmen must adopt a more offensive mindset in confronting their adversary, which may even extend to preferring pre-emptive and preventative actions.

While preferring offensive action does not represent a major shift in mindset for most airmen, this shift may be more difficult to achieve at the strategic and governmental level. Government and the military leadership may resist pre-emptive and preventative operations due to potential political ramifications of such actions. This issue will be discussed in more depth in Chapter 6 that deals with issues of strategy.

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51 AAP 1000–D—*The Air Power Manual*, p. 54.

Strike

The ability to attack with the intention of damaging, neutralising or destroying a target.

Air Power Manual, 6th edn, p 56

Even though 'strike' describes the role in which the potential of hypersonic systems is most often discussed, hypersonic systems will not change the air power role of strike. While speed and survivability will undoubtedly give an offensive edge to the possessor of hypersonic systems, the concepts that guide and inform the conduct of strike missions will remain unchanged. Hypersonic weapons will improve a force's strike capability by significantly improving its ability to deliver a survivable payload to generate effects against targets in a reduced timeframe. This ability will shape the way that deliberate and dynamic strikes are planned, executed, and assessed, but will not redefine the air power missions that fall under the strike role. These missions are strategic attack, close air support, air interdiction, anti-surface and anti-submarine warfare, electronic warfare, and information operations.

What hypersonic systems will provide is a force, best described as an assured rapid strike capability. The strike is assured insofar as the survivability of the weapon provides commanders with confidence that once launched, and assuming no mechanical failures in flight, the weapon will make it to its intended target without effective interference by an adversary's air defence systems. This will reduce the number of weapons required to ensure a higher probability of kill (P_k) against a desired target.

The rapidity of strike enabled by hypersonic weapons relates to compressing the time between the decision to act being made and the effect of the hypersonic strike being realised. Figure 5-1 illustrates how the increase in speed influences the ability to reduce times between decision to engage and effect being generated. This acceleration of the targeting cycle will affect both the synchronisation of effects as part of a deliberate targeting process, and the responsiveness of dynamic targeting. While hypersonics will not dramatically alter this cycle and process, they will provide the commander with a greater degree of flexibility in developing strike options during operations and mission planning.

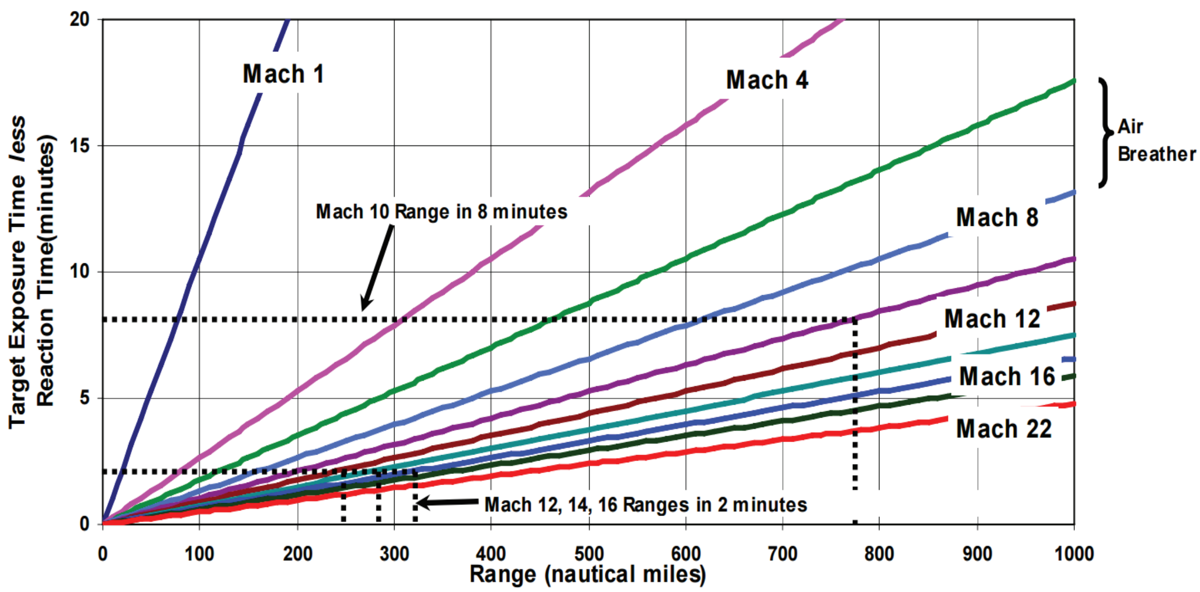

Figure 5-1. Nominal hypersonic weapon engagement times[52]

52 United States Air Force Scientific Advisory Board, *Why and Whither Hypersonics Research in the US Air Force*, SAB-TR-00-03, Washington, DC, 2000, p. 46.

A consequence of the assured rapid-strike capability hypersonic systems is the potential to drive operational and strategic decision makers towards favouring pre-emptive and / or preventative strikes when facing an adversary equipped with hypersonic weapons. An adversary able to strike a force's vital areas at short notice, and with a high degree of certainty that the weapon will get through, will provide the force in possession of such a capability with a distinct first-strike advantage. For forces facing a hypersonic threat, therefore, ensuring that the adversary does not have the capacity to strike first will be prioritised. This will shape targeting priorities and the decision making associated with conducting strategic strike missions. Whereas this situation is similar to the nuclear counter-force strategy, the fact that a state may be more willing to use conventional hypersonic weapons in conflict rather than employ a nuclear option might change the assumptions underlying mutually assured destruction. Additionally, the power of the hypersonic weapon configured with a conventional warhead, not classified as a weapon of mass destruction (WMD), may lower the willingness and decision threshold for initiating their use, when compared to the limitations of using WMD.

Intelligence, Surveillance and Reconnaissance

> *ISR synchronises and integrates the planning and operation of sensors, assets, and processing, exploitation and dissemination systems in direct support of current and future operations.*
>
> Air Power Manual, 6th edn, p 70

Hypersonic technology will demand more from a force's intelligence capabilities, but could favourably complement the force's collection capabilities. Despite this give and take in the relationship between hypersonic systems and the ISR enterprise, hypersonics will not disrupt the fundamentals of the ISR role. The demands from, and the possibilities of, hypersonic systems will rather reinforce the existing need to maximise the integration of sensors, and the processing, exploitation and dissemination systems as part of a hypersonic force's capabilities and processes.

Fully realising the potential advantages of a hypersonic strike capability depends on the capability of a force to generate the timely intelligence upon which the strike will be based. The demand for timely intelligence is not new, as non-hypersonic weapons systems similarly demand the timely actionable intelligence to be provided although hypersonic systems push this need to a new level. If the engagement time for a Mach 8 weapon against a target 600 nautical miles (approximately 1100 km) away is eight minutes, a process that takes even an hour to disseminate intelligence to support targeting decision-making inhibits the overall capability of a hypersonic system.

Timely intelligence is also critically required for a force facing a hypersonic threat. As outlined above, the only foreseeably effective counter to a hypersonic weapon is to attack the system prior to its launch. Maintaining awareness of the status of a potential adversary's hypersonic systems will therefore become a key strategic intelligence target. Because of the limited warning times associated with countering these types of systems, it should be expected that the emergence of hypersonic weapon systems will drive shifts in intelligence priorities and processes so that the intelligence cycle will support effective responses to hypersonic attacks.

In the event that a hypersonic system has been launched, detecting and tracking it will pose a novel challenge for surveillance systems. While current space-based infra-red systems may detect a hypersonic launch, tracking a hypersonic vehicle as it transits to its destination or target is more challenging. When compared to ballistic missile threats, hypersonic boost-glide weapons take much less time to track and engage by remaining below the radar horizon for much longer by virtue of their flatter trajectory. Whereas vehicles operating in the high hypersonic range may provide detection opportunities because of their manoeuvring or the potential generation of plasma and, as the vehicle slows, this opportunity will disappear. Adapting to the surveillance challenge posed by hypersonic systems will not only demand improvements in sensing and ISR capabilities, it may also provide them.

During the Cold War, the US SR-71 demonstrated that speed and survivability are important enablers of responsive airborne ISR in contested environments. Hypersonic ISR systems may therefore become an important complement to existing systems and capabilities. Belief in the possibilities of hypersonic ISR systems is driving the development of the next generation of high-speed ISR capabilities, such as Lockheed Martin's proposed SR-72 'Son of Blackbird'. As with its predecessor, these systems will be expensive, with one estimate placing an SR-72 demonstrator at US$1 billion, likely placing them beyond reach of all but a few air forces.[53]

Irrespective of the limited potential for proliferation, hypersonic ISR systems, such as the SR-72, will not alter the principles of ISR; they will rather force the adaptation and evolution of the processes for planning and controlling ISR operations. If these systems do become operational, their numbers will undoubtedly be limited and, as such, would be treated as strategic assets controlled at the highest level. Accordingly, it is best to view hypersonic systems as a potential complement to other manned and unmanned strategic airborne and space-based ISR assets, such as the U-2, Global Hawk and satellite systems. Smaller forces, such as the Australian Defence Force, will be unlikely to invest in hypersonic ISR because of the potential costs associated with it, although they may benefit through access to intelligence collected by such a system.

Air Mobility

The ability to move personnel, materiel or forces using airborne platforms.

Air Power Manual, 6th edn, p 65

Air mobility is an air power role that has received little attention regarding understanding the potential military impact of hypersonic technology. This relative lack of interest is surprising as hypersonic aircraft can improve responsiveness in air logistic support missions, and also may see a new mission set added into the air mobility role, that of space launch.

Hypersonic responsive airlift over global distances could significantly improve supply chain management, and responsively deliver humanitarian and disaster relief (HADR). The possibility of a hypersonic airlifter supplying inter-theatre logistics as part of 'hub-and-spoke' approach could changes logistics management, particularly regarding centrally managed critical items. Hypersonic mobility would also be useful in the context of HADR by enabling critical supplies and personnel to be dispatched to affected areas rapidly, thus reducing global response times to disasters.

Despite the relative lack of military interest in hypersonic air mobility assets, civilian firms have shown interest in developing hypersonic passenger jets. Even though these proposals are currently only ideas, some of which remain quite fanciful[54], the CEO of Boeing recently said that he believed that hypersonic air travel may occur within the next two decades.[55] While potential does exists, a number of factors would limit the utility of hypersonic air mobility. Size and weight limitations would reduce the carrying capacity of a hypersonic airlifter, thus reducing its capability to provide sustained responsive airlift to a force. Additionally, infrastructure requirements to cater for hypersonic vehicles may restrict the locations to which hypersonic airlifters could operate. However, cost appears to ensure hypersonic air logistic support remains theoretical. The limited utility of such a capability, together with the design challenges needing to be overcome mean that the cost of investing in hypersonic air mobility assets would far exceed the potential benefits they could provide. Accordingly, prospects for hypersonic aircraft filling in traditional air mobility missions are more distant than for the other core air power roles.

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53 Andrea Shalal-Esa, 'Lockheed shows plans for hypersonic spy plane; focus on low cost', *Reuters*, 2 November 2013, http://www.reuters.com/article/us-lockheed-hypersonic/lockheed-shows-plans-for-hypersonic-spy-plane-focus-on-low-cost-idUSBRE9A011820131101 accessed 10 October 2017.

54 Kristin Tablang, 'Fly from New York to Dubai in 22 minutes on board this hypersonic private jet concept', *Forbes*, 16 January 2016, https://www.forbes.com/sites/kristintablang/2016/01/16/charles-bombardier-the-antipode-futuristic-private-jet-concept/#5f4385207f7e accessed 10 October 2017.

55 Phil LeBeau, 'Boeing planning on hypersonic jets for commercial lights, though the Concorde's memory lingers', *CNBC*, 19 June 2017, https://www.cnbc.com/2017/06/19/boeing-planning-hypersonic-commercial-flights-within-a-decade.html accessed 10 October 2017.

However, hypersonic technology does create the potential for developing a new mission set within the air mobility role: space launch. The use of air-breathing reusable space launch vehicles as a way of reducing the costs of space launch was highlighted in Chapter 2 as motivating influence for hypersonic research. Were this technology to be operationalised, it would represent a viable development path for military applications of hypersonic technology to enable smaller forces to access space. It is important here to distinguish between the mission to launch an object into space (space launch) and the missions associated with operations in space (space operations). This distinction is important in framing military space operations, as any militarisation of space activities will likely have undesired strategic implications. It is for this reason that 'space launch' has been raised as a possible mission set within the air mobility role.

Command and Control (C2)

> *The process and means for the exercise of authority over, and lawful direction of, assigned forces.*
>
> Air Power Manual, 6th edn, p 80

Irrespective of whether or not a military force possesses its own hypersonic systems, operationalising hypersonic systems will require the C2 processes governing the employment of air power to adapt and evolve. The compression of the decision cycle made possible by the hypersonic capabilities will enable a corresponding increase in the tempo and responsiveness of air campaigning. For a force in possession of these systems, capitalising on increased tempo will require the streamlining of processes for planning, employing, and assessing air operations.

While appropriate mechanisms for ensuring the control of scarce and strategically sensitive systems are necessary, these control mechanisms must be developed and refined to ensure that they do not introduce nor perpetuate delays in decision-making. To do so would nullify one of the key advantages gained from the investment in hypersonic technology. Maximising operational tempo will be a driving force in future designs for the decision-support and decision-making tools needed in air campaign planning and management in a future battlespace in which forces employ hypersonic systems. The speed of the system may not compensate for any inefficiencies or delays that impede air campaign planning.

The advent of hypersonic systems will require the planning and execution of air campaigns to be adapted, particularly the targeting process, so that an appropriate balance is struck between control of scarce assets and the retention of strike decision making. Required for air campaigns will be the flexibility to address the opportunities and threats posed by hypersonic systems.

Finally, battlespace management will need to address a number of novel challenges in coordinating and integrating endo- and exo-atmospheric hypersonic systems with their slower moving counterparts. Battlespace managers and air traffic controllers should be able to adapt to the increased speeds of new systems by modifying existing separation and traffic management procedures. What will challenge them is developing an effective means to integrate the coordination of systems that operate across air and space domains during the conduct of a single mission. Though this concept of cross-domain control is acknowledged in the air and space battle management function defined within the C2 role, adapting from the conceptual to the operational will require further development once hypersonic systems become a reality and the nature of the challenge is understood more fully.

Hypersonic technology will not invalidate the air power C2 tenet of centralised control/decentralised execution, but the tenet will have to be adapted to deal with the high tempo possibilities provided by the technology. Efforts to adapt are already underway, driven by the need to realise fully the technological benefits of fifth-generation systems. It is possible that the necessary adaptations of air power C2 processes will have been implemented prior to the arrival of hypersonic systems.

Force Generation and Sustainment

> *Generation of the necessary personnel, skills and materiel to conduct and sustain air operations — both domestic and expeditionary — while maintaining the ability to regenerate the force during and after operations.*
>
> Air Power Manual, 6th edn, p 93

The basic principles of force generation and sustainment will remain largely unchanged in a hypersonic force. Even though these systems will undoubtedly place new and different demands on air base operations and technical support structures, such demands are to be expected, as they are experienced when introducing any new capability.

The complexity of hypersonic systems will pose unique logistic management challenges. The extreme environments in which hypersonic vehicles will be required to operate means that any mishandling may degrade the system's operational effectiveness, with potentially catastrophic results. Design tolerances for hypersonic systems will be unforgiving of any mishandling. Similarly, exotic materials and fuels that are necessary for hypersonic operations will require special handling and storage, thus complicating support arrangements.

Base infrastructure will also need to adapt to support hypersonic vehicles. What exactly that adaptation involves will vary, depending on the types of systems being operated.

Research, education, and training will continue to play an important role in the effectiveness of a technologically sophisticated force. Hypersonic systems will bring with them new and unique challenges for those who develop, manage, and use them. However, this will also be the case with other cutting edge technologies: artificial intelligence, quantum technology, and cyber systems will demand an educated, technologically literate workforce supported by innovative research and industrial sectors.

While hypersonic force generation and sustainment needs will be more complicated than for current aircraft and armament systems, the change will be evolutionary, not revolutionary, in character. The experience that air forces, such as the Royal Australian Air Force, are undergoing in the transition to the more complex and complicated systems will force changes in attitudes about, and approaches to, generating and sustaining complex systems. Such experience will start the process of adaptation that will likely ensure that air forces are well prepared to incorporate more complex hypersonic systems into their order of battle.

Force Protection

> *All measure and means to minimise the vulnerability of personnel, facilities, materiel, information and operations to any threat from an adversary or operating environment while preserving the freedom of action and the operational effectiveness of the force.*
>
> Air Power Manual, 6th edn, p 86

The final air power role to be considered is the enabling role of force protection. Hypersonic weapons will not fundamentally change this role, but they will make a review of attitudes to risks in air base and other major infrastructure protection necessary. As highlighted above, for future air base planning, air forces should expect that hypersonic systems will likely defeat currently foreseeable air defence systems.

Active and passive protection measures against air and missile threats will continue to play an important role in air base design and development. However, the characteristics of long-range ballistic and hypersonic missile threats may render active air base defences, such as traditional point and area missile defence systems, largely ineffective. Therefore, missile defence will increasingly rely on cyber, electronic warfare, and passive countermeasures such as mobility, redundancy, hardening, deception, concealment, and dispersal.

With warning times significantly reduced, and reaction times insufficient to enable a response after a hypersonic system has been detected as being inbound, air bases must be optimised to enable the base's operational capability to survive a first strike. Accordingly, operational hypersonics will likely drive the incorporation of more passive defence measures into air base designs. These design considerations will seek to enhance the resilience of operating bases and the survivability of the aircraft operating from them. Such measures will pose infrastructure and planning challenges for many militaries, including Australia's, which have established permanent air bases and designed base infrastructures in the absence of a credible missile threat.

Beyond domestic air base protection, expeditionary forces operating from foreign bases may have only a limited capability to implement passive air base and aircraft defence measures at forward operating bases. That is, unless these have already been incorporated into air base designs by the host nation. When facing a hypersonic-equipped adversary, concerns over the potential vulnerability of high-cost low-density air assets may limit the range of deployment options available to an expeditionary force. Such concerns and the constraints that they will place on air operations will undoubtedly shape operational decision making in an area of hypersonics.

This chapter has used air power doctrine to examine the potential impact of hypersonic systems. Based on the current understanding of the technology and operational possibilities of hypersonic systems, it is safe to assume that such systems will not fundamentally change the philosophy or theory of air power. However, operationalising hypersonic technology will drive airmen to adapt and evolve the way in which air power is generated, sustained, and employed. The most notable area for improvement will be to develop of processes that maximise information flows, and reduce unnecessary and restrictive control measures that impede the tempo of effective decision making. However, the area in which hypersonic systems will have the greatest impact is the shifting mindset that must occur in light of the inherent survivability of hypersonic systems and the likelihood that these systems will succeed in penetrating current and foreseeable air defence systems. Understanding the strategic implications of this is the focus of the next chapter.

STRATEGIC RISKS AND OPPORTUNITIES

The question of if, and to what degree, Australia should invest in the research, development, and/or acquisition of hypersonic technology and systems is sensitive. While hypersonic systems provide a tactical, operational, and strategic advantage to states that possess them, there is a downside to this opportunity. The decision to acquire and operationalise hypersonic systems by the Australian Government will need to be based on balancing both the strategic threat and opportunity associated with them. Needing to be considered are one opportunities: the ability of hypersonic technology to support Australian space operations; and two risks, the possibility for the technology to trigger a regional arms race, and the potential for hypersonic systems to drive strategic planning towards preventative and pre-emptive action.

Space access

One of the important benefits of developing hypersonic systems, which is driven by both military and non-military interests, is reducing the cost for access to space. A state that successfully operationalises a land-based capability to launch a payload into a sub-orbital, hypersonic, and intercontinental trajectory will have also gained the technology necessary to enable a space launch capability. This would result in increased and open access to launch objects into the earth orbit. Previously, only space-faring nations using established space launch capabilities or intercontinental ballistic missiles could afford the systems and develop the knowledge needed to accelerate payloads into hypersonic trajectories, both sub-orbital and orbital. Many nations are conducting considerable research into affordable air-breathing and rocket solutions to propel air vehicles that will carry a mission payload at hypersonic speeds. Low-cost access to space is one of the specified driving forces behind the hypersonic research programs being undertaken at Australian universities.

Developing a domestic, low-cost space launch capability could provide Australia with the benefits associated with an indigenous capability to access space. The most direct benefit to Australian interests would be the impetus that such a launch capability would provide in developing a domestic space industry. A domestic space program would position Australia well to exploit the many economic and technological benefits that it would offer. Australia could also benefit from being a regional leader in space launch capabilities insofar as they would provide both economic and strategic benefits internationally, politically and commercially.

Space access presents the greatest strategic opportunity for Australia from developing hypersonic systems. But there is a downside.

Regional arms race

Unfortunately, technologies associated with hypersonic space launch are dual-use, meaning that the benefits gained for civilian use could be easily adapted to military purposes. Consequently, an Australian investment in acquiring and developing hypersonic systems, even with an explicit focus on non-military applications, could be construed as a way of providing Australia with military advantage. Acquiring hypersonic systems that would provide a speed and survivability edge to Australian forces may lead to a regional arms race as other states seek to ensure that their militaries remain competitive in a future hypersonic age.

A state that successfully operationalises a long-range launch capability for accelerating a payload into a hypersonic trajectory will also be capable of delivering long-range survivable weapons at high speed against targets from the safety of its home base. Facing such a threat would create a security concern among regional states, leading to a potential security dilemma. Even if strike capabilities were not developed, introducing hypersonic systems into roles other than airlift and ISR, in technology that might not be openly accessible to regional countries, may unwittingly disrupt regional relationships if non-hypersonic countries believe they are being disadvantaged.

It follows that developing a hypersonic capability by a state, irrespective of its stated intentions, may trigger a regional arms race. Neighbouring states, in an effort to boost their own security, may directly invest in complex and advanced air defence systems, or may acquire their own hypersonic systems. Such an outcome would be potentially destabilising to regional security.

Were Australia to develop operational hypersonic systems, the Government would need to develop and implement confidence-building measures with regional partners and allies to ensure the Australian intent is not mistaken as a security threat to regional security.

A drive to preventative/pre-emptive actions

The final strategic risk is the most consequential. The speed and survivability of hypersonic weapons may shift strategic behaviour towards favouring pre-emptive or preventative actions to counter an adversary's hypersonic capability 'left of launch'; this has the potential to de-stabilise the situation in periods of heightened strategic tensions.

The speed and survivability of hypersonic systems means that, when pitted against current and foreseeable air defence capabilities, the hypersonic will likely get through to its target. There are two ways to addressing this challenge. The first is to improve force resilience (both personnel and equipment) and develop a level of resilience and attrition tolerance both within the force and the broader community. However, achieving these outcomes is difficult during peacetime because the cost associated with hardening the force may be difficult to justify, as is gaining the population's willingness to accept losses and damage in the absence of an identifiable and proximate threat. Faced with the complication of preparing to absorb attack, the second option of adopting a first strike strategy if faced with a hypersonic threat may be preferable.

Recent experience has highlighted the political and strategic complications generated by pursuing a preventative or pre-emptive strategy. The level of strategic appetite, which the Australian government may have for pre-emptive strikes against an adversary's hypersonic capabilities, cannot be accurately predicted without accounting for the circumstances at the time. However, the question of pre-emption does not only apply to Australian strategic policy, were Australia to develop hypersonic systems. It may also generate a change in the strategic policy of regional states that may be threatened by Australia possessing such systems. Such changes may make Australia a potential target for regional pre-emptive attacks if the security situation was to deteriorate and uncertainty existed as to whether Australia might employ hypersonic systems against a potential adversary. These factors must be considered before Australia acquires or develops hypersonic systems in the future.

Strategic and security interactions between states are complex, so the question of whether and to what extent these strategic risks will be expected cannot be predicted with any degree of certainty while hypersonic technology remains in the experimental stage. Nevertheless, policy makers and force developers must be aware of these strategy considerations as they begin to formulate an Australian approach to hypersonic systems as a viable operational technology. The adoption of hypersonic technology must be balanced against the strategic implications of its operationalisation.

CONCLUSION

It is not possible to predict how operational hypersonic systems will redefine the battlespace. Accordingly, this paper has intentionally avoided providing guidance or prescribing whether hypersonic systems should be introduced into the Australian Defence Force, or how Australia should respond to other states' hypersonic developments. The aim of this paper was to raise its readers' awareness of the developments in hypersonic technology, its potential application in air and space power, and its likely disruptive effects.

Operationalising military hypersonic vehicles will be a step-change that offers great promise for enhancing the operational and strategic responsiveness of air power in the future battlespace. Associated with the potential benefits of hypersonics will be the demands for organisational and procedural changes that will be required if a force is to capitalise fully on the speed and survivability advantages such systems promise. Further complicating the adaptation and evolution of hypersonic technology will be the need to integrate legacy systems with hypersonic capabilities, and drive new capabilities and the development of new means for managing situational awareness and decision-making.

Hypersonic enabled capabilities are not expected to disrupt the enduring roles and concepts that the Royal Australia Air Force currently uses to describe the fundamental principles for applying air and space power. However, the characteristics of hypersonic air power will the level and range of complexity of the systems needed in the force designs for the future battlespace. Adapting to the disruption of hypersonic air power will require operators, force designers, and policy makers to think deeply about the realities of hypersonic technology, critically about the potential strategic impacts of these systems, and creatively about how best to optimise integrating them into the joint force.

This paper has sought to expand its readers' knowledge about hypersonic technology so that they appreciate what the technology means for the Royal Australian Air Force, the Australian Defence Force, and broader Australian strategic policy. As the technology continues to rapidly mature, it is by thoroughly understanding it and its potential tactically, operationally, and strategically that we must shape and influence future force designs. Of specific importance are ISR and C2 systems that will be disrupted by the speed and survivability of deep, penetrating hypersonic vehicles in a possible future battlespace.

Acknowledgements

The Air Power Development Centre wishes to thank the numerous expert contributors who have kindly supported this project with their learned consultations and written contributions.

The *Beyond the Planned Air Force* Team acknowledges the close cooperation it has enjoyed with the Defence Science Technology Group in the development and writing of this working paper. This paper would not have been possible without the efforts and inputs of Dr Shane Dunn, supported by expert contributions from Drs Mark Bateup and Darren Sutton and the research work by Mr Goran Torlak. The Team is also grateful for the opportunities to have had expert consultations with Dr Andrew Neely, UNSW Canberra.

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