航 空 航 天

CHINA AEROSPACE STUDIES INSTITUTE

A CASE STUDY OF THE PRC'S HYPERSONIC SYSTEMS DEVELOPMENT

Prepared by TextOre, Inc.
Peter Wood and Roger Cliff

Printed in the United States of America by the China Aerospace Studies Institute

ISBN 9798672412085

To request additional copies, please direct inquiries to:
Director, China Aerospace Studies Institute
Air University
55 Lemay Plaza
Montgomery, AL 36112

Design by Heisey-Grove Design

E-mail: Director@CASI-Research.org
Web: http://www.airuniversity.af.mil/CASI
Twitter: https://twitter.com/CASI_Research | @CASI_Research
Facebook: https://www.facebook.com/CASI.Research.Org
LinkedIn: https://www.linkedin.com/company/11049011

China Aerospace Studies Institute

CASI's mission is to advance understanding of the capabilities, development, operating concepts, strategy, doctrine, personnel, organization, and limitations of China's aerospace forces, which include: the PLA Air Force (PLAAF); PLA Naval Aviation (PLAN Aviation); PLA Rocket Force (PLARF); PLA Army (PLAA) Aviation; the PLA Strategic Support Force (PLASSF), primarily space and cyber; and the civilian and commercial infrastructure that supports the above.

CASI supports the Secretary, Chief of Staff of the Air Force, the Chief of Space operations, and other senior Air and Space leaders. CASI provides expert research and analysis supporting decision and policy makers in the Department of Defense and across the U.S. government. CASI can support the full range of units and organizations across the USAF, USSF, and the DoD. CASI accomplishes its mission through conducting the following activities:

- CASI primarily conducts open-source native-language research supporting its five main topic areas.

- CASI conducts conferences, workshops, roundtables, subject matter expert panels, and senior leader discussions to further its mission. CASI personnel attend such events, government, academic, and public, in support of its research and outreach efforts.

- CASI publishes research findings and papers, journal articles, monographs, and edited volumes for both public and government-only distribution as appropriate.

- CASI establishes and maintains institutional relationships with organizations and institutions in the PLA, the PRC writ large, and with partners and allies involved in the region.

- CASI maintains the ability to support senior leaders and policy decision makers across the full spectrum of topics and projects at all levels, related to Chinese aerospace.

CASI supports the U.S. Defense Department and the China research community writ large by providing high quality, unclassified research on Chinese aerospace developments in the context of U.S. strategic imperatives in the Asia-Pacific region. Primarily focused on China's Military Air, Space, and Missile Forces, CASI capitalizes on publicly available native language resources to gain insights as to how the Chinese speak to and among one another on these topics.

Preface

Great Power Competition necessitates understanding with whom one is competing. It also requires understanding the breadth and depth that competition and how your competitor is progressing. Hypersonic systems are an emerging area of military technology with potentially transformative effects. Although different types of hypersonic systems have been in development and testing for more than 60 years, several countries, including the United States and China, have made significant advances in this area in recent years. This report is the next in the series of studies by the China Aerospace Studies Institute that seeks to lay the foundation for better understanding the Aerospace Sector of the People's Republic of China (PRC).

As the United States and its allies and partners continue to develop hypersonic systems of their own, as well as the doctrine and tactics that will support not only just their employment, but also how to counter those of an adversary, it is important to understand how the People's Republic of China is progressing along its path.

Drawing on Chinese-language government publications, news articles, authoritative writings on strategy and tactics, and academic studies, this report reviews the organizations and people responsible for developing hypersonic technology in China, the systems and facilities supporting their efforts, and specific hypersonic weapon systems known to be in service or under development in China.

We hope you find this volume useful, and look forward to bringing you further details on the foundations of Chinese aerospace in this series.

Dr. Brendan S. Mulvaney

Director, China Aerospace Studies Institute

Structure of the Report

This report is organized into five main sections:

- Section 1 provides a brief overview of the history of hypersonic technology development in general and describes recent developments that have caused China to put new emphasis on acquiring hypersonic systems.
- Section 2 describes key organizations and people responsible for developing hypersonic technology in China.
- Section 3 describes China's specialized technologies and facilities for developing hypersonic systems.
- Section 4 describes specific hypersonic weapon systems known to be in service or under development in China.
- Section 5 summarizes the findings of the report and describes some key implications.

Sections

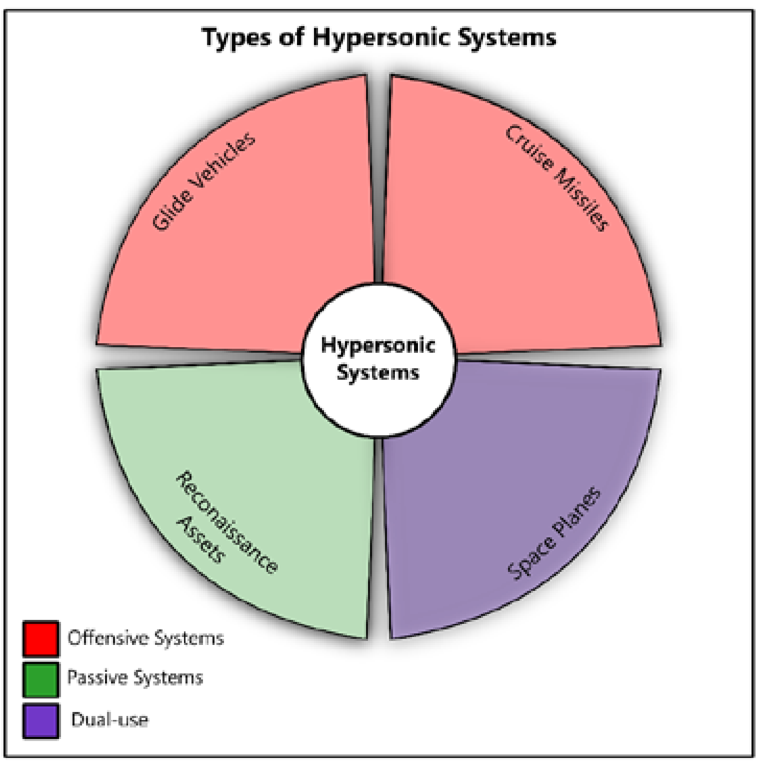
Abbreviations

ABM	Anti-Ballistic Missile
AMS	Academy of Military Sciences
ASBM	Anti-Ship Ballistic Missile
CAD	Computer Aided Design
CASC	China Aerospace Science and Technology
CCP	Chinese Communist Party
CFD	Computational Fluid Dynamics
CMC	Central Military Commission
EDD	Equipment Development Department
EW	Early Warning
GAD	General Armaments Department
HGV	Hypersonic Glide Vehicle
ISR	Intelligence, Surveillance, and Reconnaissance
MaRV	Maneuverable Reentry Vehicle
NUDT	National University of Defense Technology
PLA	People's Liberation Army
PLAAF	People's Liberation Army Air Force
PLAN	People's Liberation Army Navy
PLARF	People's Liberation Army Rocket Force
PLASSF	People's Liberation Army Strategic Support Force
PRC	People's Republic of China
R&D	Research and development
RMB	Renminbi
SAM	Surface-to-Air Missile
SASTIND	State Administration for Science, Technology and Industry for National Defense
THAAD	Terminal High Altitude Area Defense

Section 1: Background

The term "hypersonic" typically refers to systems capable of traveling in excess of five times the speed of sound (Mach 5), a convention also adopted by the Chinese military.[1] In more familiar terms, this corresponds to a speed of about 3,836 mph (6,174 kph) at sea level, under "average" atmospheric conditions.

Hypersonic systems can be manned, like the U.S. X-15 rocket-powered aircraft tested in the 1960s, or unmanned. It should be noted that spacecraft reentering the atmosphere and all ballistic missiles with ranges greater than about 300 km fly at hypersonic speeds for at least portions of their flight. This study is primarily concerned with next-generation weapon systems being developed by China that maintain hypersonic speeds for extended periods and have a high degree of maneuverability at those speeds. The physics involved in such high-speed maneuverability present major challenges in areas such as computer modeling, material sciences, and control mechanisms. It is worth bearing in mind, however, that although the focus of research in China in recent years has been on maneuverable ballistic missile warheads and hypersonic cruise missiles that can defeat contemporary anti-missile defense systems, historically hypersonic flight research and development (R&D) has encompassed a much broader range of applications, including manned and unmanned reconnaissance, interceptor, and bomber aircraft, as well as civilian applications. Thus, the technologies that emerge from the current hypersonic weapons programs could have far-reaching ramifications for the Chinese aerospace industry across many sub-sectors.



While considered a cutting-edge technology, conceptually, controlled hypersonic flight has been a subject of study in the United States and the Soviet Union/Russian Federation since the 1950s. Practical applications of the technology have been under development since at least the 1960s.[2]

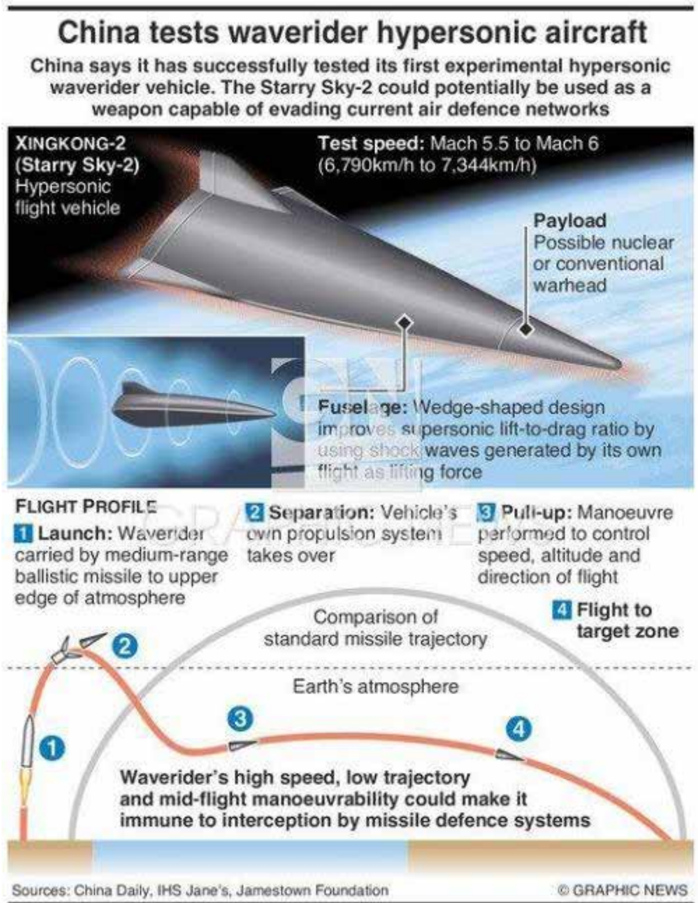
For the United States, concerted study of hypersonic systems appears to have initially focused on reconnaissance. Only five years after Gary Powers' U-2 spy plane was shot down over the Soviet Union, a planning document for reconnaissance noted that the U-2 was obsolete and that Soviet advances in surface-to-air missiles (SAMs) threatened the A-12 reconnaissance aircraft (SR-71, OXCART). Drones (many of which were downed over Vietnam and China) were perceived as having high vulnerability and limited utility. As a result, hypersonic gliders and powered aerial vehicles were developed by the CIA under the codenames ISINGLASS and ISINGLASS II.[3] As one report put it regarding an early stage of R&D, "The interest is in a boost glide vehicle, air launched from a carrier no larger than a B-52, and capable of a trajectory of 6,000 nautical miles or more."[4] While eventually canceled, these efforts pioneered an engineering paradigm that all subsequent hypersonic systems have essentially followed.

The emergence and rapid development of China's current hypersonic weapons program appears to have been driven by the shifting strategic balance and technological advancement of its neighbors and the United States. China is now pursuing hypersonic technology on a number of fronts with clear objectives. Militarily, hypersonics fit into a broader arc of China's systematic development of strategic weapons.

China began considering hypersonic systems soon after the initiation of its ballistic missile and nuclear programs. Chinese sources credit the term "hypersonic" to Qian Xuesen [钱学森 – a.k.a. Hsue-Shen Tsien],[5] the Caltech-trained mathematician and aerospace engineer widely considered to be the father of the Chinese aerospace program. Qian's thesis adviser at Caltech had been the aerospace pioneer and early hypersonic dynamics researcher Theodore von Kármán, and Qian's earliest theoretical works on hypersonic issues date back to his days at Caltech. After graduating in 1939, Qian was recruited by von Kármán to remain at Caltech, where he later worked on the Manhattan Project, as well as the U.S. Army's nascent rocketry program. Qian returned to China in 1955, after having come under suspicion as a Communist sympathizer during the McCarthy era. Upon his return he was appointed director of the PLA's Fifth Academy, tasked with ballistic missile and nuclear weapons development.

The fledgling Chinese ballistic missile program received a significant boost in 1958, when China received its first R-2 ballistic missiles (an improved version of the wartime German V-2) as well as the associated technical documentation from the Soviet Union. Domestic production of the missile as the DF-1 began soon after, despite disruptions caused by the Sino-Soviet break in 1960.[6] While Chinese state-run laboratories have been studying hypersonic flight as part of the ballistic missile program since the 1960s, the work remained mostly theoretical, as the Chinese government focused limited resources on developing proven conventional ballistic missile and ramjet technologies.

Preliminary research on supersonic-combustion ramjets ("scramjets") did not begin until the late 1980s, as part of the "Reusable Space-Earth Transportation Systems" [天地往返运输系统]" project under the 863 Program. By the early 1990s, substantial progress had been made on scramjet research under Project 921, China's manned space program, although these results were still characterized as "preliminary." A serious effort to develop hypersonic flight vehicles did not begin until sometime in the mid 2000's, after a group of senior Chinese aerospace engineers led by the veteran ramjet designer Liu Xingzhou (1933–2011) submitted a proposal to the central leadership outlining the strategic value of hypersonic flight vehicles in 2004. Soon after, the "Hypersonic Flight Vehicle Science & Technology Project" [高超声速飞行器科技工程] was initiated under the National Medium-to-Long Term S&T Development Plan [国家中长期科学技术发展规划纲要] (2006–2020). In 2008 China began work on its first large-scale hypersonic wind tunnel, the JF12, billed as "the world's largest hypersonic wind-tunnel". The first flight of China's first hypersonic glide vehicle took place in 2014.



Chinese Hypersonic System R&D Timeline	
1956	Qian Xuesen founds the Institute of Mechanics
1957	Qian establishes a ramjet engine research laboratory [冲压发动机研究室], predecessor of the 31st Institute of China Aerospace Science and Industry Corporation[7]
1958	China receives first R-2 missiles (improved version of wartime German V-2) in October 1958[8]
1960	First successful ignition of a ramjet engine
1966	PLA Second Artillery (now PLA Rocket Force) founded 1 July 1966
1969	First successful ramjet flight test
1983	Successful test flight of first "indigenously-designed" ramjet engine (believed to be the CF-08 ramjet engine used on the C-101 anti-ship missile)
1987	Preliminary research on scramjets begun as part of the "Reusable Space-Earth Transportation Systems" project under the 863 Program
1994	State Key Laboratory of High Temperature Gas Dynamics [高温气体动力学国家重点实验室] established
2000	Jiang Zonglin appointed Director of the High Temperature Gas Dynamics Lab
2004	Group of aerospace engineers led by veteran ramjet designer Liu Xingzhou [刘兴洲] submits proposal for the development for hypersonic flight vehicles
2006	Hypersonic Flight Vehicle S&T Project initiated under the National Medium-to-Long Term S&T Development Plan (2006–2020)
2008	JF12 hypersonic wind tunnel project initiated; Jiang Zonglin appointed project director
2012	JF12 hypersonic wind tunnel comes online
2014	CASC 11th Academy, First Research Institute Hypersonic Vibration Test project completes first test[9]
2015	Wang Zhenguo [王振国] and National University of Defense Technology (NUDT) team demonstrate regenerative cooling scramjet for the first time

A primary impetus driving recent hypersonic weapons R&D in China has been the emergence and deployment of increasingly effective missile defense systems – both air defense systems against conventional cruise missiles and ballistic missile defense systems. China's neighbors are developing and deploying missile defense systems at a rapid pace. Northeast Asia is already home to three advanced ballistic missile defense systems, including the PAC-3 SAM system fielded by U.S., Japanese, and South Korean forces; the Terminal High Altitude Area Defense (THAAD) missile defense system operated by U.S. forces in South Korea; and the Aegis BMD system operated by the U.S. Navy as well as the Japanese Maritime Self-Defense Force (JMSDF).[i] In particular, Chinese strategic analysts reportedly believe that the AN/TPY-2 radar deployed to South Korea as part of the THAAD deployment will seriously undermine China's nuclear deterrent capabilities: Not only will these radars provide coverage of the airspace over much of northeastern China,[10] through which missiles fired from PLA Rocket Force units based in central China toward targets on the west coast of the United States would likely traverse, but they may also be able to distinguish real warheads from decoys when they are released from the booster rockets.[11]

Despite U.S. assurances that the THAAD system in South Korea will pose little threat to China's strategic interests, it is undoubtedly true that the U.S. has been continuously improving its capability to detect, characterize, and intercept ballistic missiles.[12] In addition to the deployment of missile warning radars to Japan and South Korea, improvements to U.S. capabilities to intercept Chinese ballistic missiles include the installation of additional ground-based interceptors (GBIs) at U.S. missile defense sites in Alaska and California. A total of 44 GBIs have now been deployed and there are plans for another 20.[13]

Some of China's other neighbors are also working on systems to defeat incoming ballistic missiles. To China's south, the Indian Defense Research and Development Organization (DRDO) is building a layered ballistic missile defense consisting of the domestically-produced Prithvi Air Defense system and Advanced Air Defense system, augmented with Israeli (MRSAM) and Russian (S-400) systems.[14] Previous reporting indicated that there were plans to deploy some of these systems outside Mumbai and the Delhi metropolitan area.[15] According to expert observers, Mission Shakti, an anti-satellite missile (ASAT) test conducted in March 2019 by the DRDO, likely employed a modified version of the Prithvi missile and thus constituted a demonstration of India's missile defense capabilities as well.[16]

To China's north, Russia is also developing a highly capable missile defense system. The S-500 "Prometey" (Prometheus) [С-500 «Прометей»] is a Russian SAM/anti-ballistic missile (ABM) system slated to replace the S-400 system. Russian Defense Minister Sergei Shoigu has stated that the S-500 will be ready for delivery to the Russian military in 2020.[17] In June 2019, Rostec CEO Sergey Chemezov revealed that Rostec had begun production of the S-500 for testing, but did not specify a delivery date.[18]

According to reports, the S-500 has a range of up to 600 kilometers. It is able to track and engage up to 10 targets moving at up to 7 kilometers per second (Mach 20) at once. Officials at Russia's Almaz-Antey have said that the S-500 is capable of intercepting ballistic missiles of all types. A new interceptor missile was designed for the system in order to accomplish this – specifically, design considerations allowing it to operate outside of the atmosphere were integrated.[19]

Chinese strategists see the development of these missile defense systems as profoundly disruptive. Writing in 2003, Lt. Gen. Zhao Xijun, then-Deputy Commander of the PLA Second Artillery Force, predicted that other countries unilaterally enhancing missile defense strength would "increase the chances of nuclear war and trigger a new round of high-tech arms race."[20] While not explicitly mentioned, the development of hypersonic weapons

---

i Japan had planned to purchase two units of a fourth system, the Aegis Ashore, before cancelling the order in June 2020 due to local opposition and cost concerns.

is consistent with the idea of a 'new round of high-tech arms race,' given their greater ability to defeat missile defense systems.

More recently, an assessment of U.S. and Russian nuclear modernization published in *PLA Daily* stressed that deployment of early warning radars such as THAAD has "seriously undermined the strategic balance of the region." It further stated that China "…must enhance credible and reliable nuclear deterrence and nuclear counterattack capabilities and enhance strategic checks and balances."[21] At the same time, while China-Russia relations have been strong, Chinese military journals continue to emphasize the capabilities of Russian missile defense systems, suggesting some unease at the Sino-Russian strategic disparity in this area, especially given Chinese perceptions of Russian dominance in the development of hypersonic weapons.[22]

Taken together, these developments significantly decrease the deterrent power of China's nuclear strategy of "no first use" and assured retaliation. An additional consideration is that China's nuclear and conventional missile forces already operate at a significant disadvantage due to China's apparent lack of early warning satellites, which greatly reduces the time Chinese leaders would have to confirm that China was under attack and respond. Advanced systems capable of overcoming these disadvantages and restoring the strategic balance are therefore a high priority. Hypersonics likely form part of an emerging, multi-part "integrated strategic deterrence" [整体战略威慑] composed of nuclear, conventional, space and cyberwarfare capabilities.[23]

Section 2:
China's Hypersonic R&D Ecosystem

Hypersonic flight poses a number of daunting technical challenges, including those relating to heat management, G-stress, and navigation. Most hypersonic weapon systems, unlike ballistic missiles, spend the majority of their flight within the atmosphere. Yet hypersonic atmospheric flight, even at high altitudes, generates tremendous amounts of heat. Moreover, like all trans-atmospheric vehicles, including spacecraft and ballistic missile re-entry vehicles, hypersonic vehicles such as hypersonic glide vehicles (HGVs) returning through the atmosphere experience intense stresses, a challenge compounded by the need to perform braking and other high-G maneuvers to improve accuracy and evade interception for offensive systems. The design of hypersonic vehicles must therefore possess sufficient structural strength against shearing forces while simultaneously reducing weight and radar cross-section. Lastly, atmospheric hypersonic flight can generate waves of plasma that interfere with communication signals from ground stations and satellites. Particularly for strikes against moving targets, offensive systems require continuously-updated information on target location. While China has developed a layered system of over-the-horizon radars, long-range drones, imagery satellites, and increasingly accurate navigation satellites, the inclusion of rubidium atomic clocks on the newer Beidou satellites reportedly improved their resolution from approximately 10 meters to 2.5–5 meters, the usefulness of the improved ISR system will be greatly diminished if the data cannot be reliably communicated to hypersonic flight vehicles.

The development of a successful hypersonic weapon system, therefore, requires significant technical advances on multiple fronts. Although Chinese aerospace experts have been advocating for the development of hypersonic weapons since at least the late 1990s, a coherent effort to develop these systems did not begin until 2006, when the Hypersonic Flight Vehicle Science & Technology Project was initiated as a "key project" under the National Medium-to-Long Term S&T Development Plan (2006–2020). The CMC Science and Technology Commission [科学技术委员会], which plays an important role in determining long-term priorities,[24] appears to have taken the project under its auspices and is likely coordinating the disparate efforts in the various relevant fields that comprise the essential elements of a successful hypersonic weapons program.

For example, meeting the heat-management requirements of hypersonic vehicles generally requires a multi-pronged solution combining innovations in material science and creative heat-sinking designs. For this reason, cryogenic fuels are typically used, both for their higher energy density and their ability to act as heat sinks when circulated close to leading edges that take the brunt of atmospheric heating. However, the technical complexity of novel heat-resistant materials has been one of the most intractable bottlenecks in the development of hypersonic technologies, and the Russian hypersonic weapons program has apparently been hampered by a dearth of carbon fiber heat-shielding material.[25]

Not surprisingly, then, heat management is an area of research which has received heavy investments from the Chinese state, with multiple teams of researchers reporting "breakthroughs" in recent years. In 2017, for instance, a research team at Central South University's [中南大学] State Key Laboratory for Powder Metallurgy [粉末冶金国家实验室] announced a "breakthrough" in ceramic coatings necessary for hypersonic vehicles. Led by China Academy of Engineering academicians Huang Boyun [黄伯云] and Xiong Xiang [熊翔], the team discovered a material composed of zirconium, titanium, boron and carbon able to withstand temperatures of up to 3,000 degrees Celsius (5,432 degrees Fahrenheit).[26] A year later, another team working at Central South University announced the successful development of a type of "light-weight, ultra-high temperature, refractory metal-based composite material" which is said to have supported China's development of a hypersonic vehicle.[27] The development of the new material is based on micron-nanometer technology that combines ultra-high temperature ceramics and nano-composite material to strengthen the refractory metals. According to Chinese news reports, research in this area is said to have received support from the 863 and 973 programs as well as the National Natural Science Foundation [国家自然科学基金委员会] since 2002,[28] well before the official initiation of the Hypersonic Flight Vehicle project, although the apparent rapid progress made in recent years likely reflects a significant ramp-up in state investments in connection with the hypersonics program.

Key Academic and Corporate Research Institutions

China Academy of Aerospace Aerodynamics (CAAA) [中国航天空气动力技术研究院]
AKA: **11th Academy of CASC [中国航天科技集团第十一研究院]**
Website: http://www.caaa-spacechina.com/
Location: Beijing, China

The China Academy of Aerospace Aerodynamics (CAAA) is China's leading research institute in the field of aerodynamics research and development. CAAA's lineage can be traced back to the Department of Aerodynamics Research under the PLA's Fifth Academy, founded in 1956 under the directorship of Qian Xueshen to jumpstart China's ballistic missiles and nuclear weapons programs. CAAA was reorganized as a subsidiary institution under the China Aerospace Science and Technology Corporation (CASC) in 2004.

Today, CAAA has evolved from a dedicated specialist in aerodynamics R&D, into an "integrated" technology center with five major areas of operations, including aerodynamics, special aircraft, environmental engineering, measurement and control systems, and new materials. Notably, CAAA boasts "more than 30 specialized high-tech experimental facilities including… low-speed, transonic, and hypersonic wind tunnels, electric arc heaters, and electric arc wind tunnels". CAAA is credited with the development of the Starry Sky II hypersonic glide vehicle, believed to be a testbed for China's scramjet engine program. In addition, CAAA has also developed the Caihong [彩虹] (Rainbow) series of UAVs under its Special Aircraft division.

As of March 2020, CAAA employs more than 3,900 employees, including more than 40 "distinguished experts" at the national or ministerial level. Approximately 60% of the CAAA workforce was described as "professional technical personnel".[29]

China Academy of Launch Vehicle Technology (CALT) [中国运载火箭技术研究院]
AKA: **1st Academy of CASC** [中国航天科技集团第一研究院]
Website: http://calt.spacechina.com/
Location: Beijing, China

The China Academy of Launch Vehicle Technology (CALT) is China's premier designer and manufacturer of space launch vehicles as well as ballistic missiles. Founded in 1957 as the First Sub-Academy of the PLA Fifth Academy, it was tasked with the development of China's first ballistic missile. In subsequent years the organization had retained its institutional coherence largely intact, despite a number of name changes and administrative reshuffles. It became a subsidiary of CASC in 1999.

CALT is best known as the developer of China's Long March family of space launch vehicles and Dongfeng family of ballistic missiles, although in recent years it has diversified into a broad range of civilian sectors, boasting of "industry-leading" status in fields including coal gasification, special vehicles, new energy and new materials, intelligent manufacturing and artificial intelligence. CALT is the probable developer of the HGV-tipped DF-17 MRBM.

As of July 2020, CALT employs more than 33,000 employees, including seven Academicians of the China Academy of Sciences and China Academy of Engineering, more than 1,200 holders of doctorates, and more than 6,000 holders of Master's degrees. CALT reports corporate assets totaling more than RMB103.795 billion (approx. U.S.D15 billion).[30]

College of Aerospace Science and Engineering, National U. of Defense Technology (NUDT)
[国防科学技术大学航天科学与工程学院]
Formerly: **NUDT College of Aerospace and Materials Engineering [航天与材料工程学院],**
NUDT Department of Aerospace Technology [航天技术系]
Website: www.nudt.edu.cn
Location: Changsha, Hunan [长沙市,湖南省]

The NUDT College of Aerospace Science and Engineering (CASE) was founded in July 1956 as the Program in Missile Engineering at the PLA College of Military Engineering, predecessor of the NUDT. After the establishment of the NUDT in 1978, the department was renamed the Department of Applied Mechanics, before it was renamed yet again as the Department of Aerospace Technology in 1984. In 1999, the Department of Aerospace Technology was expanded to become the NUDT College of Aerospace and Materials Engineering. The college was renamed to become the College of Aerospace Science and Engineering in 2013.

As of 2017, CASE offered three primary fields of study, including Aerospace Science and Technology, Material Science and Engineering, and Mechanics. CASE also boasted two "National Key Academic Departments" [国家重点学科], namely Aerospace Propulsion Theory & Engineering, and Aircraft Design; and three "Category I Provincial Key Academic Departments", namely aerospace science and technology, material science and engineering, and mechanics.[31] MG. Wang Zhenguo, Deputy Chief Engineer of China's "Hypersonic Flight Vehicle S&T Project," was an alumnus as well as longtime faculty member at the College.

Institute of Mechanics, Chinese Academy of Sciences [中国科学院力学研究所]
Website: www.imech.cas.cn
Location: Beijing, China

Billed as the "first national institution for mechanics research" established in China, the CAS Institute of Mechanics (IMCAS) was founded in 1956 by Qian Xueshen upon his return from the U.S. Today, IMCAS boasts five physical (as opposed to computer simulation) laboratories and one research center. These include the State Key Laboratory for High Temperature Gas Dynamics (LHD); the State Key Laboratory for Nonlinear Mechanics (LNM); the State Key Laboratory for Microgravity Research (a.k.a. National Microgravity Laboratory); the

State Key Laboratory for Fluid-Structure Interaction System Mechanics (LMFS); the Advanced Manufacturing Process Mechanics Laboratory (AMML); and the Aerospace Flight Technology Innovation Research Center. As of June 2017, IMCAS employs more than 380 scientific and technical personnel, including eight academicians of the Chinese Academy of Sciences and Chinese Academy of Engineering; 10 grantees of the National Science Fund for Distinguished Young Scholars; more than 70 research fellows; and more than 150 other scientific and technical personnel at the level of senior technician or above.

IMCAS sponsors 5 academic journals, including 2 English-language journals: *Acta Mechanica Sinica*, and *Theoretical & Applied Mechanics Letters*.[32]

State Key Laboratory for High-Temperature Gas Dynamics [高温气体动力学国家重点实验室]

The State Key Laboratory for High Temperature Gas Dynamics (LHD) was set up in 1994 by CAS Academician Yu Hongru [俞鸿儒], an expert in aerodynamics and one of the first students recruited to the Institute of Mechanics in 1956. The Laboratory has been successively expanded in size and prominence, becoming a State Key Laboratory in 2005,[33] although it remains subordinate to the Institute of Mechanics. Headed by physicist Jiang Zonglin[姜宗林] (profiled below) since 2000, LHD was the driving force behind the design and implementation of the JF12 wind tunnel, billed as "the world's largest hypersonic wind tunnel," which has been instrumental in China's hypersonic weapons program.

State Key Laboratory for Powder Metallurgy (SKLPM), Central South University (CSU)
[中南大学粉末冶金国家重点实验室]
Website: sklpm.csu.edu.cn
Location: Changsha, Hunan [长沙市,湖南省]

The State Key Laboratory for Powder Metallurgy (SKLPM) was established at Central South University (CSU) in Changsha, Hunan in 1989; formally opening in 1995 after passing its state certifications. As of January 2019, the Laboratory employed 77 permanent research staff, including two Academicians; seven "Thousand Talents" scholars; six grantees of the National Science Fund for Distinguished Young Scholars; seven Distinguished Professors from the Changjiang Scholars program; and 57 other professors and researchers. Major research areas of the laboratory include: integrated computational materials engineering and applications of powder metallurgy materials; new principles and methods of powder metallurgy materials formation and densification; advanced powder metallurgy materials; light alloys and carbon-based materials.

SKLPM claims to have provided "hundreds of special powder metallurgy materials" for many of China's key S&T projects and strategic weapons. The high performance new materials developed at the lab are said to have been successfully employed on China's C919 commercial jetliner; the Tiangong series of space stations; the Shenzhou series of spacecraft; as well as the new generation of rocket engines used on the Long March 5, 6 and 7 series of launch vehicles.[34] [35] Notably, between 2017 and 2018, two different research teams at SKLPM announced "breakthroughs" in ceramic coating materials necessary for the development of hypersonic flight vehicles. Also in 2017, CSU announced a cooperation agreement with the University of Manchester from the U.K., under which SKLPM would collaborate with the Manchester-based Henry Royce Institute to jointly develop a new type of ceramic coating material for use on hypersonic aircraft and spacecraft.[36]

Notable Chinese Experts on Hypersonic Systems

Within China's hypersonic R&D ecosystem there are a number of prominent researchers. Profiles of two of them are provided below.

Wang Zhenguo [王振国]

Wang Zhenguo is one of China's most prominent experts in hypersonic propulsion technology. Notably, he is the de facto Chief Engineer of China's "Hypersonic Flight Vehicle Scientific and Technological Project," the CMC initiative behind China's hypersonic weapons program.[37]

Born in June 1960, Wang completed his undergraduate degree at the National University of Defense Technology (NUDT) in 1982 and proceeded to study for a doctorate at NUDT's Department of Aerospace Technology [航天技术系]. He received his Ph.D. in 1993 and became an academician of the Chinese Academy of Engineering in 2017.[38] Wang holds the rank of Major General.[39]

Wang has spent his entire career with NUDT and has long been engaged in teaching and research on the theory and technology of aeronautical and astronautic propulsion. He is credited with "groundbreaking" achievements in the theory and application of liquid propellant rocket engines and scramjets [超燃冲压发动机], as well as near-space flight vehicle design.[40] In 2015 Wang and his team successfully developed what was described to be the world's first kerosene-burning scramjet with regenerative cooling [再生冷却超燃冲压发动机], which successfully underwent long-duration testing. Wang and his team are also credited with the design and development of China's first scramjet-powered hypersonic vehicle, which completed its first successful autonomous flight test in 2015.[41] For his work on hypersonic propulsion technologies, Wang has received some of the PRC's highest honors for scientific and technical achievements.

Jiang Zonglin [姜宗林][42]

Jiang Zonglin is one of China's most high-profile experts on hypersonic modeling and testing. Born in 1955, Jiang received his undergraduate and master's degrees from Harbin Marine Engineering Academy [哈尔滨船舶工程学院] (now Harbin Engineering University [哈尔滨工程大学]). After graduating he worked as an engineer at the CASC 11th Academy (or 701st Institute). He began work on his Ph.D. at Peking University's Department of Mechanics in 1990 and studied the mathematical principles behind shock wave simulation under Zhou Peiyuan [周培源], a Caltech-trained theoretical physicist best known for his contributions to fluid dynamics. After graduating in 1993, Jiang taught for five years as an assistant professor of mechanics at Tohoku University in Japan, while continuing his research on shock waves under the mentorship of Kazuyoshi Takayama, a leading expert in the field. At the end of 1999, academician Yu Hongru [俞鸿儒] from the Chinese Academy of Sciences Institute of Mechanics [中国科学院力学研究所] brought Jiang back to China under the "Hundred Talents Program" [百人计划]. Jiang subsequently joined Yu's Institute and was appointed director of the Key Laboratory on High Temperature Gas Dynamics.[43]

Jiang's most important accomplishment at the Institute of Mechanics to date has been the conception, design, and implementation of the JF12 wind tunnel, billed as "the world's largest hypersonic shockwave wind-tunnel." Completed in 2012, the JF12 wind tunnel is believed to have played a crucial role in the development of China's DF-ZF hypersonic glide vehicle. For his role helming the JF12 project, Jiang received the Ground Testing Award from the American Institute of Aeronautics and Astronautics in 2016.[44]

International Collaboration

As with other defense science projects, China appears to have benefited significantly from cooperation with other countries, particularly in hypersonic testing and material science. While most such cooperation is framed in terms of its applications to civil projects, such as a spaceplane, the research would clearly benefit military applications as well.

For example, China recognizes that it currently lacks sufficient capabilities in ultra-high-temperature ceramics and is seeking foreign assistance to help address this deficiency. As part of this effort, in 2017, Central South University in Changsha, Hunan announced a collaborative agreement with the University of Manchester from the U.K. to jointly develop a new type of ceramic coating material for use on hypersonic aircraft and spacecraft.[45] The material is expected to improve the resistance of equipment like rockets, multi-use spacecraft, and missiles to the effects of high temperatures when traveling at speeds of Mach 5 and higher. The UK's Henry Royce National Institute for Advanced Materials Research and Innovation, headquartered on the campus of Manchester University, will be involved in the cooperation project, with the end goal of developing a carbide coating that is capable of withstanding temperatures of up to 3,000 degrees Celsius.[46]

Not all collaboration is witting on the part of the non-Chinese partners. In January 2015, Hu Xiaoxiang (扈晓翔), a Chinese researcher enrolled in a doctoral program at the University of Agder in Norway, was deported from the country for alleged concealment of his ties to the PLA. Hu had been working on air-breathing hypersonic flight vehicles, supported by a Norwegian government grant for offshore wind energy research.[47]

While China and Russia have extensive cooperation in the fields of aeroengines, wind tunnel testing, and aviation-related metallurgy, a review of Russian and Chinese media yielded no evidence of any direct cooperation between the two countries related to hypersonic weapons.

Section 3: China's Hypersonic R&D Cycle

Over the past three decades, the Chinese aerospace industry has taken significant strides forward in its R&D capabilities. Modern computer-integrated design and fabrication systems along with automation tools such as computer-aided design software, computer-aided process planners, and digitally-controlled machine tools are now prevalent in the Chinese aerospace industry, and the leading R&D institutions – especially the various "National Key Laboratories" – now boast truly state-of-the-art equipment. While progress has been uneven across sectors, it is also undeniable that China has been able to achieve impressive results in select sectors where the state has chosen to marshal vast resources. The rapid development of China's hypersonic weapons program is a particularly noteworthy example.

Unsurprisingly, available public information suggests that the design process for hypersonic flight vehicles in China is broadly consistent with the general paradigm for aircraft design. It is a particularly exacting variant of the standard engineering design process, employing highly iterative techniques that require repeated cycles of rigorous analysis, testing, and detailed measurements. Broadly speaking, the design process proceeds through three main phases: digital modeling, scale-model testing, and flight testing.

Basic Design and Digital Modeling

Computer modeling is generally the first stage of the modern engineering design process. Prior to a scale prototype being built, extensive use of computer modeling is used to refine the design. Since the 1980s, China has made significant strides in computational fluid dynamics (CFD) and testing related to hypersonic research.

It is perhaps notable that in July 2017 Major General Deng Xiaogang [邓小刚], an expert on mathematical modeling of hypersonic gas dynamics, was appointed to lead NUDT. He previously served as NUDT's deputy commandant. Even more notably, he was appointed an alternate member to the 19th CPC Central Committee, a rare distinction for a technical expert. In December 2019 Deng was transferred to the Academy of Military Science (AMS) as a member of the Standing Committee of the AMS Party Committee.[48]

Scale-Model Testing

HYPERSONIC WIND TUNNEL TESTING

China has built a series of high-speed wind tunnels that allow for better testing of hypersonic air flow, atmospheric heating, and the heat-resistant properties of materials for reentry vehicles. While early generations of supersonic wind tunnels were driven by pistons, China has focused on detonation-driven tunnels. It began research on its first detonation-driven shock-wave (i.e., supersonic) wind tunnel in 1965. It completed its first hydrogen-oxygen detonation wind tunnel [氢氧爆轰驱动高焓激波风洞], the JF10 (below), in 1998.[49]

JF10

JF12 HYPERSONIC SHOCKWAVE DUPLICATION WIND TUNNEL [复现高超声速激波风洞].

Some 265 meters long and weighing over 1,000 tons, the JF12 has been dubbed the "Hyper-Dragon" [超级巨龙] by the Chinese media. The wind tunnel is located in Beijing's Huairou district [怀柔区].[50] Work on the JF12 began in 2008; it came online for the first time in 2012. Full series testing of the wind tunnel was not completed until 2017, 16 years after initial theoretical studies began.[51]

The 2.5 meter diameter wind tunnel allows researchers at the Institute of Mechanics to replicate conditions at altitudes of 25-40 kilometers (roughly 82,000-164,000 feet) and speeds of Mach 5-10.[52] The JF12 is also significantly more capable in terms of simulating high temperatures compared to most conventional hypersonic wind tunnels, and can reach temperatures of up to 3,500K, compared to the more typical 1,000K.[53] Most importantly, the JF12 can reportedly maintain these conditions for test times of over 100 milliseconds.[54]

Jointly supported by the Ministry of Finance and the Chinese Academy of Sciences, the wind tunnel is a key component of the Hypersonic Flight Vehicle S&T Project, one of eight major R&D projects under the National Medium- and Long-Term Science and Technology Development Plan for 2006–2020.[55] According to the Hong Kong-based *Wen Wei Po* [文汇报] newspaper (considered Beijing's quasi-official mouthpiece in Hong Kong), construction of the wind tunnel supposedly cost RMB46 million (roughly U.S.D $6.6 million).[56]

According to Jiang Zonglin (profiled above), the Chinese physicist who headed the JF12 project, the JF12's greater capabilities compared to American wind tunnels means that it "can examine many, many issues that [the U.S. side] has not discovered yet."[57]

State television coverage of the JF12 showed what appeared to be a reentry vehicle being hoisted into the wind tunnel [left], and a test vehicle that resembles some HGV models believed to be under development in China (below).[58] Notably, a team led by Jiang is apparently already at work on an even more advanced wind tunnel, the JF22, which will be capable of Mach 7-30.[59]

It is worth noting that while much of the media coverage has focused on the JF12, a national showpiece located minutes from downtown Beijing, foreign intelligence analysts have identified another major wind-tunnel facility in Mianyang, Sichuan Province [四川省绵阳市], using commercial satellite imagery. Located some 900 miles from Beijing in the mountains of southwestern China, Mianyang is a major bastion of China's Third Line military-industrial complex and home to the China Academy of Engineering Physics, the primary R&D and production center of the Chinese nuclear weapons program. The Mianyang wind-tunnel facility occupies roughly 660 acres

and is described as the largest wind-tunnel testing facility in the world, boasting at least eight "world-class" wind tunnels that can simulate speeds from transonic to Mach 24.[60] Some foreign analysts regard the facility as the likely location of China's scramjet engine hypersonic wind tunnel tests.[61]

FLUTTER TESTING

In addition to aerodynamic modeling, another application for wind tunnels is vibration testing, which is meant to help engineers overcome problems of aeroelastic flutter – high frequency vibrations encountered in hypersonic

flight. In March 2014, the China Academy of Aerospace Dynamics [中国航天空气动力技术研究院][ii] carried out China's first hypersonic flutter test at the FD-07 wind tunnel (above).[62] The FD-07 wind tunnel is a ram-type tunnel used to test continuously changing altitude and Mach numbers between Mach 4.5 and 8.0.[63] According to a release by the State Administration for Science, Technology and Industry for National Defense (SASTIND), the test filled an important technological gap for China.[64]

ii Also known as the CASC 11th Academy [中国航天科技集团公司十一院] 1st research institute [1所]

DROP TESTING

Short of live fire tests, dropping mock-up gliders and reentry vehicles offers a chance to collect data on atmospheric performance under naturalistic conditions. China apparently conducts high-altitude drop testing using weather balloons. In 2018, the Institute of Mechanics carried out a drop test of three HGV models at the Jiuquan Satellite Launch Center [酒泉卫星发射中心].[65] Stills from a video posted on the Chinese social media platform Douyin [抖音] in 2018 show four glider vehicle shapes being lofted. Three of the glide vehicles appeared

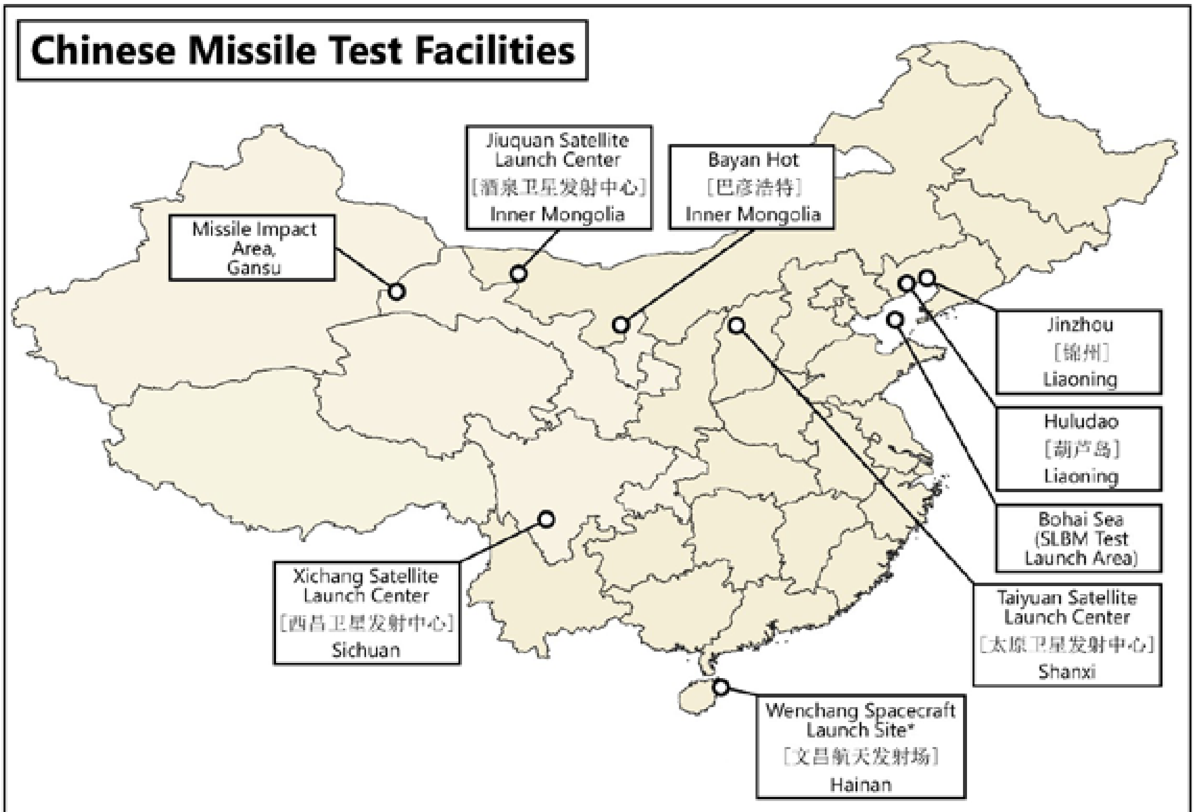
to be the D18-1S, D18-2S and D18-3S – three competing designs of boost glide vehicles known to be under development in China. According to Chinese media, this was the first variable speed drop test, an important part of developing highly-maneuverable precision strike vehicles.[66]

Flight Testing

After a design has been refined through computer modeling and wind tunnel testing, flight testing begins. While the Chinese government only offers limited information about these tests, a combination of official media and analysis of commercial satellite imagery provides some insights.

Most military-related missile and rocket testing appears to be concentrated at the Jiuquan Satellite Launch center [酒泉卫星发射中心]. This base was set up in 1959 and initially called the "Northwest Combined Guided Missile Test Base [西北综合导弹试验基地]. A missile impact area in western Gansu province has been discovered through the analysis of commercial satellite imagery and appears to include mockups of naval facilities, and airstrips. Other parts of the test range appear to be intended to test the guidance systems aboard missiles, including a digital scene matching area correlator (DSMAC).[iii] China has conducted at least 13 flight tests of hypersonic weapon systems since 2014 which appear to be under at least two programs.

iii The one in Gansu for example, is almost 2 kilometers long and was completed over the course of 2005. Ref: 40.451788°, 93.743703°



Data via Sean O'Connor, "PLA Second Artillery Corps, "Air Power Australia, 2009. Google Earth, Chinese media
*: Wenchang is still under development but believed to be intended for testing of civilian rockets only.

Table 1: Chinese Hypersonic Program Test Flights

Date	Characteristics
9 January 2014	First test of DF-ZF hypersonic glide vehicle (HGV) – 1,750km range; test successful
7 August 2014	HGV test – crashed[67]; 1,750 km intended range
2 December 2014	HGV test; test successful
7 June 2015	HGV test; test successful
19 August 2015	HGV test – 2,100 km range; test successful[68]
23 November 2015	HGV test – 1,250 km range; test successful
December 2015	Successful scramjet test reaching an altitude of 30 km and a speed of Mach 7[69]
22 April 2016[70]	HGV test – missile flew 1,250 km; test successful
1 November 2017[71]	Believed to be test of the DF-17, 1,400 km hypersonic glide vehicle. 11 minute flight time with the HGV flying at a depressed altitude of around 60 km following the completion of the DF-17's ballistic and reentry phases.
15 November 2017[72]	
March 2018	HGV test, reached Mach 5-10
3 August 2018	First test of Starry Sky-2 waverider – believed to be powered by a scramjet. Reached speeds above Mach 5.5[73]

Sources: *Jamestown China Brief*[74]; *Washington Free Beacon*; China Aerospace Studies Institute; *The Diplomat*

Section 4: Hypersonic Weapon Systems under Development in China

The emergence of hypersonic weapons can give those who possess them capabilities with potentially disruptive strategic consequences. While the value and implications of hypersonic weapons are still being debated among American strategic analysts, the PRC leadership has apparently arrived at the conclusion that they represent a sufficient game-changer in the global strategic balance to demand a national program, described by some U.S. analysts as "a kind of [Chinese] Manhattan Project", justifying up to hundreds of billions [of dollars] in investments.[75] As one Chinese AMS strategic analyst asserted in an editorial for the PLA Daily, "just as the emergence of aircraft rendered 2-dimensional defensive systems obsolete, and the emergence of stealth aircraft shattered traditional air defense systems, hypersonic weapons… will completely overturn the balance of the existing offensive and defensive systems of confrontation. The party with hypersonic weapons will establish a new supremacy [绝对优势] in asymmetric warfare and nullify existing traditional air defense and antimissile defense systems." As a result, "the strategic balance will tilt quickly toward the side with hypersonic weapons."[76]

At present, there are two major categories of hypersonic weapons under active development: "boost-glide" vehicles, and air-breathing vehicles. (Although rocket-powered hypersonic aircraft and cruise missiles are possible in theory, they are not considered efficient for practical applications at this point.) Boost-glide systems involve an aerodynamic "wave-rider" flight vehicle designed to glide on the shockwaves generated by the vehicle itself, which is mounted on a booster rocket and accelerated to hypersonic speed. The vehicle then detaches from booster and is propelled toward its target by inertia, gradually bleeding off energy as it flies. Air-breathing vehicles, in contrast, are propelled by an onboard supersonic combustion ramjet, i.e. scramjet, after being accelerated to hypersonic speed by a booster rocket and detaching. While boost-glide vehicles are simpler, lighter, smaller, and harder to detect, scramjet vehicles are capable of powered-flight and boast superior range and maneuverability. While both types of supersonic flight vehicles are under development in China, available data suggests that there have been far many more boost-glide tests than scramjet tests to date.

Boost-Glide Vehicles

China conducted its first known flight test of a hypersonic glide vehicle, the DF-ZF (also known by its early U.S. DoD designation, the WU-14), on 9 January 2014. Although the test, which was deemed successful, was confirmed by the Chinese Defense Ministry days later, at the time Beijing insisted that the test was purely "scientific" and should not be perceived as a threat against any country or "any specific target". Nevertheless, the January 2014 first flight was followed by a remarkably energetic testing regimen, with at least seven more test flights reported over the next 28 months. (See Table 1.) The first semi-official confirmation of the existence of a hypersonic tactical missile program appeared soon after: In November 2017, Zhu Xuejun [祝学军], a tactical missile designer at the China Academy of Launch Vehicle Technology [中国航天科技集团公司第一研究院], appeared on a list of nominees for the 12th Guanghua Science and Technology Prize [第十二届光华工程科技奖].[77] Her nomination form for the prize was available for public viewing for a brief period that month, and was subsequently circulated on Chinese social media. Among her achievements listed on the nomination form, Zhu was identified as the chief designer who proposed and designed China's first boost-glide tactical missile system in 2009.[78]

Hypersonic wave rider model displayed at the Beijing Military Museum

After at least nine known flight tests between 2014 and 2018, the new system appeared to have become operational by the second half of 2019, when the HGV-tipped DF-17 tactical MRBM was officially "unveiled" at the National Day military parade on 1 October 2019. The DF-17 is a solid-fueled road-mobile missile, which employs the same rocket booster from the already operational DF-16B short-range ballistic missile, but designed specifically to carry the DF-ZF hypersonic boost-glide re-entry vehicle. The DF-17 is believed to be the first HGV-equipped tactical ballistic missile in operational deployment.[79]

In January 2019, Chinese state television showed the first publicized launch of the DF-26, China's newest (and first) conventionally-armed intermediate-range ballistic missile capable of reaching Guam.[80] Notably, the video footage appears to show an HGV re-entry vehicle mounted on top of the DF-26 missile. In June 2019, CASC released a CGI video showing a notional strike by hypersonic glide vehicles against hardened enemy command centers. While of limited intelligence value, the depiction of a solid-fueled TEL-borne missile and its use against high-priority targets is largely consistent with the general understanding of the purpose of these weapons.[81]

State television footage of DF-26 test launch

CGI model of DF-17 hypersonic re-entry vehicle

Hypersonic Scramjets

For air-breathing engines, that is, those without onboard solid fuel or liquid oxygen, turbine engines (turbojets, turbofans, and turboprops) are typically used at speeds below Mach 3, and ramjet engines are needed for speeds between Mach 3 and Mach 5. Scramjets are typically needed to operate at speeds beyond Mach 5.

Scramjets have been tested aboard aircraft, and the technology would be a core part of China's Project Tengyun aerospace plane program [腾云工程],[82] which envisions a fully reusable aerospace vehicle, based on a two-stage-to-orbit and horizontal take-off, horizontal landing design. The first stage of the vehicle is to be a carrier aircraft powered by combined cycle turboscramjet engines, which would launch the more conventional rocket-powered second stage vehicle into space. Both stages are to be reusable and would return to earth by horizontal landing. China hopes to conduct the first flight of the system by 2030.[83] Notably, in 2015 Chinese researchers test-flew an unspecified "hypersonic experimental aircraft" [高超音速验证机], said to have a top speed exceeding that of the SR-71 Blackbird.[84] Some Chinese media observers believe that the experimental craft is a testbed for a new combined cycle engine, described as a type of turboramjet. If the experimental craft had indeed reached hypersonic speeds as reported, then the engine would have been a turboscramjet, likely connected to the Tengyun project.

Another hypersonic flight vehicle that appears to employ a scramjet is the Starry Sky 2, being developed by the China Academy of Aerospace Aerodynamics (中国航天空气动力技术研究院). The vehicle is said to have been in development for 3+ years. According to an August 2018 news report, the vehicle engaged its onboard engine at an altitude of 30,000 meters during a recent flight test, reaching Mach 5.5-6, and flew for more than 400 seconds and more than 1,000 kilometers.[85]

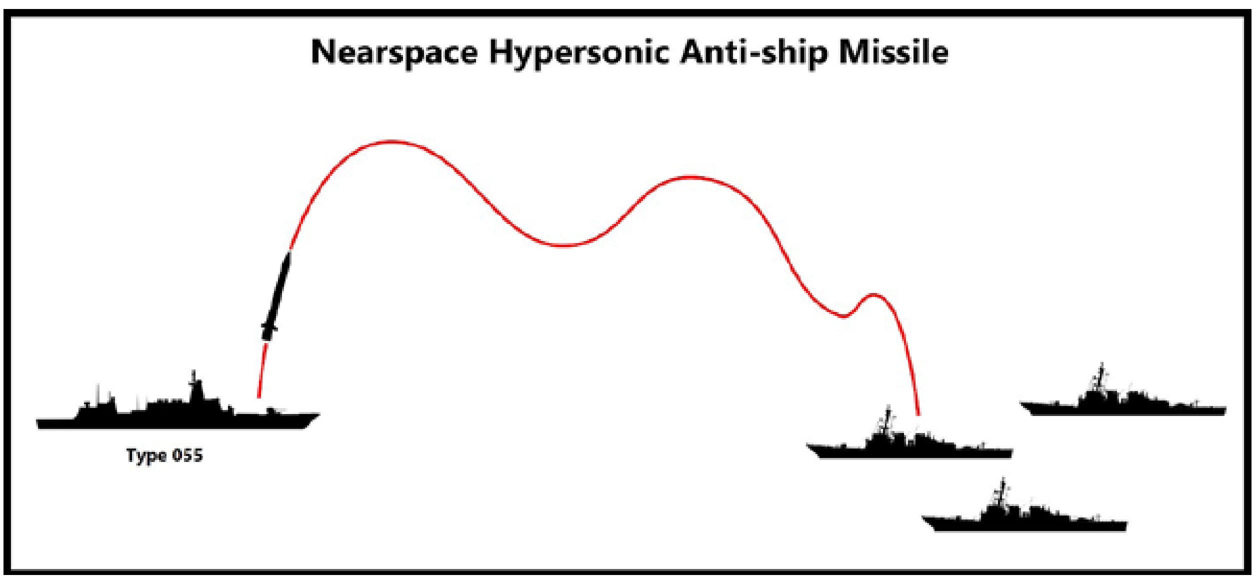
Cooling Systems for Scramjet Vehicles

Given the tremendous heat buildup on the leading edges of hypersonic flight vehicles caused by atmospheric friction, cooling is a major issue for all hypersonic flight vehicles, but a particularly daunting one for air-breathing scramjet-powered designs. Regenerative cooling, that is circulating fuel through areas which generate high heat to assist with cooling, has existed as a concept since at least 1903. While the concept has been successfully applied to rocket engines, where it reduces thermal loading on combustion chambers, the cooling of air-breathing hypersonic vehicles presents a higher level of difficulty due to the complex aerodynamic shape of these vehicles and the greater complexity of scramjet engines. Chinese researchers, including the NUDT's Wang Zhenguo profiled in an earlier section, have taken on these challenges in applying regenerative cooling techniques to scramjet vehicles. Much of the Chinese efforts in this area have been devoted to identifying alternative formulations of aviation fuel with superior heat transfer characteristics.

While regenerative cooling appears to be the major direction of research in this area, other approaches, such as more traditional water-based transpiration cooling solutions, have received attention as well. For example, in 2017 Nanjing University of Aeronautics and Astronautics was granted a patent for a "super-combustion ramjet water cooling device," which offers "the ability to generate auxiliary thrust, greater structural simplicity, and greater safety" according to the system's designers.

Anti-ship Systems

One of the most frequently discussed applications for hypersonic weapons is as anti-ship weapons. Since the 1980s, China has been developing a suite of ballistic missiles for intended use against U.S. aircraft carriers and other major surface combatants, such as the DF-21D Anti-Ship Ballistic Missile (ASBM). Notably, a photograph taken of a slide from a presentation by a PLA Navy rear admiral on "Naval Missions and Tasks and the Development of Naval Weaponry" (海军使命任务与海军武器装备建设) depicts the launch of what appears to be a hypersonic glide vehicle from a surface warship, as well as the missile's flight path to its target. See image below.



Although traditional anti-ship cruise missiles such as the American Harpoon series and the French Exocet series have proven to be very effective since their introduction in the 1970s, as naval defense systems have advanced and proliferated, these decades-old designs are now approaching obsolescence. Faced with an array of increasingly effective anti-missile countermeasures, China likely sees a combination of maneuverable ballistic missiles and hypersonic cruise missiles as necessary to overcome ships' defensive systems. The intensified development of hypersonic technologies should therefore be seen as complementary to the development of ASBM technology.

Section 5: Conclusion

Some caution is necessary in estimating the capabilities and intended purposes of China's hypersonics R&D. During the Cold War, for example, the Soviet Union vastly overestimated the utility and end-uses of a number of U.S. S&T programs, including the Space Shuttle program, which they believed to be a sort of spaceborne bomber program. Nonetheless, Chinese scientists and engineers have clearly made real progress in both the theoretical and the practical aspects of hypersonic system development. Given the large number of flight tests, open source information would appear to indicate that at least some parts of China's hypersonic weapons programs have reached a stage of development likely to fall between levels six and eight on the DOD's Technology Readiness Level (TRL) scale.

In particular, based on the DF-17 and DF-ZF displayed at the National Day parade in 2019, China apparently now has an operational medium-range boost-glide vehicle capability. The footage of a test of a DF-26 fitted with an HGV, moreover, suggests that China will also soon have an intermediate-range boost-glide vehicle capability, if it does not already.

Since China was previously believed to already have maneuverable reentry vehicles and an anti-ship ballistic missile capability for missiles of both of these ranges, the main additional capability provided by boost-glide vehicles is an improved ability to evade missile defenses. A ballistic missile with a maneuverable reentry vehicle follows a ballistic trajectory for much of its flight path, during which it is subject to intercept by traditional ballistic missile defense systems. An HGV, by contrast, follows a much less predictable trajectory and has the capability to execute high-G maneuvers during its terminal phase, making it much more difficult to intercept. Thus, the advent of boost-glide vehicles will likely cause the challenge of defending ships and fixed targets from Chinese missile attack to be significantly more difficult than previously.

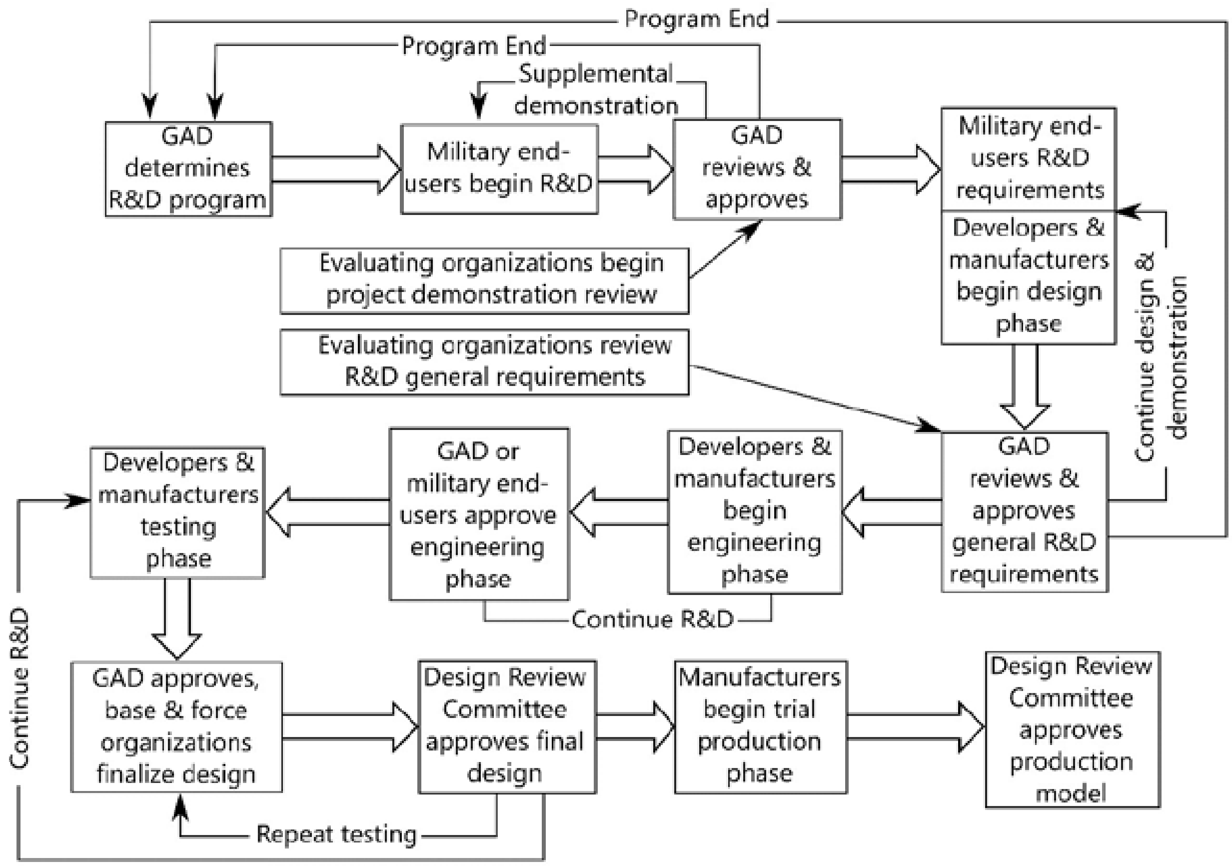
Scramjet technology in China appears to be less mature than boost-glide vehicle technology. Scramjet-powered missiles are likely to be more compact than boost-glide vehicles and thus more readily launched from aircraft or ships, as opposed to transport-erector-launcher (TEL) vehicles. Scramjets (or combined-cycle engines that include a scramjet phase) are also likely to be the propulsion system for reusable hypersonic vehicles, either manned aircraft or unmanned aerial vehicles, if these are fielded in the future.

China's hypersonic technology development efforts have been highly secretive. Nonetheless, it is clear that Chinese military and civilian leaders see hypersonics as potentially having a transformative effect on warfare. In addition, the development of hypersonic technology has not been an area of emphasis in the United States until recently. Chinese strategists likely see this as an area of military technology in which China can achieve parity or even potentially surpass the United States. As a result, China has been devoting significant effort into this area and further advances are likely to emerge in the future.

Appendix A:
The R&D Process in China

A 2010 book published by the National Defense Industry Press included a chart showing the Conventional Weapons Development Process, which is translated below. The General Armaments Department (GAD) [中国人民解放军总装备部] was replaced by the Central Military Commission Equipment Development Department (EDD) [中央军委装备发展部] in January 2016, so this figure may no longer be accurate.

Conventional Weapons Development Process



Appendix B: Technology Readiness Levels

Source: Army.mil [Accessed July 2019], https://www.army.mil/e2/c/downloads/404585.pdf

Technology Readiness Level		Description
1	Basic principles observed and reported	Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Appendix C: Glossary

Computational Fluid Dynamics (CFD)	计算流体力学
Ballistic Missile Defense	弹道导弹防御
Boost-glide missile	助推滑翔导弹
Flight Test	飞行试验
G-force	G力
Hypersonic	高超声速/ 高超音速
Hypersonic Glide Vehicle	高超音速滑翔载具
Metal matrix composite	金属基复合材料
Prompt Global Strike	全球即时打击计划
Spaceplane	太空飞机 /空天飞机
Silicon carbide	碳化硅
Titanium aluminide	钛铝
Waverider	乘波体
Supersonic Combustion Ramjet (Scramjet)	超声速燃烧冲压发动机(超燃发动机) / 超音速冲压喷射装置
Vibration test	颤振试验
Wind tunnel	风洞

Bibliography

Acton, James. "Hypersonic Boost-Glide Weapons," Science & Global Security, 23:191–219, 2015. http://scienceandglobalsecurity.org/archive/sgs23acton.pdf

Acton, James. "Silver Bullet?" Carnegie Endowment for International Peace, 2013. http://carnegieendowment.org/files/cpgs.pdf.

Cheung, Tai Ming and Thomas G. Mahnken, eds. The Gathering Pacific Storm: Emerging U.S.-China Strategic Competition in Defense Technological and Industrial Development, Cambria Press, 2018.

Cheung, Tai Ming. Fortifying China: The Struggle to Build a Modern Defense Economy. Ithaca: Cornell University Press, 2013.

Erickson, Andrew. "Chinese Anti-Ship Ballistic Missile (ASBM) Development: Drivers, Trajectories and Strategic Implications," Jamestown Foundation, May 2013.

Feigenbaum, Evan. China's Techno-Warriors: National Security and Strategic Competition from the Nuclear Age to the Information Age, Stanford: Stanford University Press, 2003.

Gormley, Dennis M., Andrew S. Erickson, and Jingdong Yuan. A Low-Visibility Force Multiplier: Assessing China's Cruise Missile Ambitions, National Defense University Press, Washington, D.C., 2014

"Hypersonic Weapons — A Challenge and Opportunity for Strategic Arms Control," UN office for Disarmament Affairs, and UN Institute for Disarmament Research, 2019. https://s3.amazonaws.com/unoda-web/wp-content/uploads/2019/02/hypersonic-weapons-study.pdf

Lewis, John W. and Xue Litai. China's Strategic Seapower: The Politics of Force Modernization in the Nuclear Age, Stanford University Press, 1995.

Lewis, John W. and Xue Litai. China Builds the Bomb, Stanford University Press, 1988.

MacDonald, Bruce W. and Charles D. Ferguson. "Understanding the Dragon Shield: Likelihood and Implications of Chinese Strategic Ballistic Missile Defense," FAS, September 2015. https://fas.org/wp-content/uploads/2015/09/DragonShieldreport_FINAL.pdf

Makienko, Konstantin, Mikhail Barabanov, Vasily Kashin, and Ivan Khokotova (translator). Shooting Star: China's Military Machine in the 21st Century, East View Press, March 15, 2012.

Molenda, Jenevieve. "China Conducts Tests of Hypersonic Boost Glide Vehicles," Missile Threat, Center for Strategic and International Studies, October 1, 2018. https://missilethreat.csis.org/china-conducts-tests-of-hypersonic-boost-glide-vehicles-from-high-altitude-balloon/.

Nurkin, Tate, Kelly Bedard, James Clad, Cameron Scott, and Jon Grevatt. "China's Advanced Weapons Systems," U.S.CC, 12 May 2018. https://www.uscc.gov/sites/default/files/Erickson_Testimony.pdf

Podvig, Pavel and Hui Zhang. Russian and Chinese Responses to U.S. Military Plans in Space, American Academy of Arts and Sciences, 2008. https://www.belfercenter.org/sites/default/files/files/publication/militarySpace.pdf.

Saalman, Lora. "Prompt Global Strike: China and the Spear," APCSS, 2014. https://apcss.org/wp-content/uploads/2014/04/APCSS_Saalman_PGS_China_Apr2014.pdf

Saalman, Lora. "China's Calculus on Hypersonic Glide," Stockholm International Peace Research Institute, 15 August 2017, https://www.sipri.org/commentary/topical-backgrounder/2017/chinas-calculus-hypersonic-glide

Stokes, Mark. "China's Evolving Space and Missile Industry - Seeking Innovation in Long-Range Precision Strike," in Cheung, Tai Ming, ed. Forging China's Military Might – A New Framework For Assessing Innovation. Baltimore: Johns Hopkins University Press, 2014.

Zhao, Tong. "Conventional Counterforce Strike: An Option for Damage Limitation in Conflicts with Nuclear-Armed Adversaries?" Science and Global Security 19, no. 3 (2011): 195–222, http://scienceandglobalsecurity.org/archive/sgs19tongzhao.pdf.

Zhao, Tong. "Perception Gap in the THAAD Dispute – Causes and Solutions", China International Strategy Review, 22 November, 2018. https://carnegieendowment.org/files/Perception_Gap_in_the_THAAD_Dispute.pdf.

Zhao Xijun [赵锡君], "慑战--导弹威慑纵横谈," 国防大学出版社, 2003.

Endnotes

1 Hypersonic propulsion technology,” (中国人民解放军军语), 中国人民解放军军事科学院, 2011, p. 588.

2 An enormous number of declassified translations of Soviet scientific studies on hypersonic flight are available on the CIA Records Search Tool (CREST) website. These materials give an insight into the early stages of research on the topic outside the United States. Examples include “Aerodynamic Features Of Hypersonic Speeds,” 2 September 1958. *Herald of the Air Fleet*, No. 11, 1957. https://www.cia.gov/library/readingroom/docs/CIA-RDP81-01043R002600130024-9.pdf; An excellent overview of the Soviet’s progress through 1990 is “Soviet Hypersonics R&D: Applications to Civil and Military Aviation,” September 1990. https://www.cia.gov/library/readingroom/docs/DOC_0000498793.pdf

3 “Development Goals For The 1970 - 1980 Era,” CREST, 24 May 1965, Declassified 3 September 2003. https://www.cia.gov/library/readingroom/docs/CIA-RDP71B00822R000100110006-0.pdf

4 “Proposed Boost Glide Device,” CREST, 6 March 1965, Declassified 1 March 2002. https://www.cia.gov/library/readingroom/docs/CIA-RDP33-02415A000500190012-2.pdf

5 “空天利器——高超声速飞行器,” (科学世界), 4 September 2014. http://www.cannews.com.cn/2014/0904/104328.shtml

6 “DF-1”, GlobalSecurity.org. https://www.globalsecurity.org/wmd/world/china/df-1.htm

7 Japan had planned to purchase two units of a fourth system, the Aegis Ashore, before cancelling the order in June 2020 due to local opposition and cost concerns.

8 “U.S. expert says THAAD can’t distinguish between real and decoy warheads,” Hankyoreh, 4 October 2016. http://english.hani.co.kr/arti/english_edition/e_international/764068.html

9 Zhao Tong, “Perception Gap in the THAAD Dispute – Causes and Solutions”, China International Strategy Review, 22 November, 2018. https://carnegieendowment.org/files/Perception_Gap_in_the_THAAD_Dispute.pdf

10 “Hyten: To address Russian and Chinese missile threats, it’s all about the sensors,” *Defense News*, 7 August 2018. https://www.defensenews.com/digital-show-dailies/smd/2018/08/07/hyten-to-address-russian-and-chinese-missile-threats-its-all-about-the-sensors/

11 Jen Judson, “U.S. installs final ground-based missile interceptor to counter ICBM threat,” *DefenseNews*, https://www.defensenews.com/land/2017/11/07/final-ground-based-missile-defense-interceptor-in-place-at-fort-greely/, November 7, 2017.

12 “Where Would India Fit in a Missile Defense Partnership in the Indo-Pacific?,” *The Diplomat*, 24 January 2019. https://thediplomat.com/2019/01/where-would-india-fit-in-a-missile-defense-partnership-in-the-indo-pacific/

13 “Delhi, Mumbai selected for ballistic missile defence shield” *Times of India*, 24 June 2012. http://timesofindia.indiatimes.com/articleshow/14370157.cms

14 “India’s Anti-Satellite Test Wasn’t Really About Satellites,” *Wired*, 27 March 2019. https://www.wired.com/story/india-anti-satellite-test-space-debris/

15 “«Продавать не будем»: в России начали производить С-500,” Газета.ru, 30 June 2019 https://www.gazeta.ru/army/2019/06/30/12467125.shtml?updated

16 “Объявлено о начале производства С-500,” Военно-Промышленный Курьер, 30 June 2019 https://vpk-news.ru/news/51150

17 “Конструктор раскрыл возможности С-500,” Lenta.ru, 19 June 2019 https://lenta.ru/news/2019/06/19/s500/

18 Zhao Xijun [赵锡君], (慑战--导弹威慑纵横谈), 国防大学出版社, 2003. p. 37.

19 “铸造国家安全战略支柱的海外样本.——美俄等核大国强化核威慑的主要举措及启示,”30 November 2018. http://www.81.cn/jfjbmap/content/2018-01/30/content_198321.htm. An earlier article in the PLA Daily from 2016 gave the authors Li Xianrong [李显荣] and Yang Wei [杨敏] affiliation as the China Academy of Military Science [军事科学院] “霸权逻辑下的傲慢与偏见,” *PLA Daily,* 21 November 2016

20 林旭斌, 张灿, “俄罗斯新型高超声速打击武器研究,” (战术导弹技术), No. 1. 2019; Gui Xiao [桂晓], “Composition and future development of Russia’s Missile Defense System [俄罗斯反导系统的集成与未来发展趋势]”, China Military Science [中国军事科学] May 2016, pp.128-139.

21 Michael S. Chase, Arthur Chan, China’s Evolving Approach to “Integrated Strategic Deterrence”, RAND, 2016. https://www.rand.org/pubs/research_reports/RR1366.html p.55.; Examples of use of this term can be found in media coverage of the PLARF’s establishment in January 2016. “统合作战部队 火箭军可破潜在战略封锁圈,” 大公网, 4 January 2016. http://news.takungpao.com/mainland/focus/2016-01/3262846_print.html

22 Mark Stokes “China’s Evolving Space and Missile Industry - Seeking Innovation in Long-Range Precision Strike,” in Cheung, Tai Ming, Ed. Forging China’s Military Might – A New Framework For Assessing Innovation. Baltimore: Johns Hopkins University Press, 2014. Kindle Edition. p. 241/ Loc 5093; Lumbering Forward: China’s Aviation Industry, CASI 2019. p. 27.

23 Derek Bisaccio, “Report: Russia Lacking Materials for Large-Scale Production of Hypersonic Weapon,” *Defense Security Monitor*, 2 July 2019. https://dsm.forecastinternational.com/wordpress/2019/07/02/report-russia-lacking-materials-for-large-scale-production-of-hypersonic-weapon/

24 丁春雨, 姚羽; “高超声速飞行不是梦！耐3000度材料来了”, *Xinhua News*, 21 September 2017. http://xinhua-rss.zhongguowangshi.com/13698/-3491052174416245829/2328158.html

25 "标志性成果2," Central South University, 16 March 2018. http://sklpm.csu.edu.cn/Content.aspx?moduleid=18de01b3-dc5b-4a3a-8476-09a107005828&id=807a0bed-c069-41a5-9504-c568e0b60002

26 "中南大学研发出耐3000º烧蚀的新材料," *Xinhua*, 21 August 2017. http://www.xinhuanet.com/tech/2017-08/21/c_1121519048.htm

27 "我院概况", CAAA, 22 March 2020. http://caaa-spacechina.com/n300/n306/index.html

28 "本院概况", CALT. http://calt.spacechina.com/n481/n489/index.html

29 "航天科学与工程学院", 国防科学技术大学本科招生网, 3 June 2017. http://www.gotonudt.cn/site/gfkdbkzsxxw/htkxygcxy/index.html

30 "力学研究所概况", CAS Institute of Mechanics, June 2017. http://www.imech.cas.cn/gkjj/jgjj/

31 "情况," State Key Laboratory of High-temperature Gas Dynamics , [Accessed July 2019]. http://lhd.imech.cas.cn/gk/

32 "实验室简介", SKLPM, Central South University. http://sklpm.csu.edu.cn/Content.aspx?moduleid=8cb32bef-d253-4beb-9a13-3434bd6a5a6c

33 "粉末冶金国家重点实验室", Cnpowder.com.cn, 7 January 2019. http://m.cnpowder.com.cn/new48954.html

34 "China and England Cooperate to Develop New Material that Will Help Hypersonic Aircraft [中英合作研制出有助于高超声速飞行的新材料]," *China Aviation News* [中国航空报], 27 July 2017, http://www.cannews.com.cn/2017/0727/165677.shtml

35 "Hot Spot Focus | Complete Resume! What Do the 67 Academicians of Chinese Academy of Engineering Who Are Newly Elected in 2017 Do? [热点聚焦｜最全简历! 2017年新增选67名中国工程院院士都干啥!]," *Science and Technology Daily* [中国科技网], 28 November 2017, http://www.stdaily.com/kjzc/jiedu/2017-11/28/content_601108.shtml.

36 "Newly Elected Academicians from National University of Defense Technology [国防科大新入选院士]," Military Institute of Engineering (Harbin Engineering University) Beijing Alumni Association [军事工程学院 (哈军工) 北京校友会], 3 January 2018, http://www.hjgbj.com/a/muxiaoxinxi/305.html; "Wang Zhenguo, Department of Mechanical and Transportation Science, Hall of Academicians, Chinese Academy of Engineering [中国工程院院士馆机械与运载工程学部• 王振国]," Chinese Academy of Engineering Exhibition Hall Website [中国工程院院士馆], Accessed on 4 June 2018, http://ysg.ckcest.cn/html/details/8026/baseInfo/grxx_jbxx/default.html.

37 "WANG Zhenguo, Department of Mechanical and Transportation Science, Hall of Academicians, Chinese Academy of Engineering [中国工程院院士馆机械与运载工程学部•王振国]," Chinese Academy of Engineering Exhibition Hall Website [中国工程院院士馆], Accessed on 4 June 2018, http://ysg.ckcest.cn/html/details/8026/baseInfo/grxx_jbxx/default.html.

38 "WANG Zhenguo, Department of Mechanical and Transportation Science, Hall of Academicians, Chinese Academy of Engineering [中国工程院院士馆机械与运载工程学部• 王振国]," Chinese Academy of Engineering Exhibition Hall Wesbite [中国工程院院士馆], Accessed on 4 June 2018, http://ysg.ckcest.cn/html/details/8026/baseInfo/grxx_jbxx/default.html.

39 "Bravo! China Has Independently Achieved Scramjet Hypersonic Vehicle Flight [很牛! 我国实现超燃冲动力高超声速飞行器自主飞行]," *Xinhua* [新华网], 9 October 2015, http://www.xinhuanet.com/science/2015-10/09/c_134697451.htm.

40 "姜宗林", University of Chinese Academy of Sciences [中国科学院大学] Website, Accessed July 2019. http://people.ucas.ac.cn/~0003153

41 "高超巨龙 惊艳出世 — 记获得国家技术发明奖二等奖的复现风洞团队," *S&T Daily*, 10 January 2017. http://digitalpaper.stdaily.com/http_www.kjrb.com/kjrb/html/2017-01/10/content_359517.htm?div=2

42 "Final Program," AIAA.org, 2016. https://www.aiaa.org/docs/default-source/uploadedfiles/aiaa-aviation-forum/2016-aviation-final-program.pdf?sfvrsn=6c26f880_0. p.21; "Research Group of the Shock Tunnel of Duplicating Hypersonic Flight Conditions; "Institute of Mechanics, Chinese Academy of Sciences," Chinese Academy of Sciences, January 2017. http://www.cas.cn/zt/hyzt/2017gzhy/jckjcjj/201701/P020170113405471583862.pdf

43 "China and England Cooperate to Develop New Material that Will Help Hypersonic Aircraft [中英合作研制出有助于高超声速飞行的新材料]," *China Aviation News* [中国航空报], 27 July 2017, http://www.cannews.com.cn/2017/0727/165677.shtml

44 The Henry Royce Institute is the UK's national institute for advanced materials research and innovation. It is a partnership of nine UK universities and other research organizations, set up as a hub-and-spoke collaborative venture between the University of Manchester (the hub), Culham Centre for Fusion Energy, Imperial College London, National Nuclear Laboratory, University of Cambridge, University of Leeds, University of Liverpool, University of Oxford and the University of Sheffield "The UK National Institute for Advanced Materials Research and Innovation." https://www.royce.ac.uk/

45 Alex Joske, "Picking flowers, making honey - The Chinese military's collaboration with Foreign Universities," 30 October 2018. p.13. https://s3-ap-southeast-2.amazonaws.com/ad-aspi/2018-10/Picking%20flowers%2C%20making%20honey_0.pdf?H5sGNaWXqMgTG_2F2yZTQwDw6OyNfH.u

46 "国防科大校长已调整, 中候补邓小刚卸任," *The Beijing News*, 19 December 2019. http://www.bjnews.com.cn/feature/2019/12/19/664112.html

47 "JF-10氢氧爆轰驱动高焓激波风洞," State Key Laboratory of High-temperature Gas Dynamics website, 23 July 2013. http://lhd.imech.cas.cn/kyzb/201307/t20130723_116736.html

48 "开启我国大型气动实验装备建设由仿制到创新研制新纪元—JF12复现高超声速飞行条件激波风洞研制成功," *S&T Daily*, 3 September 2012. http://css.stdaily.com/special/content/2012-09/03/content_514157.htm

49 "从模拟到复现 中国将建 '超级风洞'," *S&T Daily*, 22 March 2018. http://digitalpaper.stdaily.com/http_www.kjrb.com/kjrb/html/2018-03/22/content_390914.htm?div=-1

50 "Research Group of the Shock Tunnel of Duplicating Hypersonic Flight Conditions Institute of Mechanics, Chinese Academy of Sciences," Chinese Academy of Sciences, January 2017. http://www.cas.cn/zt/hyzt/2017gzhy/jckjcjj/201701/P020170113405471583862.pdf; "[*China News Daily*] 20171121," CCTV-4, 21 November 2017 https://www.youtube.com/watch?v=I95dBapkZ08

51 "复现高超声速飞行条件激波风洞JF12喜获奖励", Institute of Mechanics, Chinese Academy of Science, 20 February 2017. http://lxyd.imech.ac.cn/info/detail.asp?infono=21373

52 [*China News Daily*] 20171121," CCTV-4, 21 November 2017 https://www.youtube.com/watch?v=I95dBapkZ08

53 "开启我国大型气动实验装备建设由仿制到创新研制新纪元—JF12复现高超声速飞行条件激波风洞研制成功," *S&T Daily*, 3 September 2012. http://css.stdaily.com/special/content/2012-09/03/content_514157.htm

54 "中国独创九倍音速风洞," *Wen Wei Po*, 11 June 2016. http://news.takungpao.com/paper/q/2016/0611/3331695_wap.html.

55 [*China News Daily*] 20171121 | *CCTV-4*, 21 November 2017 https://www.youtube.com/watch?v=I95dBapkZ08

56 "(朝闻天下) 20180317 06:00," *CCTV*, 17 March 2018. http://tv.cctv.com/2018/03/17/VIDEwEPyyROzlDQhD0u3dCGL180317.shtml

57 "中国超高速激波风洞项目启动 最高速度达10公里/秒," *Reference News* [参考消息], 17 April 2018. http://mil.news.sina.com.cn/china/2018-04-17/doc-ifzihnep0105433.shtml

58 "绵阳风洞群——亚洲最大的航空风洞试验中心", 民族复兴网 , 6 September 2018. http://www.mzfxw.com/e/action/ShowInfo.php?classid=18&id=107673

59 Indian Army Col. Vinayak Bhat (Ret.), a satellite imagery specialist, has identified a facility he believes to be a hypersonic wind tunnel testing facility in Mianyang, Sichuan "And Now, the 1st Detailed Look At China's Secretive Hypersonic Test Facility," *Live Fist*, April 2017. http://defense-news-alert.blogspot.com/2017/04/and-now-1st-detailed-look-at-chinas.html; Reference: Coordinates: 31.429145° 104.673074° As of 17 November 2018 extensive construction work was ongoing at the facility.

60 Also known as the CASC 11th Academy [中国航天科技集团公司十一院] 1st research institute [1所]

61 "中国攻克高超声速飞行难题 破国外60多年垄断," *People's Daily Online*, 16 March 2014. http://politics.people.com.cn/n/2014/0316/c70731-24647937.html

62 季辰, 刘子强, 李锋, "钝前缘梯形翼高超声速风洞颤振试验 (Hypersonic Wind Tunnel Flutter Test for a Blunt-Leading-Edge Delta Wing)," Physics of Gases (气体物理), 2018, Vol. 3 Issue (1): 54-63.

63 "航天高超声速颤振试验填补国内技术空白," SASTIND, 18 March 2014.http://www.sastind.gov.cn/n127/n199/c304143/content.html

64 "同时测试三种模型 中国高超音速武器研发迈大步," *Reference News* [参考消息], 1 October 2018. http://www.cankaoxiaoxi.com/mil/20181001/2334491.shtml

65 Jenevieve Molenda, "China Conducts Tests of Hypersonic Boost Glide Vehicles," *Missile Threat*, Center for Strategic and International Studies, October 1, 2018. https://missilethreat.csis.org/china-conducts-tests-of-hypersonic-boost-glide-vehicles-from-high-altitude-balloon/.

66 The one in Gansu for example, is almost 2 kilometers long and was completed over the course of 2005. Ref: 40.451788°, 93.743703°

67 Erika Solem, Karen Montague. "Chinese Hypersonic Weapons Development," *Jamestown China Brief*, 21 April 2016. https://jamestown.org/program/updated-chinese-hypersonic-weapons-development/

68 John A. Tirpak, "The Great Hypersonic Race," *Air Force Magazine*, 27 June 2018. https://www.airforcemag.com/article/the-great-hypersonic-race/

69 牛玉俊, "超声速武器如何影响战争 (How hypersonic weapons affect warfare)", *PLA Daily*, 14 February 2019. http://www.xinhuanet.com/mil/2019-02/14/c_1210059534.htm

70 "第十二届光华工程科技奖候选人推荐人选名单," China Architectural Society of China, 7 November 2017. http://www.chinaasc.org/news/117142.html

71 Raymond Wang, "Digging Into China's 'Tactical' Hypersonic Boost-Glide Vehicle Program," *The Diplomat*, 5 September 2018. https://thediplomat.com/2018/09/digging-into-chinas-tactical-hypersonic-boost-glide-vehicle-program/

72 Ankit Panda, "Introducing the DF-17: China's Newly Tested Ballistic Missile Armed with a Hypersonic Glide Vehicle", *The Diplomat*, 28 December 2017. https://thediplomat.com/2017/12/introducing-the-df-17-chinas-newly-tested-ballistic-missile-armed-with-a-hypersonic-glide-vehicle/

73 "On-Site Reporting of Live Missile Launch Training Carried Out by Unidentified PLA Rocket Force Brigade [直击火箭军某旅导弹实射训练]," *CCTV* [央视网], 23 January 2019, http://tv.cctv.com/2019/01/23/VIDEDwOlOjM6kuTIxoFTSKCR190123.shtml.

74 "First images of China's new DF 17 ballistic missile," Available at: https://www.youtube.com/watch?v=k2z3BHHEhdQ

75 "可重复使用飞行器：让你坐民航一样往返天地," *S&T Daily*, 7 June 2015. http://www.stdaily.com/kjrb/kjrbbm/2017-06/15/content_553201.shtml

76 Jean Deville, "China's Spaceplane Projects: Past, Present and Future," The China Aerospace Blog, 11 May 2020. https://china-aerospace.blog/2020/05/11/chinas-spaceplane-projects-past-present-and-future/

77 "中国新型高超音速验证机试飞成功 比'黑鸟'更快," *Observer* [观察者] 19 September 2015. http://news.sohu.com/20150919/n421569088.shtml

78 "中国首个高超音速飞行器有多厉害?," *81.cn*, 29 August 2018. http://www.81.cn/bqtd/2018-08/29/content_9266674.htm

79 章思龙, 章思龙, 周伟星 , 鲍文, "Review on Regenerative Cooling Technology of Hypersonic Propulsion [高超声速推进再生冷却研究综述]," (推进技术) *Journal of Propulsion Technology*, Vol. 39, Issue 10. October 2018. http://www.tjjs.casic.cn/html/2018/10/20181003.htm

80 E.g. Zhong F, Fan X, Yu G, et al. Heat Transfer of Aviation Kerosene at Supercritical Conditions[J]. *Journal of Thermophysics and Heat Transfer*, 2009, 23(3): 543-550. DOI:10.2514/1.41619; Chen W, Fang X. Modeling of Convective Heat Transfer of RP-3 Aviation Kerosene in Vertical Miniature Tubes under Supercritical Pressure[J]. *International Journal of Heat and Mass Transfer*, 2016, 95: 272-277. DOI:10.1016/j.ijheatmasstransfer.2015.12.018; Li X, Huai X, Cai J, et al. Convective Heat Transfer Characteristics of China RP-3 Aviation Kerosene at Supercritical Pressure[J]. *Applied Thermal Engineering*, 2011, 31(14-15): 2360-2366. DOI:10.1016/j.applthermaleng.2011.03.036

81 苏艳, 夏有财,顾晨轩,王辉, "超燃冲压发动机水冷装置: CN205955856U," Google Patent, 2017. https://patents.google.com/patent/CN205955856U/zh

82 The assessment of the location of the presentation is based on the Northwestern Polytechnical University (NPU) seal visible on the lectern. The title of the presentation appears to be: "Naval Missions and Naval Weapons and Equipment Development - Nearspace Hypersonic Anti-ship Missiles" [海军使命任务与海军武器装备建设 -临近空间超高音速反舰导弹]. https://www.sohu.com/a/333870176_725234

83 Dwayne A. Day and Robert G. Kennedy III, "Soviet Star Wars - The launch that saved the world from orbiting laser battle stations," *Air & Space*, January 2010. https://www.airspacemag.com/space/soviet-star-wars-8758185/?all

84 See Appendix 2

85 Li Li [李励], "军事装备前沿理论与改革实践," 国防工业出版社, 2010.