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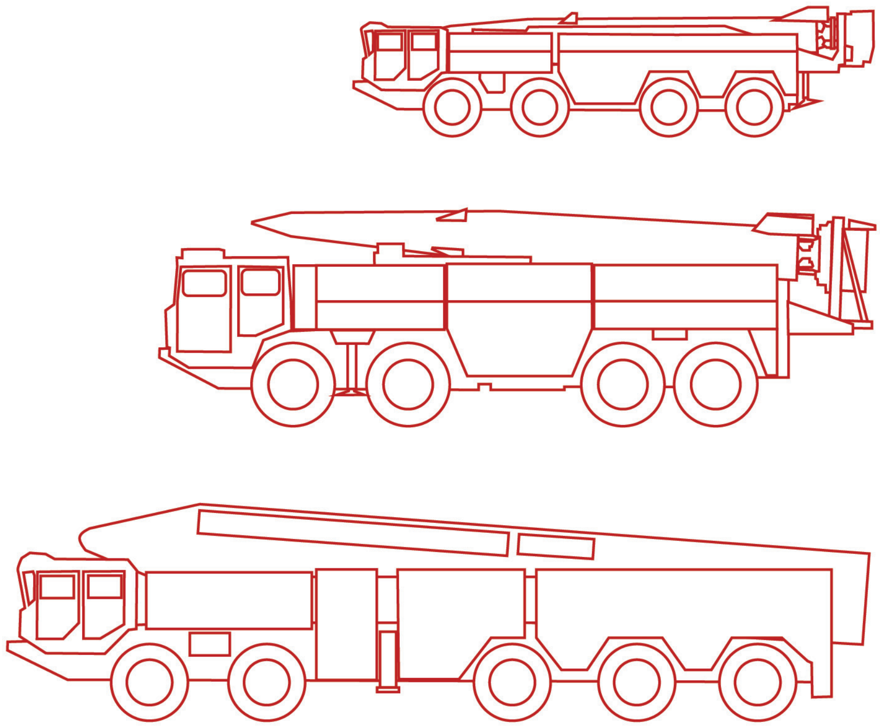
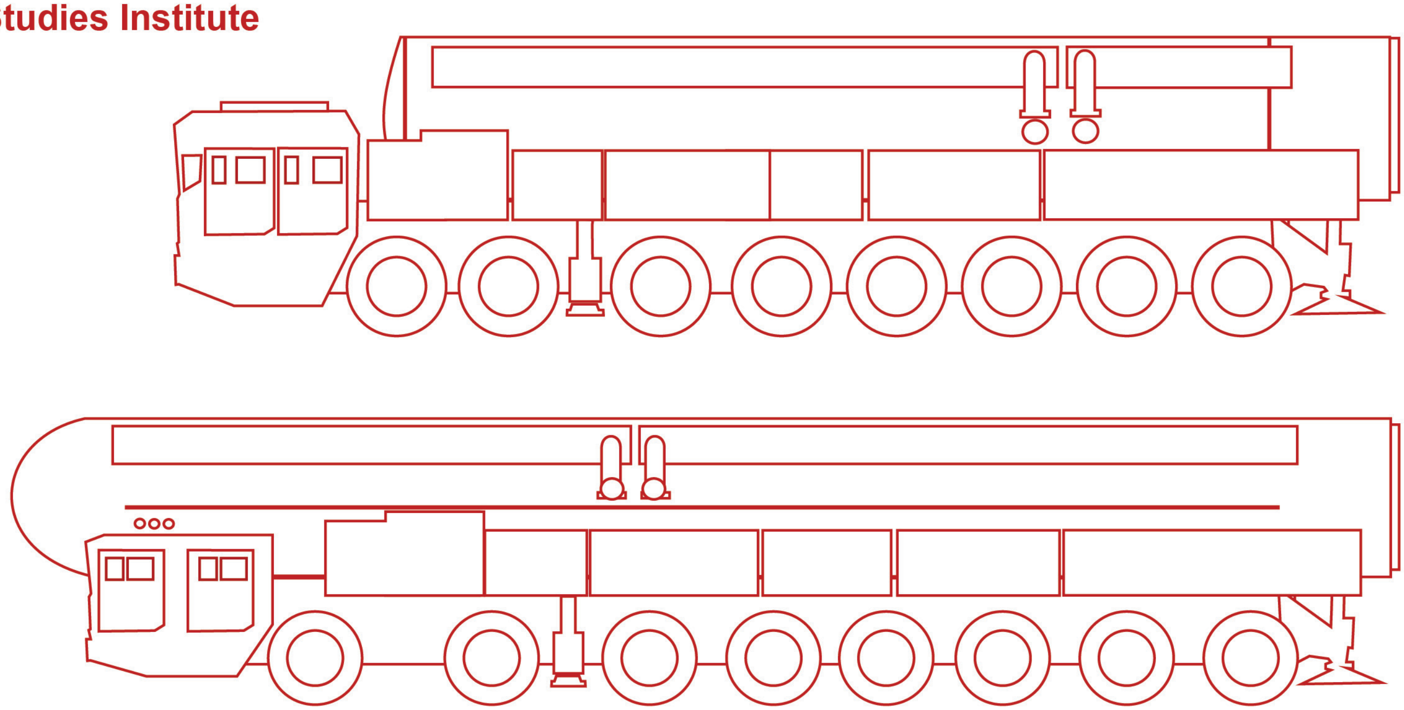
CHINA AEROSPACE STUDIES INSTITUTE

China's Ballistic Missile Industry



A BluePath Labs Report by
Peter Wood & Alex Stone
for the
China Aerospace Studies Institute



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China Aerospace Studies Institute

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Preface

Along with space and cyber, the missile forces of the Chinese Communist Party's (CCP) People's Liberation Army have seen the greatest increase in importance, and funding, over the last two decades. This progress was further emphasized when, as part of the 2015 reforms, the Second Artillery was upgraded to a full service, along with all of the bureaucratic heft that comes with that status, and was renamed the People's Liberation Army's Rocket Force, the PLARF.

While the PLA has placed a strong emphasis on its missile forces since they entered the nuclear weapons club, it was only within the last few decades that the missile forces began to come to the forefront in PLA strategic thinking. While research and development started to gain traction, as detailed in this report, it was not until the advent of the Dongfeng (East Wind) -21D, often dubbed the "Carrier Killer" in the press, in the early 2000s that the West began to realize the renewed attention that ballistic missiles were enjoying in the PLA. China continues to have the most active and diverse ballistic missile development program in the world and has drawn specific attention in the Department of Defense's 2020 China Military Power Report.

Drawing on Chinese-language sources, 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). This report describes China's ballistic missile capabilities and development. It reviews the history of the PRC's research and development of ballistic missiles and traces the institutions that are key to these systems. It details the components and systems that are integral to these weapons and describes the companies, research academies, and production facilities, that form the core of the industry in the PRC.

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

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Acronyms

AASPT	Academy of Aerospace Solid Propulsion Technology
ASBM	Anti-ship ballistic missile
AVIC	Aviation Industry Corporation of China
BS EDI	Beijing Special Engineering Design and Research Institute
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CAAA	China Academy of Aerospace Aerodynamics
CALT	China Academy of Launch Vehicle Technology
CAS	China Academy of Sciences
CASC	China Aerospace Science and Technology Corporation
CASIC	China Aerospace Science & Industry Corporation
CAST	China Academy of Space Technology
CCP	Chinese Communist Party
CMC	Central Military Commission
EDD	Equipment Development Department
FYP	Five-Year Plan
GNSS	Global navigation satellite system
ICBM	Intercontinental ballistic missile
IRBM	Intermediate-range ballistic missile
MCF	Military-Civilian Fusion
MIIT	Ministry of Industry and Information Technology
MRBM	Medium-range ballistic missile
NDU	National Defense University
PLA	People's Liberation Army
PLARF	People's Liberation Army Rocket Force
PRC	People's Republic of China
RMB	Renminbi
SASTIND	State Administration for Science, Technology, and Industry for National Defense
SRBM	Short-range Ballistic Missile
SLBM	Submarine-launched Ballistic Missile
SOE	State-owned enterprise
TEL	Transporter-Erector Launcher
TSLC	Taiyuan Satellite Launch Center
UDMH	Unsymmetrical dimethylhydrazine

Key Findings

THE INSTITUTIONAL LANDSCAPE FOR BALLISTIC MISSILE R&D HAS REMAINED LARGELY UNCHANGED SINCE ITS ESTABLISHMENT

Despite repeated cycles of breakups and consolidations, the system of academies and bases China built up between the 1950s and 1970s continue to act as the backbone of the missile R&D. Within the current CASC/CASIC defense industrial establishment, five research academies (CASC 1st Academy, CASC 4th Academy, CASC 6th Academy, CASIC 4th Academy, and CASIC 6th Academy) are the principal actors in the design, development, testing, and production of ballistic missiles, forming the "small core" of the ballistic missile industry. All five academies that make up the current ballistic missile small core trace their lineage back to the four research sub-academies created under the Fifth Academy of the Defense Ministry in the 1950s and the defense industrial bases these sub-academies set up in China's interior during the Third Front Construction movement. The core competencies of these academies are largely shaped by the role their predecessors played between the 1960s and 1980s.

FURTHER CONSOLIDATION OF THE INDUSTRY IS LIKELY

China's ballistic missile industry has already undergone repeated rounds of consolidation. A repeated theme throughout the 20 years (2000-2020) covered in this report is the effort to gain efficiency and reduce waste through consolidation of the various components of the industry. This includes not only the creation of CASC and CASIC in July 1999 but repeated rounds of consolidation of factories and research institutes dedicated to the development of key subsystems. At the same time, the outcome of the decision in 1999 to divide China's five defense corporations into ten companies is steadily being reversed in other defense sectors and CASC and CASIC have pledged to deepen strategic cooperation and all domain deep integration.

TALENT ATTRACTION AND RETENTION REMAIN SIGNIFICANT ISSUES

While the major companies involved in missile production have added almost fifty percent more workers since 2000, and R&D and production facilities have been expanded, the industry continues to have trouble attracting and retaining top talent.

CHINA HAS RAPIDLY EXPANDED ITS MANUFACTURING CAPACITY FOR MISSILES AND SPACE LAUNCH VEHICLES

Developments described in Chinese media, when combined with observations of known production sites using commercial satellite imagery indicate a significant rise in capacity. In particular, the production of solid rocket motors and rocket bodies have been increased to support a rapidly expanding space launch sector, but known facilities for missile assembly and production have also expanded.

THE COMMERCIAL LAUNCH SECTOR IS HELPING DRIVING EXPANSION AND RESEARCH

As China seeks to further leverage civilian input to boost defense R&D capabilities under initiatives such as the MCF strategy, the missile sector appears to be engaged in closer collaboration through the signing of strategic cooperation agreements with universities and the private sector at large, especially with respect to dual-use technologies and research fields such as material science and engineering. But while Chinese media highlights adoption of computer-aided design, big data analysis and artificial intelligence (AI), simulation testing, and additive manufactring, a closer examination reveals that oftentimes these developments represent long-overdue adoption of well-established practices.

Introduction

Ballistic missiles are one of the most prominent parts of China's growing arsenal of advanced weapons. CCP General Secretary Xi Jinping has described the PLA Rocket Force (PLARF) [中国解放军火箭军], primary operator of China's missile forces, as the "core force of China's strategic deterrence, the strategic support of China's status as a major power, and an important cornerstone of safeguarding national security…the Rocket Force has played an irreplaceable role in containing war threats, creating a favorable strategic posture for our country's security, and maintaining global strategic balance and stability."[1] To meet the requirements of these missions, the PLA Second Artillery (now known as the Rocket Force) has grown significantly. Forty years ago, China was only capable of fielding a small number of mostly nuclear missiles. In the 1990s new conventional systems were fielded and the development of more capable long-range systems began. Eleven missile brigades were created between 2001 and 2010. That growth has only accelerated, with the total number of brigades jumping from 29 to 40 between May 2017 and February 2020.[2]

A report from the National Aerospace Intelligence Center (NASIC) in 2017 noted "China continues to have the most active and diverse ballistic missile development program in the world. It is developing and testing offensive missiles, forming additional missile units, qualitatively upgrading missile systems, and developing methods to counter ballistic missile defenses."[3] The rate of tests remains high, with DOD's 2020 report on the PLA noting that "In 2019, the PRC launched more ballistic missiles for testing and training than the rest of the world combined."[4]

Despite the significance of these developments, and in contrast to the body of work on the Chinese defense industry more generally, there do not appear to be any recent publicly available studies dedicated to the topic of the ballistic missile industry itself. Two book chapters in volumes by RAND and edited by Tai Ming Cheung, respectively, provided snapshots of China's ballistic missile industry in the context of the broader missile research and development (R&D) ecosystem.[i] The latter chapter by Mark Stokes, as well as his prior work on the topic, provided greater detail on specific institutions engaged in ballistic missile development. Studies of Chinese strategic weapons programs by Evan Feigenbaum and John Lewis with Xue Litai provided important historical details.[ii] Andrew Erickson's 2013 study of Chinese Anti-Ship Ballistic Missile (ASBM) development was very helpful in understanding motivations for development and key events in missile development timelines.[iii]

The only study dedicated specifically to the ballistic missile industry is a paper from 1992 by John Lewis and Hua Di [华棣].[iv] In this study, we attempt to provide an up-to-date look at the contours of the ballistic missile R&D ecosystem—the corporations, research institutes, and factories—and explain how China has reached this level. In doing so we hope to fill what we perceive as an important gap in the literature on China's military modernization.

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i Evan S. Medeiros, Roger Cliff, Keith Crane and James C. Mulvenon, *A New Direction for China's Defense Industry*, RAND, 2005, 51-108. Mark Stokes "China's Evolving Space and Missile Industry - Seeking Innovation in Long-Range Precision Strike," in Tai Ming Cheung, ed. Forging China's Military Might: A New Framework for Assessing Innovation, Johns Hopkins University Press, 2014.

ii Evan Feigenbaum, *China's Techno-Warriors: National Security and Strategic Competition from the Nuclear Age to the Information Age*, Stanford: Stanford University Press, 2003; John Wilson Lewis and Xue Litai, China Builds the Bomb Stanford: Stanford University Press. 1988; John Wilson Lewis and Xue Litai, *China's Strategic Seapower: The Politics of Force Modernization in the Nuclear Age*, Stanford Press, 1995.

iii Andrew Erickson, *Chinese Anti-Ship Ballistic Missile (ASBM) Development: Drivers, Trajectories and Strategic Implications*, Washington D.C.: The Jamestown Foundation, 2013. http://www.andrewerickson.com/wp-content/uploads/2018/03/Chinese-Anti-Ship-Ballistic-Missile-Development_Book_Jamestown_2013.pdf

iv John Wilson Lewis and Hua Di, "China's Ballistic Missile Programs: Technologies, Strategies, Goals," *International Security*, Fall 1992 (Vol. 17, No. 2).

Scope Note

This study limits itself to ballistic missiles, rather than the broader missile industry in China. The term ballistic missile itself as a category is rapidly becoming outdated, as most ballistic missiles no longer strictly follow parabolic arcs and many of the missiles in service in China have maneuvering reentry vehicles.[5] However, this study uses that term due to its wide recognition and to differentiate between cruise missiles. Due to the reasons of scope and clarity, and the fact that Chinese discussions continue to overwhelmingly use the term ballistic missile [弹道导弹], we continue with this term and use common definitions of short-, medium-, and intermediate-range and intercontinental ballistic missiles. While we will touch on some of the Close-Range Ballistic Missiles (CRBM), that is, ballistic missiles with max range under 300km, we are also excluding Multiple Launch Rocket System (MLRS) from this study.

Organization of this Report

Section 1 aims to provide a birds-eye view of the ballistic missile R&D landscape. It begins with an examination of the “small core” of industries and institutions that make up the bulk of organizations involved in ballistic missile research and production. It next turns to the question of developments in research, development, and production capabilities to understand the “small core’s” modernization efforts.

Section 2 examines the technologies and subsystems used in ballistic missiles, profiling the organizations primarily responsible for their development and production and noting significant developments. Building on the explanation of the “small core” in Section 1, this section looks at ballistic missile development through the lens of the design considerations, processes and subsystems involved, and the research institutions and factories engaged in development.

1. Ballistic Missile R&D: An Institutional Perspective

Section 1.1 identifies the principal actors in the design, development, testing, and production of ballistic missiles and explains how they fit into China's defense-industrial complex. Section 1.2 analyzes the historical developments that have shaped the Ballistic Missile R&D "Small Core" to make sense of the current R&D landscape. Section 1.3 then assesses the research, development, and production capabilities of China's ballistic missile industry.

1.1 Overview

Since the establishment of the First Ministry of Machine Building and the Second Ministry of Machine Building in 1952, China's defense industrial base has undergone rounds of reforms stretching over six decades. The rough landscape of China's current defense industry was formed in the 1980s, with a total of seven Ministries of Machine Building, responsible for the fields of civil machinery, nuclear industry, aviation, electronics, weapons, shipbuilding, and aerospace. In the 1990s, these ministries were corporatized to form a group of state-owned defense industrial conglomerates, which, after another cycle of breakups and consolidations, include the following:

State-Owned Defense Conglomerates	
Sector	**State-Owned Defense Conglomerates**
Aviation	Aviation Industry Corporation of China Limited (AVIC) [中国航空工业集团有限公司]
	Aero Engine Corporation of China Limited (AECC) [中国航空发动机集团有限公司]
Space and Missile Systems	China Aerospace Science and Technology Corporation Limited (CASC) [中国航天科技集团有限公司]
	China Aerospace Science and Industry Corporation Limited (CASIC) [中国航天科工集团有限公司]
Shipbuilding	China State Shipbuilding Corporation Limited (CSSC) [中国船舶集团有限公司][6]
Armaments and Ordnance	China North Industries Group Corporation Limited (NORINCO) [中国兵器工业集团有限公司]
	China South Industries Group Corporation Limited (CSGC) [中国兵器装备集团有限公司]
Electronics and Information Technology	China Electronics Technology Group Corporation Limited (CETC) [中国电子科技集团有限公司]
	China Electronics Corporation Limited (CEC) [中国电子信息产业集团有限公司]
Nuclear Technology	China National Nuclear Corporation Limited[7] (CNNC) [中国核工业集团有限公司]

These companies are owned by the State-Owned Assets and Administration Commission of the State Council (SASAC) [国务院国有资产监督管理委员会], but the State Administration for Science, Technology, and Industry for National Defense (SASTIND) (under the Ministry of Industry and Information Technology, MIIT) is in charge of overseeing their business operations. These state-owned enterprises (SOEs) maintain military procurement relationships with the CMC Equipment Development Department (EDD) and service equipment procurement bureaus.

Two important characteristics of China's state-owned defense conglomerates are the sectors they focus on and their corporate leadership. The former is what Chinese experts term "sectorization" [行业化], that is, each conglomerate is largely focused on a particular industrial sector such as aviation, shipbuilding, or electronics.[8] The second characteristic is the role of the Chinese Communist Party in their leadership structures. Rather than simply SOEs, they are perhaps best described as Party-led state-owned enterprises.

The missile and space launch vehicle sector is dominated by two companies: CASC and CASIC.[v] CASC and CASIC were created in 1999 by splitting the China Aerospace Corporation into two corporate entities, out of a need to foster competition within the defense-industrial complex. Both CASC and CASIC are led by a board of directors who serve as senior leaders of the corporation's Party Group [党组], the highest level of a Party structure that extends down to the lowest levels of the company. The Chairman of the Board serves as the Party Secretary [党组书记]. Officials from the CCP Central Organization Department [中组部] and SASAC are often present during board meetings.[9] The executive management of both corporations has a department that manages Party-Masses relations [党群工作组].[vi] Party organizations at all levels regularly hold study sessions or Party-building activities.

Apart from this Party structure, CASC and CASIC are organized similarly, encompassing a corporate management layer consisting of between 10 and 20 departments, several research academies, holding companies (including publicly listed companies), and other affiliated organizations.[10] Among these various entities, the research academies are the principal actors engaged in R&D and production activities within the corporations. For example, the research academies under CASC are collectively referred to as "large scientific R&D and production joint entities" [大型科研生产联合体].[11] These academies vary in size but are organized similarly to their parent companies, often consisting of a management layer, design departments, research institutes, manufacturing and testing facilities, wholly-owned subsidiary companies, holding companies, and a graduate school that offers graduate and Ph.D. programs.[12]

While CASC and CASIC were created in 1999, the core research academies and factories in both CASC and CASIC have existed, in one form or another, under one agency or another, for decades. Further reinforcing the sectorization mentioned above, these academies have historically had different core competencies that remain the primary differentiator between CASC and CASIC. CASC is the nation's sole supplier of intercontinental ballistic missiles (ICBMs) and the Long March (LM) [长征][vii] series launch vehicles and is also responsible for the development, production, and launch testing missions of some tactical missiles and other weapon systems, the R&D and production of

Grassroots CCP members take Party Oath

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v CASIC for example also produces cruise missiles and surface-to-air missiles. China's other defense industry giants such as AVIC produces air-to-air and air-to-ground systems, while NORINCO has developed air-to-ground, anti-tank and multiple launch rocket systems.

vi Masses refers the public (outside of the Party itself).

vii Also referred to by the acronym CZ, short for *Chang Zheng*, the transliteration of "Long March" in Chinese.

applied technology satellites (weather, communications, navigation, earth resources, etc.), manned spaceships, space stations, deep space exploration craft, and other space products.[13] CASIC mainly focuses on tactical missiles and also has comprehensive technical R&D and production systems for surface-to-air missiles, cruise missiles, tactical ballistic missiles, and solid fuel launch vehicles.[14]

The reliance on CASC and CASIC for research, development, and manufacturing of missile systems are unlikely to decrease even with the implementation of the Military-Civil Fusion (MCF) Strategy, which includes efforts to restructure the defense industrial base and further open up the defense industrial market to civilian actors. Policy guidance has called for the formation of a "'small' core, 'large' collaboration, 'specialized,' and open weaponry equipment scientific research and production system" during the 13th Five-Year Plan (FYP), but makes a distinction between defense products that reflect China's core capabilities [核心能力], essential capabilities [重要能力] and general capabilities [一般能力].[15] State actors and market forces are encouraged to jointly develop products that reflect "essential capabilities" and civilian participation and competition are welcome for products that reflect "general capabilities."[16] The R&D of defense products that reflect core strategic capabilities, however, is likely to remain in the hands of state-owned defense conglomerates, the so-called "small core" [小核心].

Within the CASC/CASIC defense industrial establishment, five research academies are the principal actors in the design, development, testing, and production of ballistic missiles, forming the "small core" of the ballistic missile industry. They include CASC 1st Academy, CASC 4th Academy, CASC 6th Academy, CASIC 4th Academy, and CASIC 6th Academy.[viii]

Central Players Engaged in Ballistic Missile RD&A

Academy	Full/Alternate Name	Corporate Name	HQ Location	Core Competency	Missiles Developed
CASC 1st Academy	China Academy of Launch Vehicle Technology (CALT) [中国运载火箭技术研究院]		Beijing	Lead system integrator, Launch vehicles, ballistic missiles	DF-4, DF-5, DF-5B, DF-41, DF-15, DF-31/JL-2, DF-31A, DF-26, DF-41
CASC 4th Academy	Academy of Aerospace Solid Propulsion Technology (AASPT) [航天动力技术研究院]	Shaanxi Aerospace Science and Technology Corporation [陕西航天科技集团有限公司]	Xi'an	Large solid rocket motors	
CASC 6th Academy	Academy of Aerospace Propulsion Technology (AALPT) [航天推进技术研究院]		Xi'an	Liquid propulsion systems	
(New) CASIC 4th Academy	CASIC Academy of Launch Technology [航天科工运载技术研究院]	China Space Sanjiang Group [中国航天三江集团公司]	Wuhan	Tactical ballistic missile system integrator	DF-11 DF-16 DF-21/JL-1
CASIC 6th Academy	Academy of Propulsion Technology [航天科工动力技术研究院]	Hexi Machinery Corporation [中国河西化工机械公司]	Baotou	Tactical solid rocket motors	

viii As shown in the table above, each research academy can be referred to at least three different ways (excluding nicknames) and the preferred title varies depending on the academy in question. For example, CASC 1st Academy is frequently referred to as the "missile academy" [火箭院] or CALT, while CASIC 4th Academy is known as "China Space Sanjiang" [航天三江]. For clarity, CASC and CASIC academies are referred to by their number in their *current form* throughout this study.

Among these five academies, CASC 1st Academy and CASIC 4th Academy are responsible for the overall design of ballistic missile systems and act as system integrators. CASC 6th Academy specializes in liquid propulsion systems and cooperates extensively with CASC 1st Academy. CASC 4th Academy and CASIC 6th Academy both focus on solid propulsion systems. The core competencies of these academies were largely shaped by the role their predecessors played between 1960–1990. To make sense of this current landscape for ballistic missile R&D, especially concerning the division of labor within this “small core” R&D system, the next section examines its historical evolution and discusses the legacy of the Third Front Construction movement in the 1960s and 1970s.

1.2 The Origin and Evolution of the Ballistic Missile R&D “Small Core”

China’s missile R&D establishment started life as the Defense Ministry’s Fifth Academy, a long-range ballistic missile R&D organization created by the Party’s Central Military Commission (CMC) in 1956.17 Beginning in 1956, it operated as a part of a government agency, until 1993 when the Ministry of Space Industry was corporatized to form the China Aerospace Corporation, which was then reorganized and split into two defense conglomerates CASC and CASIC in 1999. As a result of these splits and mergers CASC and CASIC subsidiaries have accumulated multiple names and identities. The following chart shows the most important of these reorganizations:

Evolution of CASC and CASIC
1956-1964
Fifth Academy of the Defense Ministry [国防部第五研究院]
1964-1982
Seventh Ministry of Machine Building [第七机械工业部]
1982-1993
Ministry of Space Industry/ Ministry of Aerospace Industry [航天工业部/航空航天工业部]
1993-1999
China Aerospace Corporation (& China National Space Administration) [中国航天工业总公司]（国家航天局）
1999-2018
China Aerospace Science and Technology Corporation [中国航天科技集团公司] China Aerospace Science and Industry Corporation [中国航天机电集团公司 (1999), subsequently 中国航天科工集团公司 (2001)]
2018-Present
China Aerospace Science and Technology Corporation Limited (CASC) [中国航天科技集团有限公司] China Aerospace Science and Industry Corporation Limited (CASIC) [中国航天科工集团有限公司]

1.2.1 Building the Small Core (1950s-1970s)

Between November 1957 and July 1964, four subordinate research organs were created under the Fifth Academy.[18] These became the foundation for the system of academies in CASC/CASIC that remains today.

For a short period following its creation in November 1957, the First Sub-Academy was put in charge of the overall design of all ballistic, surface-to-air, and cruise missiles.[19] Eight research offices/laboratories [研究室], each responsible for a specific area of technology research and development such as structure and strength, aerodynamics, etc., were established under the First Sub-Academy.[20ix] In September 1958, the development of the Dongfeng series of land-based ballistic missiles began.[21]

Following the creation of the Second, Third, and Fourth Sub-Academies, the division of labor was further defined in 1963: the First, Second, and Third Sub-Academies were each placed in charge of the design and development of the Dongfeng (ballistic), Hongqi (surface-to-air), and Haiying (Anti-ship) missile series, respectively.[22] The Fourth Sub-Academy was given the responsibility for R&D on solid propulsion systems. Some of the research offices or departments initially under the First Sub-Academy were subsequently reassigned according to their areas of responsibilities.[23]

Sub Academies under the Defense's Ministry's Fifth Academy24

Sub Academy Under the Defense Ministry's Fifth Academy	Area of Responsibility	Successor
First sub-Academy [一分院]	Dongfeng [东风] (DF) Series	CASC 1st Academy
Second sub-Academy [二分院]	Hongqi [红旗] (HQ) Series	CASIC 2nd Academy
Third sub-Academy [三分院]	Haiying [海鹰] (HY) Series	CASIC 3rd Academy
Fourth sub-Academy [四分院]	Solid Rocket Motors	CASC 4th Academy and CASIC 6th Academy

In November 1964, the Fifth Academy became the Seventh Ministry of Machine Building [第七机械工业部]. Subsequently, the "sub academies" [分院] were renamed "academies" [院].[x] According to Li Farui [李法瑞], a missile control expert and a former Party Branch Secretary with the Overall Design Department of CASC 1st Academy (CALT), the First Academy created under it several research institutes (RIs) named with double-digit serial codes starting with the number "1," namely the 11th, 12th, 13th, 14th, 15th, 17th, and 19th RIs.[25] Most of these research institutes still act as the backbone of R&D for the First Academy today.[xi] Between 1958 and 1964, the First Academy worked on the development of strategic ballistic missile models including the DF-1, DF-2, DF-2A, and DF-3.[26] In March 1965, spurred on by directives from Zhou Enlai to achieve a flight-test of a full-range ICBM before 1975, the First Academy initiated a *Surface-to-Surface Missile Development Plan (1965-1972)* [地地导弹发展规划 (1965-1972)] to build "four types of missile in eight years" [八年四弹], which included the DF-2 MRBM, the DF-3 IRBM, and the DF-4 and DF-5 ICBMs.[27]

ix Among them, the First Research Office was put in charge of the overall design of missile systems and the research and development of rocket engines. It was renamed the Overall Design Department [总体设计部] in 1958 and over the years became known as the cradle of China's launch vehicles and chief designers. It is the predecessor of the CASC 1st Academy's (CALT) 11th RI, also known as the Beijing Institute of Astronautical Systems Engineering [北京宇航系统工程研究所], a system integrator of strategic ballistic missiles and the Long March series of launch vehicles.

x Throughout this study, to clearly differentiate research academies in their current form and their historical form, the term sub-Academy is used to refer to the various incarnations of research academies between the 1950s and the early 1990s.

xi One important exception being the 17th RI, or Beijing Institute of Control Electronic Technology [北京控制与电子技术研究所], that specializes in the overall design of control systems. The 17th RI stayed a First Academy subsidiary until the 1980s when it was resubordinated under the Second Academy, and transferred over to the newly created CASIC 4th Academy in 2002.

The Dongfeng program cemented the First Academy's status as the powerhouse of Chinese ballistic missile R&D.[xii]

The Fourth Sub Academy was created as the Defense Ministry's Solid Engine Research Institute [国防部五院固体发动机研究所] in Luzhou [泸州], Sichuan Province in 1962. In 1965, it was moved to Hohhot, the capital of the Inner Mongolia Autonomous Region, and became known as the Fourth Academy of the Seventh Ministry.[28]

The Fourth Research Department, a research department initially established under the First sub-Academy specializing in solid rocket engine R&D, was likely transferred to the Fourth Sub Academy in 1965.[29]

In November 1966, the Fourth Academy began to research and development of the third-stage solid-propellant rocket engine to be used on the Long March 1 that sent China's first man-made satellite, the Dongfanghong-1, into orbit. Based on its success in producing 1-m diameter solid-rocket motors, the Fourth Academy proposed producing a small tactical missile it dubbed the DF-41, later renamed the DF-61. However, the effort "quietly died" due to a lack of interest.[30] This failure, ironically, gave birth to the JL-1 (Julang [巨浪]) submarine-launched ballistic missile (SLBM) program in March 1967, when, according to Lewis and Hua, the central leadership decided to assign the Fourth Academy the JL-1 program "almost as a consolation prize." This consolation prize led to a watershed moment in 1982 with the successful launch of the JL-1 SLBM, which enabled the shift in R&D focus to solid propellant rocketry.[31]

Another landmark event that shaped the current ballistic missile R&D landscape was the "Third Front Construction" movement [三线建设]. Fearing the threat of invasion, beginning in 1964 China began the large-scale relocation of defense production facilities and personnel from the provinces in the Northeast and along the East Coast to the remote regions of south-western and western China to protect them from the threat of Soviet attack.

Between 1964 and 1980, the central government invested an estimated 205.2 billion RMB to the effort, building 1,100 entities, including large and medium-sized companies, defense R&D and production facilities, scientific research institutes, and universities. According to a CCTV documentary series on the subject, the Third Front Construction movement was the largest population migration in the history of the PRC.[32] Beginning in 1964, as part of the Third Front Construction effort, the Seventh Ministry of Machinery and its subordinate academies oversaw the construction and staffing of defense industrial bases [军工基地] with the code designations 061 through 068. These bases later either evolved into new CASC/CASIC research academies or were absorbed into existing academies.

xii According to Lewis and Hua, this provoked the leadership of the Fourth Academy, who proceeded to propose the development of a single-stage solid propellant tactical missile in 1966. See: John W. Lewis and Hua Di, "China's Ballistic Missile Programs," 32.

The creation and development of the following bases notably changed the current ballistic missile R&D landscape:

- The First sub-Academy oversaw the construction of Base 062 and Base 067. Base 062, located in Wanyuan, Sichuan Province, was created as a rocket manufacturing base and later evolved into half of the current CASC 7th Academy. Base 067, situated in Feng County [凤县], in western Shaanxi Province, specialized in liquid propulsion systems.[33] In 1993, Base 067 was relocated to Xi'an and officially renamed CASC 6th Academy.
- One of the bases the Third sub-Academy was responsible for building was Base 066 in Yuan'an County, Xiaogan, Hubei Province. In the latter half of the 1980s, Base 066 was split off from the Third Academy as an independent missile research and industrial complex.[34]
- In the 1970s, as part of the Third Front Movement, a decision was made to relocate the majority of the Fourth Academy's key equipment and R&D workforce to Lantian County, Xi'an, Shaanxi Province, establishing a new headquarters designated Base 063. The remaining offices and labs in Hohhot were named the Fourth Academy's Inner Mongolia Headquarters [四院驻内蒙古指挥部] and remained a subsidiary of CASC 4th Academy until 2002 when it was spun off from CASC and reestablished as the CASIC 6th Academy.

Third Front Defense Industrial Bases Tied to Ballistic Missile R&D				
Base	**Location**	**Responsible Institution [分建单位]**	**Current Form**	**Core Competency**
Base 063 (Fourth Sub Academy)	Xi'an, Shaanxi		CASC 4th Academy; CASIC 4th Academy	Solid Propulsion Systems
Base 066	Yuan'an, Hubei	Third sub-Academy	CASIC 4th Academy (formerly CASIC 9th Academy)	DF-11 SRBM
Base 067	Xi'an, Shaanxi	First sub-Academy	CASC 6th Academy	Liquid Propulsion Systems

By the 1970s, the research academies, institutes, and production bases that make up the current ballistic missile R&D landscape had all been established. Some of these institutions, especially those under the First sub-Academy, remained relatively unperturbed during the rounds of reorganizations that followed; others were repeatedly shuffled between the various academies and later between CASC and CASIC. However, the mergers, breakups, and consolidations have merely rearranged the landscape by moving pieces around, instead of creating brand new organizations. The next section looks at their development from the 1980s onward with particular emphasis on the organizational shifts within the small core.

1.2.2 Developing the Small Core (1980s-1990s)

The ballistic missile R&D landscape which formed between the 1950s and 1970s and consisted of a few academies and production bases proved resilient. Despite two rounds of organizational reforms, it remained largely unaltered in the 1980s and 1990s. While these organizations remained static, the focus of Chinese ballistic missile R&D would change due to two significant developments.

The test-firing of a 2m-diameter solid rocket engine in late 1983 helped shift the focus from the development of liquid to solid propellants, and renewed interest in the JL-2/DF-31 models. At the same time, the pivot of national efforts to economic and market reforms and modernization and consequent withdrawal of defense R&D funding spurred growth in the development of tactical missiles for export.

In the early 1980s, Deng Xiaoping and his strategists made the judgment that "peace and development are the themes of today's era, and large-scale wars cannot be waged in a short time" and pivoted to focusing on economic development. Following Deng's guidance, national defense and force building took a back seat.[35] As noted by Lewis and Hua in their study, as part of the economic reform, the Party Central Committee's new policy directive issued in 1979 stipulated that the defense industries should use civilian sales to support military R&D.[36] However, it did not take long for the military to realize that such sales were insufficient to pay for military R&D and soon had to resort to military exports of SRBMs to survive and continue to support R&D activities.

Lewis and Hua's research suggests that limited funding pushed the Academies to shift to survival mode, directly resulting in the creation of the DF15/M9[xiii] and the DF11/M11 series. Even the First Academy, with its celebrated DF programs making it the objective of envy in the 1960s, had to pivot to the development and export of SRBMs to fund its military R&D. As noted by Lewis and Hua:[37]

> *Facing a two-thirds cut in its R&D appropriation for 1985 and watching the Second and Third academies prosper from their sale of tactical missiles, the First Academy decided to build its own tactical surface-to-surface ballistic missiles for export. ... Engineers in the First Academy concluded that they could easily and cheaply adapt the technologies from China's second-generation strategic missiles to a new class of short-range tactical ballistic missiles... On April 28, 1984, the First Academy initiated work on the missile, the M-9.*

Facing similar funding pressures, Base 066, a defense industrial base located in Xiaogan, Hubei Province formerly affiliated with the Third Sub Academy, began using its expertise in developing solid-propellant boosters for other types of missiles to develop a solid-fuel ballistic missile called the M-11/DF-11 for the PLA in 1985.[38] They also noted that Base 066 received assistance from two research institutes under the First Academy to solve technical problems during development, suggesting some level of cooperation.[39]

The creation and development of the DF15/M9 and the DF11/M11 series offer a window into understanding government institutional behavior. Medeiros et. al argued that the simultaneous existence of related, but not identical, missile systems (e.g., the DF-11 and DF-15) suggest a certain level of competition at the prime contractor level between CASC and CASIC,[40] but Lewis and Hua's account suggests that the two programs arose due to the withdrawal of state funding. While the typical assumption is that lavish spending on a program drives innovation, these two cases appear to suggest that for government institutions and SOEs, the retraction of funding has served as a strong incentive for innovation and breakthroughs.

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xiii M is the prefix used for export variants of Chinese missiles

The first test-firing of a 2m-diameter solid rocket engine in late 1983 was a significant achievement that renewed interest in the development of the JL-2 SLBM and its land version, the DF-23 (later renamed DF-31).[41] While the pre-research and design plan initial analysis for both models were undertaken by the Second Academy and the Fourth Academy (two academies who had worked on the JL-1/DF-1 model together), the task of research and development of the SLBM and its land variant was ultimately transferred to the First Academy.[42] There is little information available about the rationale behind this decision. However, it was likely driven by two factors. According to Lewis and Hua, the Second Academy was directed to focus on surface-to-air missile (SAM) development in 1986.[xiv] Some Chinese sources also suggest that the Second Academy was also told to focus on the prototyping of JL-1 and work on extending the range of the DF-21.[43] Additionally, the development of the land variant DF-31 was given priority over the JL-2,[44] which might have seen as a more natural match for the First Academy's core competency.

CHINA MISSILE EXPORTS

China exported DF-3 missiles with conventional warheads to Saudi Arabia in 1986, and the M-7/8610 to Iran in 1989.[272] Pakistan purchased the M-11 and M-9 in the early 1990s.[273] CASC and CASIC continue to develop ballistic missiles for export. Perhaps due to China's pledge to adhere to the Missile Technology Control Regime (MTCR), since 1991 there appears to have been a shift toward shorter-ranged systems which would comply with the MTCR's limit on selling delivery systems capable of delivering a 500kg payload over 300km.[274, 275] CASC has offered the M20/DF-12 - single-stage solid-fuel missile, which has a maximum altitude of 50km and vertical attack, with a top velocity of Mach 6.[276, 277] The DF-12 is capable of firing missiles from the "A-series" of <300mm guided solid-fueled missiles. They use a combined "GPS+ Inertial navigation system" and are capable of terminal maneuvering.[278] CASIC has offered the SY-400, capable of launching BP-12A ballistic missiles with a 480kg payload at ranges over 300km.

xiv According to Lewis and Hua, the Second sub-Academy was involved in ballistic missile development including a tactical ballistic missile based on the HQ-2 (the DF-7/M-7/Project 8610) and beginning in 1978 the JL-1/DF-21 MRBM program until 1986, when it was directed to focus on SAM development. See John W. Lewis and Hua Di, "China's Ballistic Missile Programs," 36.

1.2.3 Reorganizing the Small Core (2000s-Present)

The past two decades have been characterized by a slew of measures taken to reorganize the defense R&D establishment to be more competitive, innovative, and efficient. The one with the most far-reaching consequences with regard to the landscape was the 1999 decision to divide China's five defense corporations into groups of two to foster competition, which resulted in the creation of CASC and CASIC. Medeiros et. al noted that the goal at the time according to Chinese officials was to create two companies operating in the same space that would compete "in terms of their systems organization and their operational mechanisms," rather than their products.[45]

In the case of ballistic missile R&D within the CASC and CASIC ecosystem, for example, CASC 1st Academy, a direct descendant of the First sub-Academy, had by that point established itself as the principal supplier of both strategic and tactical ballistic missiles and has a complete R&D system for solid and liquid propulsion systems supported by the 4th and 6th Academy. Academies allocated to CASIC, on the other hand, specialized in the R&D and production of SAMs, cruise missiles, and tactical weapons. To create competition, in 2002, the organizations that had been responsible for the development and production of the JL-1/DF-21 missile were transferred from CASC to CASIC, creating CASIC's 4th and 6th Academies.

Specifically, the CASIC 6th Academy was created in 2002 by separating the CASC 4th Academy's solid rocket motor research establishment—called the Fourth Academy's Inner Mongolia Headquarters, located in Hohhot—from CASC. CASIC 4th Academy absorbed, among others, the former Fourth sub-Academy's Fourth Overall Design Department [第四总体设计部], which was the unit responsible for the overall design of the JL-1 missile, and the 17th Research Institute, which specializes in the overall design of control systems.

In 2007, CASIC 9th Academy was created from the former Base 066, developer and producer of the M11/DF11 SRBM. In 2011, CASIC 4th Academy and CASIC 9th Academy merged to create the (new) CASIC 4th Academy.

Effects of Reforms in the 2000s		
Core Competency	**CASC**	**CASIC**
Overall Design	1st Academy	(New) 4th Academy (CASIC 4th Academy + 9th Academy)
Solid Propulsion	4th Academy	6th Academy
Liquid Propulsion	6th Academy	

The organizational changes made in the 2000s seemingly created two academies under CASIC to compete with CASC's 1st and 4th Academies, but the competition is lopsided, apparently limited to SRBMs and SLBMs. It is difficult to say whether these academies can effectively compete with each other under this managed and controlled competition environment. Additionally, these repeated reorganizations and consolidations have imposed switching costs. As a *China Space News* article noted, over the course of 55 years the Fourth Design Department has existed in various incarnations first as part of the Fourth Academy of Inner Mongolia, later the 1st Academy in Beijing, the 2nd Academy, under a conglomerate, the 4th Academy, and finally the new 4th Academy.[46] Despite this bumpy journey, according to Zhong Shiyong [钟世勇], director of the Fourth Design Department, the department's core business remains unchanged.[47]

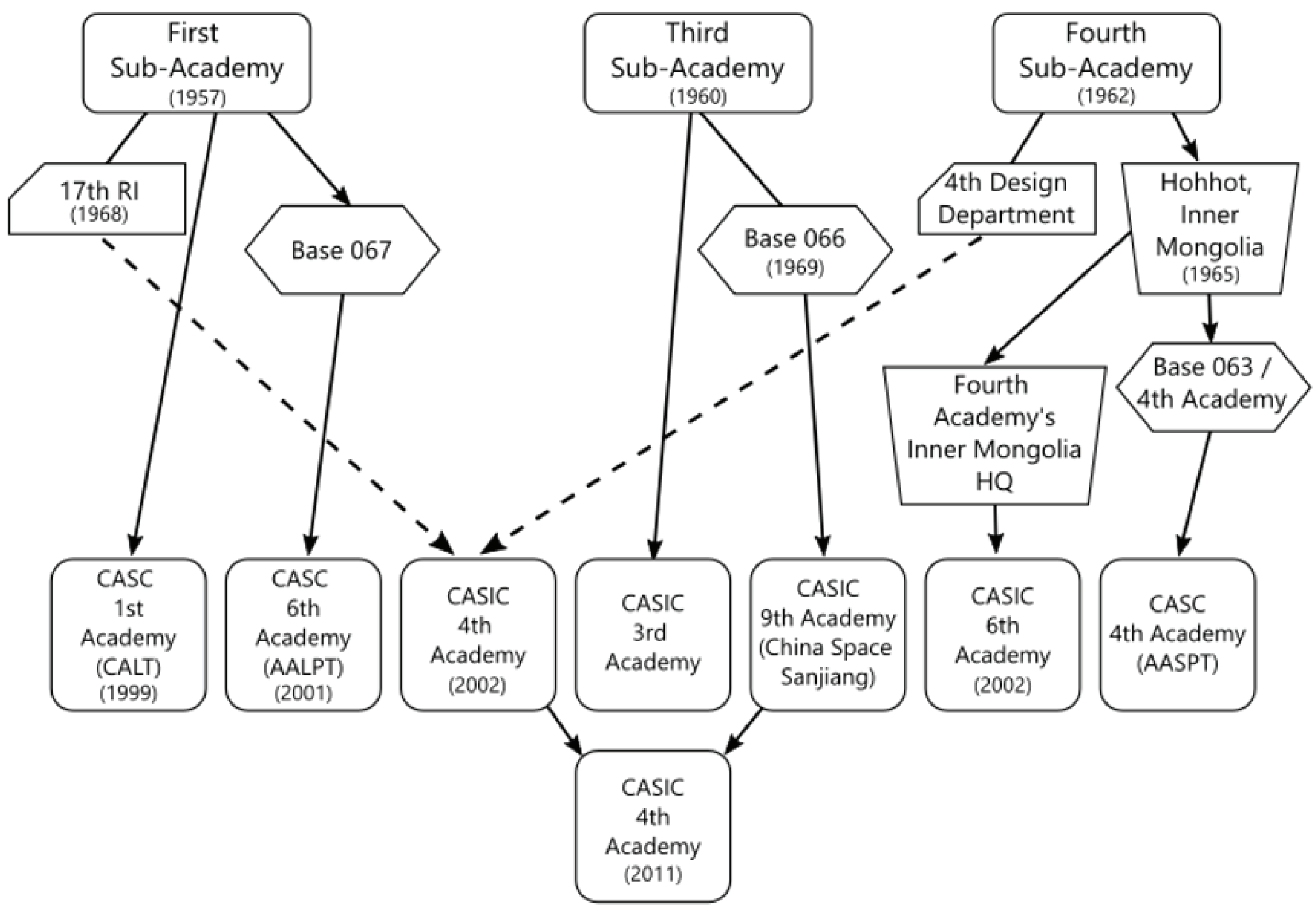
Perhaps recognizing that past reform measures have had a mixed effect at best, the outcome of the decision in 1999 to divide China's five defense corporations into ten companies is steadily being reversed. Two conglomerates that were split have since re-merged, forming Aviation Industry Corporation of China (AVIC) out of AVIC I and AVIC II in 2008, and folding China Shipbuilding Industry Corporation (CSIC) into China State Shipbuilding Corporation (CSSC) in 2019. In August 2020, CASC and CASIC held an important meeting together pledging to deepen strategic cooperation and all domain deep integration [全领域深度融合] to build a globally-advanced space corporation [世界一流航天企业集团] and a globally-advanced aerospace and defense corporation [世界一流航天防务集团公司], enhance China's competitiveness in aerospace, and jointly safeguard national security.[48] This announcement led some to wonder whether another re-merger is around the corner.

Another major line of effort aimed at improving the capabilities of the industrial base focuses on turning these SASAC-owned corporations and its subsidiaries into "truly independent market entities that operate independently according to law, that bear their own profits, losses, and risks, that can exercise self-discipline, and develop themselves."[49] While these defense conglomerates were known as "state-owned enterprises" (SOEs), they had been operating under the ambiguously termed "people-owned enterprise" ownership structure for many decades. In essence, "people-owned" SOEs operated in a similar manner as government agencies or state entities—the financial health of the enterprise was not a pressing concern, and employees were entitled to guaranteed lifetime employment and welfare support, known throughout Chinese enterprises as an "iron rice bowl."

While it is still too early to assess the impact of this new round of reforms on the R&D capabilities of the missile sector, history suggests that this type of "sink or swim" approach has once been a source for innovation.

In summary, since its founding in 1949, the PRC spent the first three decades (1950-1980) building up its ballistic missile R&D small core, and, despite reorganizations, the actual composition of the small core has not shifted significantly in the four decades since. As shown in the chart below, all five academies that make up the current ballistic missile small core trace their lineage back to the four research sub academies created under the Fifth Academy of the Defense Ministry in the 1950s and the defense industrial bases these Sub Academies set up in China's interior during the Third Front Construction movement.

Sketch of the Historical Development of the Ballistic Missile "Small Core"



While this may seem like evidence of malaise, as Medeiros et. al. pointed out in their 2005 study, the robust institutional infrastructure is the greatest contributing factor to the missile sector's moderately successful record over the years.[50] Because these Academies are essentially self-contained R&D ecosystems, they have well-established channels for communication and processes for taking an idea from blueprint to production.

1.3 Research, Development, and Production Capabilities

Although China is one of a handful of countries capable of producing its own range of ballistic missiles, its industry continues to face several problems. Assessing the research, development, and production capabilities of China's missile industry, a 2005 study by RAND found a mixed picture best described as a "pocket of adequacy."[51] It notes that while the Academy system provided a "solid institutional foundation" for development, problems such as talent retention undercut the industry's competitiveness.

Fifteen years on, this mixed picture has not been dramatically altered. As analyzed in Section 1, ballistic missile R&D continues to rely on the robust institutional infrastructure set up between 1950–1980. Despite attempts to introduce competition into the system, the degree of competition at the academy level is limited to SRBMs and SLBMs. Apart from its robust institutional infrastructure, the industry is seeing tremendous growth in the size of its workforce and its R&D and production facilities, but continues to have trouble attracting and retaining top talent. Various enterprise management and smart manufacturing solutions have been adopted by the academies and production facilities, although it remains to be seen their impact on efficiency and product development timelines.

The rest of this section outlines some of the notable developments involving CASC and CASIC academies identified in Section 1.2 to investigate progress and setbacks the missile sector has experienced and highlight some of the strengths and weaknesses of the ballistic missile R&D small core. It should be noted that it is difficult to precisely determine what percentage of the growth is driven by ballistic missile R&D needs, as the academies in question are involved in a large number of other projects beyond ballistic missiles, and the space launch industry, in particular, is likely a major driver of that growth.

1.3.1 Expansion of Production Facilities

Concept art of Factory 211's new facility

One noticeable development of the missile sector is the expansion of research and production facilities in some of the production plants.

Capital Aerospace Machinery Company (Capital Astronautics Machinery Co./Factory 211) [首都航天机械公司], a subsidiary of CASC 1st Academy (CALT) and China's oldest and largest missile and launch vehicle integration and general assembly plant and the sole manufacturer of cryogenic rocket engines, appears to have outgrown its original facility in Beijing's Fengtai District [丰台区] and is expanding its facilities to meet the rising demand for space launch vehicles, and likely in part, ballistic missile production.[xv][52] CALT and Factory 211 jointly set up a subsidiary company, the Tianjin Space Long March Technology and Equipment Co., Ltd [天津航天长征技术装备有限公司] in Tianjin's Binhai Economic Development Zone in 2008 for the manufacturing of ground launch equipment [地面发射装备项目] and other auxiliary products.[53] Additionally, a digitally rendered image of Factory 211's new campus was posted on an engineering design firm's website in December 2017, noting that the new campus, location unspecified, covers an area of 480 mu (around 80 acres), with a gross floor area of 210,000 square meters.[54]

xv Factory 211 traces its origin back to an aircraft repair shop founded by the Qing government in September 1910. It became part of China's missile R&D and production establishment in June 1958, establishing itself as China's first launch vehicle general assembly company.

Other components of the ballistic missile industry are also seeing significant improvements in production capabilities. CASIC's 4th Academy, which is responsible for the overall design and system integration of tactical ballistic missiles such as the JL-1/DF-21, has also made efforts to expand its research and production facilities. According to *China Space News*, a newspaper run by CASC and CASIC, during the 13th Five-Year Plan period (2016-2020), the 4th Academy's Fourth Design Department built four additional research and productions zones, including a core research center on Yongding Avenue in Beijing [北京永定路核心研发区], a testing & verification and trial production & processing site in Mentougou, Beijing [门头沟试验验证区/试制加工区], an industrial zone in Laishui, Hebei Province [河北涞水产业园区], as well as a high-performance computing center.[55] According to Zhang Shaojun [张邵军], Party Secretary of the Fourth Design Department, the high-performance computing center can significantly reduce R&D costs and shorten the R&D cycle by generating results that were previously only obtainable through wind tunnel testing.[56]

Following directives to increase Military-Civil Fusion, CASIC 4th Academy's Fourth Design Department also unveiled its Military-Civil Fusion Industrial Park [军民融合产业园] located in Fangshan [房山区], Beijing at the end of 2018.[57] This industrial park was described as a product of the "military-civil fusion strategic cooperation" [军民融合战略合作] between the Fourth Design Department and the Anlong Group [安龙集团], a civilian contractor that produces special purpose vehicles and other military and paramilitary equipment for the PLA, People's Armed Police (PAP), and the Public Security Bureau.

The cooperation between the Fourth Design Department and Anlong appears to be part of a larger effort from CASIC's Changyang Space City [长阳航天城] project launched in 2013 that included plans to build at least five different sections with designated functions, called parks, in Beijing's Fangshan District.[58] With a total investment of 30 billion RMB, the Space City includes, among others, an electronic technology park, a CASIC military-civil fusion industrial development headquarters, and a high-end manufacturing park.

CASIC 4th Academy's Fourth Design Department Unveils its Military-Civil Fusion Industrial Park

1.3.2 Human Resources

The 2005 RAND study observed that that the companies involved in missile R&D employ large numbers, but that the sector suffers from a myriad of issues such as low pay and poor living conditions of scientists, resulting in a high turnover rate and outflow of human capital.[59] Despite the various reforms and reorganizations described above, this observation still holds fifteen years later.

The companies of the "small core" have grown substantially in the intervening years. When CASC was created in 1999, it employed around 100,000 people. That has since climbed to 164,000 in 2018.[60] CASIC's workforce also increased from 100,000 in 2002 to 150,000 in 2020.[61] [xvi]

Of course, sheer numbers are not the whole story. The bigger question is whether the missile sector can attract and retain talent. Anecdotal evidence from popular question boards and job sites suggests that those employed in the space and missile sector are dissatisfied with the status quo. Responses to job seekers inquiring about the pay, work conditions, and career growth opportunities regularly indicate dissatisfaction with conditions at CASC and CASIC and their subsidiaries.[62] Low pay [待遇差], harsh living/working conditions [条件艰苦], SOE [bureaucratic] workstyle [国企作风], and lack of career growth opportunities [没有发展] are common themes in responses. While SOEs are traditionally known to offer a nine to five work schedule, according to multiple reports in *China Space News*, employees who are involved in critical projects frequently work overtime or forego weekends for the sake of completing the mission on time. For example, it was reported that around 70 percent of employees in CASIC 4th Academy's Fourth Design Department work over 10 hours a day on average and that it is commonplace to work overtime on weekends.[63] The coverage however puts a patriotic spin on these conditions, with the workers as examples to be followed, rather than reflecting problems in project management.[64]

On the other hand, some of the answers on questions boards also suggest that for those fresh out of school [应届生], CASC and CASIC job opportunities offer the perk of obtaining a Hukou [户口] (residency permits key for access to public services like schooling and healthcare) in cities like Beijing. Additionally, CASC and CASIC have the capacity to absorb a large number of graduates who major in traditional engineering disciplines such as materials and chemical engineering. Graduates in these disciplines have fewer alternatives to choose from compared to those majoring in information technology or similar fields. Taken together, these answers suggest that the space and missile sector has access to a large talent pool but has trouble attracting the best and brightest, especially in areas where the commercial sector can offer much higher wages.

The talent retention issue was brought to the public eye in September 2018, when the departure and the subsequent fallout of Zhang Xiaoping [张小平], a liquid-propelled engine designer from the CASC 6th Academy, went viral in Chinese social media and sparked a huge discussion on SOE's talent retention problem.

Born in 1970, Zhang was a researcher with the CASC 6th Academy's 601 Research Institute in Xi'an that specializes in liquid propulsion systems. In September 2018, Zhang left his job with 601 RI for the commercial space company Landspace [蓝箭航天]. His departure became national news overnight because of a two-page document submitted by the 601 RI to the Xi'an Labor Dispute Arbitration Commission requesting Zhang's return to his original post. The document detailed the detrimental effect Zhang's departure has on several of China's strategic space programs. This incident and the following debate culminated in an article published in *People's Daily* at the end of September critiquing talent management practices in SOEs.[65]

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xvi For comparison, according their websites, U.S. defense contractor Lockheed Martin and Raytheon employ approximately 110,000 and 78,000 people worldwide, respectively. Northrup Grumman will build the "Ground Based Strategic Deterrent" to will replace the Minuteman 3, has 90,000 employees worldwide. "About Lockheed Martin," https://www.lockheedmartin.com/en-us/who-we-are.html; "Explore Our Businesses," https://www.rtx.com/Our-Company/Our-Businesses/ca, accessed October 2020; "Who We Are," https://www.northropgrumman.com/who-we-are/, accessed October 2020.

According to the document which was included in the *People's Daily* article, Zhang is a "principal figure" [主要人物] in the research and development of at least five major engine programs that includes liquid oxygen (LOX)/kerosene engines producing 120 and 480 tons of thrust and a 100-ton class [百吨级] LOX/methane engine producing 100 tons of thrust.[66]

The document noted that Zhang's job title is "researcher" [研究员], while his administrative grade is deputy director designer [副主任设计师], which according to those familiar with the matter, ranks only fourth in the bureaucratic hierarchy, preceded by director designers, deputy chief designers, and chief designers.[67] However, according to the 601st RI, Zhang assumed "the most critical technical post" [最关键的技术岗位] and was the "life and soul" [灵魂人物] of these R&D programs, playing an essential role that is "irreplaceable." Furthermore, according to the 601st RI, Zhang's departure has had "profound impact" [极大影响] on the execution and timeline of these programs, especially the 480-ton liquid oxygen kerosene engine program, which had run into "technical difficulty at a deep level" [深层次的技术难题].[68] The document concluded by saying that Zhang's departure will negatively impact the development of China's heavy launch vehicle at a fundamental design level and hinder progress on its crewed lunar landing program to an extent.

This incident exposed significant vulnerabilities in the space and missile R&D system. As discussed in previous sections, CASC 6th Academy is the only research academy focusing on liquid propulsion systems within the "small core," and Zhang's departure reveals a single point of failure within the liquid propulsion R&D system. As pointed out by many commentators after the incident went viral, Zhang appears to have shouldered the most critical task in the organization, but without a proper title and compensation package to match. The People's Daily article hinted that Zhang's annual salary at the 601st RI was between 120,000-200,000 RMB ($17,672-$29,453), but was offered around one million RMB ($147,264) by Landspace.[69]

In addition to problems with attracting and retaining top talent, there is an outflow of manual laborers and skilled workers from manufacturing into the service industry, which could also adversely impact the defense industrial and civilian manufacturing base. In July 2020, *China News Week* reported a concerning trend for China's manufacturing industry: skilled laborers that worked in the manufacturing industry are instead choosing to become food delivery and express delivery services.[70] According to the report, the coronavirus pandemic has further accelerated this flow of labor between industries. Since late January 2020, Meituan and Ele.me, two big food delivery service platforms, have added more than 2 million food deliverers, of which nearly 30 percent were from the manufacturing sector and over 80 percent are young people under 40. According to the article, "twenty or thirty years ago, 'going to work in factories in coastal areas' was still the first choice of countless unemployed young people in mainland [China]. Now, express delivery and food delivery in big cities is becoming a preferred career option for more and more young people."[71]

While this trend might not have an immediate effect on the missile industry, some of the production plants located in inland China or second and third-tier cities could stand to lose if a similar outflow of labor takes place there as well.

1.3.3 Incorporation of Advanced Technologies into R&D and Production

Apart from growth in infrastructure and workforce, the academies and subsidiaries have made efforts to adopt and incorporate enterprise management and quality control solutions, as well as advanced technologies such as big data analysis and AI to modernize their facilities and enhance R&D and production capabilities.

While these developments are significant within the Chinese context and represent important qualitative improvements, they should not, however, be considered indicative of broader global competitiveness without proper contextualization. While Chinese media reporting (especially the headlines they use) makes many of these developments appear cutting-edge and significant, a closer examination reveals that oftentimes these represent long-overdue adoption of well-established practices.

For example, an article from 2020 noted that the First Design Department of the CASC 1st Academy is harnessing big data technology to build a rocket health monitoring system to interpret, analyze, and model data in the development process.[72] However, a key function of the monitoring system was to serve as a practical and easy-to-use data collection and search engine to realize the retrieval of various documents such as test data, design schemes, test plans, contingency plans, etc. Rather than a revolution in management practices, in reality, this project involved the digitization of a collection of technical documents and technical parameters that were scattered among the final assembly area and launch sites. While important in the context of Chinese missile development as it means that when problems occur, designers now have access to documents immediately rather than having to search through piles at different places across the country—this is not a revolutionary breakthrough. They also noted that the data collected from the R&D stage to the launch stage has been underutilized.

Despite their potential (and long advocacy from senior scientists such as Liang Sili [梁思礼] who led work on the DF-2A and LM-2) the industry has also been slow to incorporate new digital design techniques. Another article from 2020 noted that the Fourth Design Department has significantly enhanced its core design capability during the 13th FYP period (2016-2020).[73] The article reveals that before 2016, the Fourth Design Department was capable of 3D designs [三维设计能力] but not 3D simulated assembly [仿真装配]. According to 4th Design Bureau Party Secretary Zhang Shaojun [张邵军], "every modification of the [design] plan adds an additional three months [to the process]."

The long-overdue adoption of well-established practices also applies to the production plants. For example, Factory 211 started incorporating intelligent manufacturing elements in 2012 and articulated its goal of building itself into a "leading enterprise in China's aerospace intelligent manufacturing" [中国航天智能制造领军企业] in 2019.[74] It has since incorporated enterprise resource planning (ERP) systems to improve the management of business processes.[75] It was also reported that in September 2018, Factory 211 applied 3D printing technology to the main load-bearing components of the Long March 5 rocket for the first time, setting a precedent domestically.[76]

1.3.4 Close Collaboration with Universities

Since its establishment, the "small core" has frequently collaborated with other research institutions within the defense-industrial complex, military and civilian universities, and a group of commercial companies that supply parts, materials, and auxiliary products, a practice known as "big collaboration" [大协作]. One example that illustrates the extent of the cooperation, the research and development of the JL-1 SLBM, reportedly involved a total of 109 institutions and 30,000 personnel from 19 provinces.[77]

As China seeks to further leverage civilian input to boost defense R&D capabilities under initiatives such as the MCF strategy, CASC and CASIC academies continued this tradition and enabled closer collaboration through the signing of strategic cooperation agreements, especially concerning dual-use technologies and research fields such as material science and engineering.

Launch ceremony of the "Joint Laboratory for Launch Vehicle Intelligent Manufacturing

Some examples of this strategic cooperation include:

- According to Yang Lei [杨磊], director of CASIC 4th Academy's material R&D center, the model of "small core, big collaboration," in which the 4th Academy collaborated with the National University of Defense Technology (NUDT) and several other universities, has been crucial in resolving some persistent technical difficulties in materials development and processing.[78]
- CASC 6th Academy signed a comprehensive strategic cooperation agreement with Beihang University's School of Astronautics in 2015 that included talent education and training programs and joint efforts to improve the performance of liquid rocket engines.[79]
- CASIC and the Harbin Institute of Technology are engaged in what is called "comprehensive strategic cooperation" [全方位战略合作].[80]
- CASC 1st Academy's 12th RI established the Siyuan AI Science and Technology Collaborative Innovation Alliance [思源人工智能科学与技术协同创新联盟] in December 2019. The alliance allows the 12th RI to fund AI-enabled space technology research through the Siyuan Fund and enhance cooperation with other research institutes and civilian universities such as University of Electronic Science

CHINA MISSILE EXPORTS

The PLA Rocket Force has inputs at various stages of R&D, first through the S&T Committee under the Force Equipment Department [装备部], which helps set requirements, and the Rocket Force University of Engineering [火箭军工程大学], based in Xi'an, Shaanxi.[279] The PLA Rocket Force Research Institute [中国人民解放军火箭军研究院] (originally established in December 2003 as the 2nd Artillery Equipment Research Institute [第二炮兵装备研究院]) also plays a role in designing warheads and other components and participates in expert panels. The Central Military Commission's S&T Committee and expert groups (composed of industry experts and those affiliated with military academic institutions) appear to act as evaluators of project proposals, helping shape the direction of projects and ensuring they are in line with China's requirements. At lower levels, PLARF officers are assigned to commercial enterprises, factories, research institutes, and research laboratories as part of the military representative office system [军事代表].[280]

and Technology of China [电子科技大学], Central South University [中南大学], and the Suzhou Tongyuan Software Control Information Technology Co., Ltd. [苏州同元软控信息技术有限公司].[81]

- Factory 211 and Shanghai Jiaotong University [上海交通大学] signed an agreement in October 2019 to create the "Launch Vehicle Intelligent Manufacturing Joint Laboratory" [运载火箭智能制造联合实验室].[82]

1.3.5 Dependence on Foreign Inputs and Efforts at Indigenization

Chinese media continue to refer to "foreign strict technological blockades" [国外严密技术封锁] preventing technology transfer.[83] As a result, the indigenization of technologies remains a major priority. Jiang Jie [姜杰] Academician of the Chinese Academy of Sciences (CAS) and chief designer of the LM-3A rocket has acknowledged the aerospace industry's continuing reliance on imported components, raw materials, ground equipment, and software, and said that China should continue to resort to a whole-of-nation approach [举国之力] to support its space program to realize full indigenization [全部国产化].[84]

At the same time, China is expanding its partnerships with foreign companies. Officials from Yuzhmash, a Ukrainian company that produces rocket and missile bodies have met with representatives from Chinese enterprises in May 2016.[85] In 2018, Yuzhmash participated in the China International Import Expo in Shanghai. The same year city leaders from Dalian, China visited the plant.[86] There appear to be indications that its neighbor, Yuzhnoye Design Office, is also interested in cooperation with China. Public information appears limited, but Russian companies and research institutes appear to be involved with Chinese ballistic missile development or related technologies. Russian truck manufacturer Kamaz, which produces transporter-erector launchers (TELs) and other heavy vehicles, for example, has a joint venture with a Chinese company.[87] There are also some indications of cooperation with Russia's Makeyev Design Bureau, which was involved in missile and warhead design.

There are also strong indications that China is seeking to improve its ballistic missile capabilities systems through espionage, as evidenced by arrests made in the U.S. in 2011, 2016, and 2018 related to the attempted illegal export of accelerometers and gyroscopes used in spacecraft and missile navigation, as well as specialized electronics and materials.[88]

2. Development and Production of Chinese Ballistic Missiles

While the previous section adopted an institutional perspective on the ballistic missile industry, this section provides an overview of the key phases of missile development, the major subsystems, and technologies, and the major research institutes and factories involved. Where information is available, an attempt has been made to highlight recent relevant developments that could impact missile development and manufacturing.

Modern missiles are incredibly complex systems and by necessity of course this study can only cover a fraction of the subsystems involved. Section 2.1 provides an overview of China's ballistic missile types and how their missions have evolved. Section 2.2 covers propulsion, breaking out the relevant institutions and manufacturers by solid- and liquid-propulsion engines. Section 2.3 examines the guidance and control systems used in missiles. Section 2.4 covers re-entry vehicles. Section 2.5 looks at the materials used to create missile bodies and internal structural components as well as their manufacturing techniques. Section 2.6 examines testing, 2.7 addresses the factories involved in final assembly, and 2.8 discusses the factories and institutions involved in the production of the transporter-erector-launchers (TELs) and associated support vehicles for mobile ballistic missiles.

2.1 Overview of Chinese Ballistic Missile Development

The first phase of China's missile programs involved the absorption of the copious amounts of materials transferred from the Soviet Union in the late 1950s and direct replication of the R-2 missile as the DF-1.[89] With the first successful flight of a DF-1 missile in 1960, China began to quickly ramp up efforts to develop more capable missiles while simultaneously developing nuclear weapons. Until the 1980s, the overall focus was on developing missiles for China's nuclear deterrent.

Important Phases and Events in Chinese Ballistic Missile Development		
Period		**Associated Systems**
1950-1960	Technology Absorption from USSR	R-1, R-2/DF-2
1965-1972	"Four types of missile in eight years" plan	DF-2, DF-3, DF-4, DF-5
1966	2nd Artillery established	
1965-1985s	Push to acquire a strategic deterrent	DF-5
1976-1984	Development of liquid-fueled MRBMs	DF-3, DF-4*
1980s	Development of SRBMs for export	M-9/DF-15, M-11/DF-11, 8610
1984	Shift away from liquid-fueled strategic missiles[90]	
1990s	Acceleration of developing "assassin's mace" capability	DF-21C/D
1993	2nd Artillery formally takes on conventional role	
1991-Present	Shift to rapid acquisition of SRBM force	DF-11, DF-15
2000-Present	Modernization of mobile SRBM force	DF-16
2010-Present	Development of improved long-range strike capability	DF-21D, DF-26, DF-17
2015-Present	Fielding advanced mobile ICBMs	DF-31AG, DF-41
2016	PLA Rocket Force founded	
2017	Testing of silo-basing for solid-fueled ICMBs	DF-41
*Believed to remain in service in limited numbers | Dates are estimated		

2.1.1 Nuclear Missiles

Public Figures on Chinese Nuclear Warheads			
Payload Weight (kg)	Warhead Weight (kg)	Yield	Platform
1,500	1,290	15-kt	DF-2
2,150[281]	–	1-3Mt	DF-3
2,200[282]	–	3Mt	DF-4
–	–	4-5Mt	DF-5
–	470	500kt[283]	DF-31
–	500[284]	200-300kt	DF-21, DF-31/JL-2

China detonated its first nuclear weapon in October 1964. The "four types of missile in eight years" (1965-1972) plan was successful in developing: the non-nuclear DF-2; a nuclear MRBM; the DF-3 which was fielded in limited numbers beginning in 1971; and an ICBM, the DF-4, fielded circa 1975. A DF-2, a more capable missile with more than twice the range of the DF-1, successfully launched a nuclear warhead on 27 October 1966.[91] While the overwhelming focus seems to have been on fielding strategic nuclear weapons through the late 1970s, the shift in tactics from "luring the enemy deep" (trading land for time in the face of a Soviet attack) to conventional confrontation closer to the borders appears to have helped drive investment in theater and tactical nuclear weapons. Lacking aircraft capable of successfully penetrating Soviet air defenses, China fielded nuclear and conventional missiles that provided it with some ability to respond at the strategic level, but the threat of Soviet use of tactical nuclear weapons helped drive the development of theater and tactical missiles that could respond in kind. Development of theater nuclear forces (like the nuclear-equipped DF-21 and later solid-fueled types) allowed greater flexibility.[92]

However, despite a test flight in 1971, the DF-5 ICBM, the last of the "four missiles" did not have a full-range test flight until May 1980 and was not completed and fielded until the early 1980s. In 1984 a decision was made to cease further development of further liquid-fueled strategic missiles (Project 202) and focus on solid-fueled missiles. China continues to field a small complement of legacy missiles, the roll-out DF-4, and silo-based DF-5 strategic missiles. An improved variant of the silo-based liquid-fueled DF-5, the DF-5B, was displayed at a military parade in 2015 for the first time. It is believed to be equipped with multiple independently-targetable reentry vehicles (MIRVs).[93] A further upgrade, the DF-5C may be under development.[94]

In the late 1980s there appears to have been a major shift toward highly mobile ICBMs. DF-31 began development in 1985 and was displayed in a military parade through Tiananmen in 1999.[95] As detailed in later sections, work continued on reducing weight of the warhead (a major bottleneck), and on the guidance, navigation and propulsion systems. These improvements culminated in another variant, the DF-31AG, which was first displayed in September 2015. An even more capable mobile ICBM, the DF-41, was displayed in 2019. This is also of interest as the DF-41 appears to be prepared for silo-basing, meaning it could replace or supplement the 18 DF-5s believed to be in service. The overall posture also appears to be changing. According to DOD's 2020 report on the PLA, "New developments in 2019 further suggest that China intends to increase the peacetime readiness of its nuclear forces by moving to a launch-on-warning (LOW) posture with an expanded silo-based force."[96] Other basing modes, including putting the missiles on rail cars, appear to be under consideration for the DF-41.[97]

China currently has four Type 094 ballistic missile submarines (SSBNs) but plans to grow that to eight by 2030, adding the new Type 096 equipped with the more capable JL-3 SLBM.[98] The JL-3 will allow Chinese SSBNs to target most of the United States or other targets from China's near-seas and safe "bastion" areas, rather than needing to transit areas closely monitored by the U.S. and its allies.

China is also apparently in the process of deploying an air-launched ballistic missile (ALBM) deployed from an H-6 bomber, which will serve to round out China's nuclear triad, though few details appear to be available.[99]

The PLA Rocket Force has a central warhead storage facility, located in Taibai County, Shaanxi. An additional storage facility or warhead test facility appears to be located in Luzhou, Sichuan. At lower levels, warheads are parceled out to each of the PLA Rocket Force's six operational bases have Equipment Inspection Regiments [装检团], which inspect and store the warheads.[100]

China's nuclear stockpile appears to be growing. In 2019, Lt. Gen. Robert Ashley, commander of the Defense Intelligence Agency (DIA) said "Over the next decade, China is likely to at least double the size of its nuclear stockpile in the course of implementing the most rapid expansion and diversification of its nuclear arsenal in China's history."[101]

2.1.2 Conventional Missiles

While China's conventional missiles have assumed greater prominence for their role in strikes on U.S. carriers, or against Taiwan, this role is relatively recent. Though China's ballistic missile program dates to the 1950s, Chinese leaders did not seriously envision them for tactical use until the 1980s and even then primarily as an export.[102] While they were under consideration to provide strike options against a potential Soviet invasion, in 1976 the Central Special Committee decided to switch emphasis from single-stage SRBMs to support the development of the two-stage medium-range SLBMs.[103] The resulting JL-1 was successfully tested in 1982 and later used as the basis for the later DF-21 MRBM. In 1988 China's clash with Vietnam appears to have helped spur China to develop a long-range strike capability.[104] The same year a decision was made to adopt ballistic missiles for conventional strikes.[105]

The core of China's first conventional ballistic missile brigade, equipped with the DF-15, was stood up in August 1991.[106] The Second Artillery Force was formally given a role in conventional missile strike operations in 1993.[107] SRBM tests were then used to threaten Taiwan between 1995-1996 during the Third Taiwan Strait Crisis. As noted by Andrew Erickson in his study of Chinese ASBMs, Chinese leadership's observations of several events, including the dispatch of two aircraft carrier battle groups to the area near Taiwan in March 1996, and the bombing of the Chinese embassy in Belgrade in 1999 by the U.S. was a galvanizing moment to develop anti-access/area denial capabilities and resulted in the 995 Plan /New High-Technology Plan [高新技术工程] - set up to develop next-generation capabilities including "assassins mace" missile systems.[108]

The rapid adoption and production of a new IRBM—the DF-26—points toward a continuation in the move toward longer-range precision-guided missiles. The DF-26 is capable of conventional and nuclear roles, with Chinese media claiming that the warheads for either mission are easily swappable. An article in the Global Times in 2011 acknowledged that a missile matching the DF-26s parameters was under development and would be ready by 2016, and complete a three-year evaluation period afterward.[109] It first appeared publicly in a military parade in 2015 and appears to have begun deployment by 2019. Recent tests also suggest it is capable of hitting targets at sea.

2.1.3 Relationship with Civilian Space Launch Vehicles

China's ballistic missiles have had a strong influence on its space launch vehicle programs. The DF-5 served as the basis for several generations of the Long March series. [110] Solid-fueled missiles have also served as the basis of a series of space launch vehicles including the Kaituozhe (KT) [开拓者] and Kuaizhou (KZ) [快舟] series. Many of China's most senior figures involved in the early periods of development worked extensively on both systems. Fewer connections are able to be established using public information for more contemporary work due to sensitivities surrounding the projects. However, as will be discussed in greater detail in subsequent sections, developments with technology used for space launch vehicles remains a valuable basis for understanding broader trends in missile development.

Missile	Derived Civilian Rocket
DF-4	LM-1
DF-4A	LM-1D
DF-5	FB-1
DF-5A	LM-2C
DF-15	OS-M
DF-21	KT-1/KT-2
DF-25	KZ-1A
DF-31	LM-11
DF-41	KZ-11

2.2 Propulsion

The propulsion system is the heart of a missile's design. These types of engines can be broken into two main categories based on the type of propellant they use: liquid and solid.

2.2.1 Liquid Propellant

Most liquid propellant engines combine an oxidizer (or even liquid oxygen; LOX) and some form of fuel (often kerosene, or some form of hydrazine such as Unsymmetrical dimethylhydrazine [UDMH]), as this typically produces higher specific impulse (power / weight) compared to solid rocket engines. Liquid propellant engines are capable of producing high thrust, and are easy to throttle since the flow of fuel and oxidizer can be controlled by changing or shutting off the flow pumped from storage tanks to the combustion chamber. The high thrust makes them ideal for lifting heavy loads such as a satellite or multiple warheads out of the atmosphere. These engines are also commonly used for the second and third stages where course correction or additional burns may be needed to put a missile on a trajectory toward its target.

China's earliest ballistic missiles and space launch vehicles used liquid propellants as a result of their reliance on duplicated Soviet rockets. Ren Xinmin [任新民], a U.S.-trained scientist, led the development of China's liquid propellants and rocket engines.[111]

Particularly for early generations of missiles, liquid propellants incurred significant disadvantages due to complications with storage and the fact that fueling a missile could take hours. The missile transporters had limited mobility, required large groups of personnel and vehicles to support launch operations, and used toxic propellants. While the speed of this process has been improved for modern missiles, and their cryogenic propellants can be stored for much longer, they still fall far short of the rapid launch ability of solid propellant rocket engines. The need for greater tactical flexibility, combined with changes in China's strategic environment led to a refocus on solid-propellant tactical ballistic missiles. This was further emphasized with the decision in 1984 to cease the development of additional types of liquid-fueled strategic missiles.[112] At least four PLA Rocket Force brigades equipped with liquid-fuel engines remain in service, but the main driver of continuing investment appears to be China's space exploration plans and the commercial space launch sector.

The DF-5 was used as the basis for the Long March 2, -3, and -4 space launch vehicles. Despite iterative improvements in the LM-series, breakthroughs in higher-thrust engines were apparently stymied until the 1990s when China gained access to technology for the Russian RD-120 engine used in upper stages, which was used to develop the YF-100 engine.[113] The absorption of this technology helped enable the completion of the LM-5 rocket used for the Tianwen-1 Mars mission in 2020.

Chinese engineers are also working on a new space launch vehicle, the Long March 9 [长征九号]. With a scheduled first flight in 2030, the planned rocket is 9.5m in diameter and 100m long. With five times the capacity of China's current launch vehicles, it will require a LOX/Kerosene engine that will produce 500 tons of thrust. This represents a major increase in performance compared to the 120-ton rated engines used for the LM-5. In 2019 scientists at CASC's 6th Academy announced that they are testing a turbopump to provide the fuel needed for the LM-9's engine.[114]

2.2.2 Relevant Institutions and Notable Developments:

The following are the key institutions involved in liquid-fuel engine development:

- CASC 1st Academy / CALT
  - 11th RI [11所] / Beijing Aerospace Propulsion Institute [北京航天动力研究所] – The birthplace of Chinese liquid-fuel propulsion R&D, the institute was founded in 1958. It developed the YF-73 and YF-75 hydrogen-oxygen engines.[115] It cooperates with CASC 6th Academy.

- CASC 6th Academy – The primary institute within the "small core" responsible for the development of liquid-propellant engines. The Sixth Academy has developed close to one hundred liquid rocket engines and has participated in more than a hundred major launch missions and projects including China's first artificial satellite, the development of the Shenzhou spacecraft, and the Chinese Lunar Exploration Project (CLEP).
  - 801st RI [801 所] / Factory 203 [203厂] / Shanghai Space Propulsion Institute [上海空间推进研究所] is responsible for spacecraft engine design, likely including second or third-stages on missiles and space launch vehicles.
  - 7103 Factory [7103厂] / Xi'an Aerospace Engine Factory [西安航天发动机厂] is the PRC's only large scale liquid rocket engine research and production factory. The Factory has over 3,000 employees and the engines it developed have been a major part of the Chang'e 2 lunar mission and the Long March 5 rocket. According to a 2020 article, it is making increasing use of key technologies such as laser additive manufacturing, titanium alloys, and new welding techniques.[116] The company has cooperated with or received technical assistance from Russia, Ukraine, and France.[117]

2.2.3 Solid Propellant

The vast majority of China's ballistic missiles and a growing number of its civilian space launch vehicles use solid-propellant rocket motors.

Unlike liquid-propellant engines, the fuel and oxidizer are combined in a solid propellant and the rocket motor primarily consists of the propellant, igniter, and combustion chamber, surrounded by a casing." The propellant typically has a star-shaped incision the length of the case to improve combustion. No pumps are needed to combine the fuels, though liquid fuel may be injected to facilitate thrust vectoring.

While the design of these rocket motors is mechanically simpler, making a solid rocket motor involves a complex process. Oxidizer and fuel must be mixed in large-scale planetary mixers before being poured into a cast and cured. Precise control over mixture to ensure consistent burning and of the temperature during the curing process is necessary to ensure proper operation of the rocket motor. Not only is the choice of fuel and oxidizer important but the binder that holds the solid fuel together also strongly impacts performance.

While solid-propellants do not combust as efficiently as liquid fuels, reducing the maximum generated thrust, they have several advantages. The launch sequence for solid-fuel missiles is much faster, generally 15-45 minutes, and dramatically reduces the number of necessary support vehicles from over 30 (in the case of the DF-3) to 6-8 as seen in use with the DF-21 and DF-31[118] This has the added benefits of facilitating the mobility of the unit from its basing area and reducing the detectable footprint of a launch site. Storage is another benefit, as some liquid propellants must be removed due to their corrosiveness (in the case of some hypergolic propellants) or needs to be kept at cryogenic temperatures. Solid propellants can be stored for years but can be easily readied for use.[119]

In contrast to its liquid-fueled missile program, China began the development of solid-fueled missiles without assistance from the Soviet Union.[120] As a consequence, development was much slower in comparison but appears to have picked up speed after hurdles in solid-rocket motor production were overcome in the late 1970s and early 1980s. This allowed the development of the DF-21/JL-1 ballistic missile and has contributed to the development of a host of new types.

Increasing the specific energy of the propellant used, along with decreasing the weight of the missile (by using lightweight casing or advanced manufacturing techniques) are the best ways to increase range while keeping the size the same. This is particularly important for SLBMs which are launched from tubes in ballistic missile submarines. China's JL-1 and JL-2 missiles had poor performance (the latter had an estimated range of less than 7,200km), meaning they were incapable of ranging most of China's likely enemies without the submarine transiting enemy-controlled areas. Modern Nitrate Ester Plasticized Polyether (NEPE) propellants, which have greater specific energy, allowing greater payloads or range have been have been used in the DF-31. A new type of propellant also appears to have been developed by CASIC's 4th Academy around 2006.[121]

Casting motors and the design of the rocket motor is also an important research focus for Chinese rocket scientists. China appears to have made an additional breakthrough in large-scale segmented rocket motor [分段式固体发动机] technology in 2013.[122] According to an article in *Solid Rocket Technology* by Wang Jianru [王健儒], deputy chief designer of the LM-11 at CASC 4th Academy's 41st RI, segmentation of solid-rocket motors allow more efficient and economical production of large solid rocket motors. A mature technology in the United States, Japan, and India, which have been working on it for decades, his article noted that there had been technical challenges involved in segmented solid rocket motor and flexible nozzles (which allow thrust vector control) tech.[123] CASIC started the development of a large-diameter solid propulsion engine, possibly for the JL-3, in 2013.[124]

While details on missile-specific rocket motors are scarce, there has been a general rise in investment in civilian space launch vehicles. The growth of space-based services and commercial launches to support them is further driving investment in solid-propellant rocket development and production.

As noted in Section 3.1, some of the designs for missiles were spun off into space launch vehicles, from the LM-1 to the Kuaizhou series. CASC's Kaituozhe tested the KT-1 series launch vehicles based on the DF-21 in the early 2000s. A larger series possibly based on the DF-31 was tested in 2017. It is possible that this trend is continuing, or even going the other way, with technology developed for space launch vehicles furthering missile development.

Development of the Kuaizhou rocket began in 2009. While the Kuaizhou can only carry payloads that are much smaller than the average communication satellite, its low-cost, mobility, and speed of launch offer capabilities most similar launchers cannot. The KZ-1A for example has been described as only taking seven days to be delivered to a launch site, and from there the preparation and launch cycle only four hours.[125] To support a fast launch tempo, ExPace [航天科工火箭技术有限公司], a subsidiary of CASIC, will produce some 20 solid-propellant rocket vehicles at its Wuhan facility, the Kuaizhou General Assembly Center [快舟总装总调中心], in the Wuhan National Aerospace Industry Base [武汉国家航天产业基地] in Hubei province.[126]

CASC 1st Academy has developed the Long March 11 solid-fuel carrier rocket, currently used to launch microsatellites. It first flew from Jiuquan in September 2015. A new variant, the LM-11A is being designed to send a 1.5-ton payload to sun-synchronous orbit at an altitude of 700kilometers. It is expected to make its first flight sometime in 2022.[127]

In 2014, a team led by Wang Jianru began work on a 3m-diameter design that would produce 150-tons of thrust. They successfully fired a 2m-diameter rocket in 2016.[128] Even larger rocket motors appear to be under development. According to Liang Jiqu [梁纪秋], chief designer of the Kuaizhou-series, solid-fuel rocket motors over 4-meters[129] in diameter are under development for the Kuaizhou-21 and Kuaizhou-31, which will be capable of putting 20 and 70 tons respectively in low-earth orbit.[130, xvii]

CASC is building the Dongfang Aerospace Port [东方航天港], located in the city of Haiyang in Shandong Province [海阳市]. Its associated manufacturing facility at Duoshan Hill [垛山的小山包] will be capable of producing 20 solid-propellant rockets per year and be capable of carrying out 10 launches per month.[131] The facility will also support sea-based launches. In June 2019 China conducted its first launch from an offshore platform. The self-propelled deck barge could help mitigate the risks launches pose to populated areas, as boosters have a tendency of falling on and causing damage to them as well as risking exposure to toxic chemicals.[132]

Other commercial companies are also involved in developing space launch vehicles. Beijing Interstellar Glory Space Technology Co. [北京星际荣耀空间科技有限公司] (i-Space) has developed a four-stage solid-fuel rocket, the Hyperbola 1.[133] OneSpace [零空] is building an "intelligent assembly manufacturing base" in Chongqing's Liangjiang New District [两江新区龙兴工业园] with an area of over 8,200 square meters that will be capable of producing 30 rockets per year.[134]

Commercial rocket developer S-Motor [北京灵动飞天动力科技有限公司] announced in October 2019 that it had successfully developed reverse-thrust technology for its solid-rocket motor engines.[135] Reverse thrust not only has application for commercial space launch, where precise orbits are necessary but also in ballistic missiles, where the technology can be used to adjust flight path and ensure proper separation between the warhead and other stages.[136]

xvii For comparison, the DF-5 silo-launched liquid-fueled ICBM and DF-41 solid-fueled mobile ICBMs have diameters of 3.4 and 2.3 meters, respectively

2.2.4 Relevant Institutions and Notable Developments:

The following are the key institutions involved in solid-propellant research and development:

- CASC 4th Academy – China's primary developer of solid-propellant missiles, it has a large number of affiliated institutes and factories.
    - 41st RI [41所] / Shaanxi Power Machinery Institute [陕西动力机械研究所] – Located in Xi'an it is involved in solid rocket motor design
    - 42nd RI [42 所] / Hubei Red Star Chemical Research Institute [湖北红星化学研究所] – This institute develops solid rocket motor propellant. In 2020 a production unit of the institute that produces products for the military began replacing manual labor with new remote-controlled automated guided vehicle (AGV) [无人搬运车]. These efforts have seen major efficiency gains and freed up positions that previously required large numbers of personnel.[137]
    - 401st RI [401 所] / Xi'an Space Propulsion Xi'an Aerospace Power Measurement and Control Technology Institute [西安航天动力测控技术研究所] develops solid-propellant rocket motors.
    - Factory 7414 [7414 厂] / Xi'an Space Propulsion Machinery Factory [西安航天动力机械厂] – Involved in machining rocket motor components. In 2020 the factory announced that they had made breakthroughs in metal shell fabrication [金属壳体], including titanium alloys for engines.[138]
    - Factory 7416 [7416 厂] / Xi'an Aerospace Chemical Power Plant [西安航天化学动力厂] – Responsible for Solid rocket motor preparation and assembly. This is the main solid motor propellant production and general assembly facility for larger solid motors, such as those used with the DF-31 and JL-2. The production facility appears to be located in Xi'an's Baqiao District [灞桥区].[139] In June 2018 the factory set a record for propellant production and loading due to efforts to digitalize its assembly line and to install a sophisticated quality control system.[140]
    - In June 2020, a key laboratory [重点实验室] was set up in Hubei Province under the Academy's 9th Department [九部]. The laboratory is intended to take advantage of digital cooperative design to enhance the development of advanced liquid propulsion technology and large-diameter rocket motors.[141]

- CASIC 4th Academy
    - Fourth Design Department [四设计部] /Beijing Mechanical and Electrical Engineering General Design Department [北京机电工程总体设计部] / CASIC Carrier Rocket Technology Research and Development Center [航天科工运载技术研究开发中心] - Involved in the overall design of solid-fueled ballistic missiles, including the DF-21. The 4th Academy augments the CASC First Academy in supplying solid-fueled short- and medium-range ballistic missiles, such as the DF-21D anti-ship ballistic missile system. According to the 4th Design Bureau's Party Secretary Zhang Shaojun [张邵军], the bureau spends 100 million RMB ($14.9 million) on R&D annually.[142]
    - Jiangbei Factory [江北厂] – formerly part of the 9th Academy, this factory is involved in solid rocket motor manufacturing
    - Jianghe Factory [江河厂] / Chemical Power Technology Institute [化学动力技术研究所]/ Jianghe Factory Test Center [江河厂试验中心] – Formerly under the 9th Academy it is involved in solid rocket motor manufacturing and tests solid propellant formulas. In the early 2000s, it began work on a high-energy propellant, N15, which saw a significant breakthrough in development in 2006.[143]

- CASIC 6th Academy - Responsible for development of DF-21/JL-1
  - 41st RI [41 所] / Inner Mongolia Power Machinery Research Institute [内蒙动力机械研究所], located in Hohhot, Inner Mongolia - Involved in solid rocket motor design. In 2018, a 3D-coordinated R&D platform for solid-propellant engines developed by the 41 Institute passed its evaluation. This platform allows different factories and research institutes to carry out coordinated R&D processes through centralized control and management of design data and technical status.[144]
  - 46th RI [46所] / Inner Mongolia Synthetic Chemical Research Institute [内蒙古合成化工研究所] – Involved in solid rocket motor propellant formulation. The 46th Research Institute's 605th Lab [中国航天科工六院46所605室], is the only lab under CASIC specializing in the development of high-energy solid propellant formulas.[145]
  - 601th RI [601 所] / Inner Mongolia Power Machinery Testing Institute [内蒙动力机械测试所] - Solid rocket motor test technology
  - Factory 359 [359 厂] / Honggang Machinery Factory [红岗机械厂], located in Hohhot, Inner Mongolia. The factory is involved in solid rocket motor assembly. Work on a 1780-square-meter production facility was completed in 2009, possibly to support DF-21 rocket motor production.[146]
  - Factory 389 [389 厂] / Hongxia Chemical Plant [红霞化工厂] – also in Hohhot, produces solid rocket motors.
  - A solid rocket motor production facility covering over four square kilometers is located in Hohhot's Saihan District [赛罕区].[147]

2.3 Guidance and Control

Two subsystems are responsible for keeping the missile headed toward its target and making the necessary course corrections to get it there. Section 3.1 covers the first of these, guidance systems [制导系统], and the primary types: inertial, celestial, satellite and optical or terrain matching systems. The second major subsystem, the control system that physically directs the missile, is covered in 3.2

2.3.1 Guidance

Missiles can use a number of different guidance systems. Small air-to-air missiles use infrared sensors or radars to detect their target. For ballistic missiles, which often fly hundreds or thousands of miles to their target, a different set of guidance systems is necessary.

While rudimentary guidance was sufficient for China's early generations of nuclear ballistic missiles, which were intended to put large cities under threat, the smaller payloads and sharp drop-off in effectiveness as the distance from a target increases seen in tactical and long-range conventional ballistic missiles require them to be highly accurate. While historical records and interviews indicate that China struggled to produce sufficiently accurate missiles during the 1970s and '80s, the introduction of new technologies has vastly increased these capabilities, meaning that China is now fielding missiles with Circular Error Probables (CEP) of less than five meters.

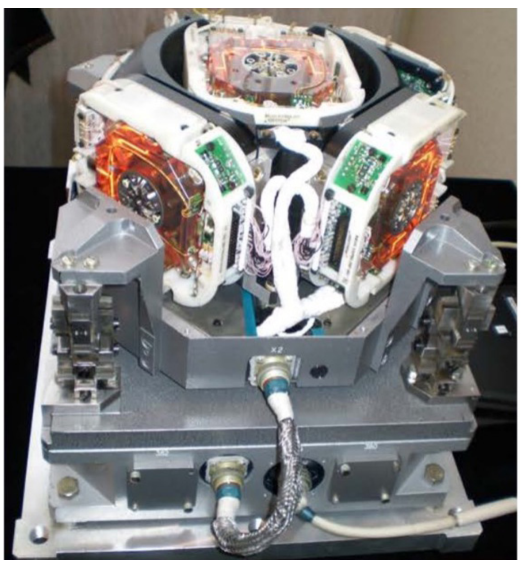
Other public estimates of the accuracy of Chinese missile systems indicate that they have improved by at least 300 percent for strategic missiles and over 500 percent for tactical missiles since the early 2000s (see Appendix 1). These guidance systems are being miniaturized and applied to other munitions. CASC subsidiaries also offer series of Joint Direct Attack Munition (JDAM)-like kits for converting traditional bombs and glide bombs into guided munitions, with listed CEPs of under 30meters.[148]

With the expansion of earth observation, China's Beidou global navigation satellite system (GNSS), and data relay satellite constellations, the technological foundations for a more accurate satellite-navigation-guided ballistic missile system have been put into place.

Inertial Navigation Systems

The first and most common type is inertial navigation systems, which precisely measure shifts in attitude.

Laser Gyroscope for Navigation Systems (Ukraine)



Inertial Measurement System (Ukraine)

These systems measure angular rate of change and are a core component of strap-down inertial navigation systems. When combined, they allow full measurement of all vectors of movement, as seen in this inertial measurement unit for spacecraft, also produced by Arsenal.

The development of inertial guidance systems began in the 1960s as part of China's short- and medium- range ballistic missile programs.

Miniaturization of inertial guidance systems was also a priority for solid propellant missiles due to their small size in comparison to the larger liquid-fueled DF-4 and DF-5. According to interviews with missile, developers involved the technology was the focus of a massive and expensive combined effort and involving many organizations across China's aerospace industry.[149] In an interview, Han Jindui [韩金堆], a missile designer at the time, noted that the earliest generations of China's solid-propellant missiles were very simple and only capable of addition operations.[150]

Few developments appear to be available regarding more recent systems.

Celestial and Satellite Guidance Systems

Errors in inertial guidance systems accumulate over distance, making multiple types of guidance systems desirable. Other navigation systems which have been employed on ICBMs and SLBMs are celestial or stellar navigation systems [星光制导/天文制导]. These are used for missiles that transit space and use an optical sensor to compare positions of bright stars against a digital map. This system has the benefit of not relying on GNSS, which can be attacked, and can be used to supplement inertial systems. Chinese scientists began work on stellar navigation as early as 1975.[151]

Satellite navigation [卫星定位], using signals from a Global Satellite Navigation Systems (GNSS) can be used to update a missile on its position and velocity. Pre-GNSS, precision timing for missile tests and satellite launches required long-distance Longwave radio time stations [长波授时台]. In the early 1970s, the 20th Research Institute along with the 761 Factory [761厂] began the development of long-wave time stations to support ICBM test flights and satellite launches. The 3262 Longwave time station in Shaanxi, which provided millisecond accuracy, began initial operations in 1976. In the mid-1970s China began developing its first set of long-distance datalinks that could provide navigation data, including the intermediate range Changhe 1 [长河 1 号] system long-range system, Changhe 2, and Changhe 3 short-range system. [152] The Changhe system was used in an SLBM test to correct inertial guidance in the South China Sea.

The medium and short-wave Type 304 Short Range Positioning System [高精度近程定位系统] had an accuracy of ±5 meters, and was effective for nearshore navigation and minesweeping operations. It was also used in tests of ICBMs and SLBMs. A mobile medium-range system, the 820, was developed by the 20th RI in the early 1980s. It was compatible with the Changhe 2 and international systems and appears to have entered service in the mid-to-late 1980s. China's access to microprocessors in the early 1980s allowed rapid development of more advanced navigation and timing systems.

China's indigenous GNSS, Beidou, began to be introduced in 2003 and was completed in 2020. While there are few details available a 2004 academic paper that examined the impact of the early Beidou constellation assessed that even a small constellation could significantly improve the accuracy of DF-5 ICBMs.[153] As of October 2020, there are 44 active Beidou satellites in operation.[154] The completed system has full global reach and is said to have centimeter-level accuracy.

Chinese companies have offered a number of ballistic missiles and MLRS systems with combined GNSS (GPS/GLONASS/Beidou) and inertial guidance for sale, including the DF-12/M-20 and the Firedragon 140A 300mm guided rocket.[155]

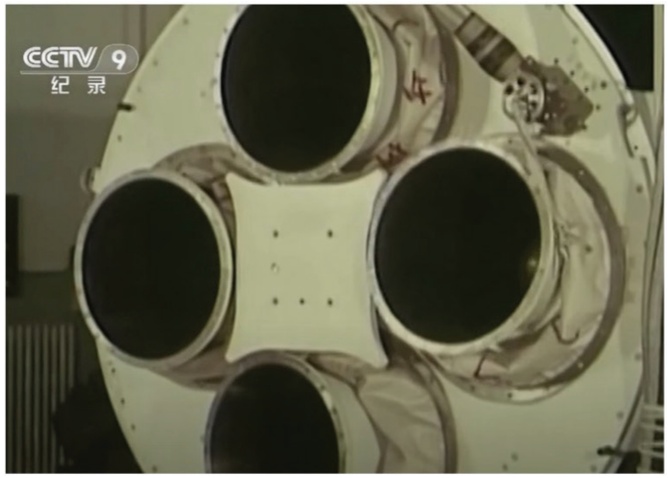
Optical and Terrain Matching (TERCOM)

Optical and radar sensors, which compare terrain or the shapes of objects against an internal database can also be used. Terrain matching (TERCOM) or Digital Scene Matching Area Correlator (DSMAC) is used in cruise missiles and may be used in ballistic missiles. [156] Optical sensors have been developed for use in ballistic missiles, including anti-ship ballistic missiles (ASBM).[157]

2.3.2 Control

As opposed to guidance, which provides instructions to the missile on its position relative to the target, the Control System ensures that the missile is steady in flight and makes course corrections to guide it to the target. To make these adjustments, depending on the missile type, several systems can be used.

Some missiles use aerodynamic control surfaces: large fins toward the rear of the missile and small ones closer to the nosecone to make adjustments while the missile is passing through the atmosphere. The direction of thrust can also be changed directly. This is typically done by two methods: gimballing the thrust chamber and nozzle itself (mounting on a frame that allows controlled movement in multiple directions) or using jet vanes to divert the rocket exhaust in the desired direction. The liquid-fueled DF-5 adopts gimballing, while the older liquid-fueled DF-3 and most solid-fueled missiles appear to use jet vanes. Video of the solid-fueled JL-1 shows that it had independently maneuvering nozzles (see inset), and the DF-21 may as well.



JL-1 SLBM

Injecting liquid fuel into the combustion chamber of solid-fuel rocket motors can also be used to direct thrust. This method appears to be much lighter (only requiring graphite vanes and a hydraulic system compared to the gimbal system) but is less precise as the vanes themselves are eroded by the motor's exhaust.

In the image to the right, you can see both the aerodynamic control surfaces on the reentry vehicle and jet vanes on a DF-15 missile.


A missile is lifted out of a support vehicle in preparation for loading into a TEL.

2.3.3 Relevant Institutions and Notable Developments:

While details on developments involving ballistic missile guidance systems themselves are scarce, it is worth noting that Chinese media describes the indigenization of microchips for aerospace applications (including CPUs and radiation-hardened microchips) as a key obstacle. This has, in part helped drive multiple rounds of reorganization.

In the early 2000s, the research institutes and factories involved guidance were reorganized to accelerate programs set out by the 10th Five Year Plan.[158] This included the creation of the Aerospace Time Instrument Company [航天时代仪器公司], also known as CASC 10th Academy, out of elements of Factory 13 and 230 in Beijing, and Factory 7107 and 7171 in Shaanxi, and Factory 803 in Shanghai.[159] Xie Tianhuai [谢天怀], who served as chief engineer for the 10th Academy was a pioneer in developing strapdown inertial systems for the LM-2C rocket and Shenzhou spacecraft.[160]

- CASC 1st Academy /CALT
    - CALT's 12th RI / Beijing Aerospace Automatic Control Research Institute [北京航天自动控制研究所], was founded in 1958. It is China's earliest integrated institution for missile and space launch vehicle development.[161] According to a 2020 report, the institute is working to develop "smart rockets" that use onboard computers to actively monitor and adapt to changes in the rocket's flight and data from internal systems, decreasing the chance of failure throughout a mission.[162]
    - 18th RI / Beijing Research Institute of Precise Mechatronic Controls [北京精密机电控制设备研究所]. The 18th RI has merged with Factory 811 [811 厂] also known as Long March Aerospace Control Engineering Co. [长征航天控制工程公司], which is focused on servo and hydraulic control.
- CASC 5th Academy
    - 502nd RI [502所] / Beijing Institute of Control Engineering [北京控制工程研究所] – Founded in 1956 this institute has been involved in most major space-related projects including the Dongfanghong-1 and Shenzhou docking mission. The institute appears to be focused on navigation, guidance, and satellite attitude control technologies, some with applications for ballistic missile reentry vehicles.[163] In 2009 the Institute established a joint Space Navigation Guidance and Control Research Center with Beihang University which included a space vehicle and missile laboratory.[164]
- CASC 9th Academy – In 2009, elements of CALT/1st Academy and Fifth Academy and 10th Academy were folded into what was called the "New 9th Academy" [新九院] to among other things, help overcome China's reliance on imported aerospace-grade microchips for aerospace applications. Much of the work on electronic systems for satellites, rockets, and ballistic missiles, including navigation guidance and control systems has been consolidated this new 9th Academy.165 It includes the following institutions engaged in work on ballistic missiles:
    - 13th RI [13所] – Founded in 1956, it is China's earliest research institute involved in inertial guidance technology. Based in Beijing it currently employs some 3,500 people and has participated in all major space exploration projects and its work incorporated into defense programs. produced designed laser inertial systems [激光惯组], and fiber optic gyroscope units [光纤陀螺组件] for the Long March-3A that has been the basis of later developments for carrier rockets.[166]
    - 16th RI [16] / Xi'an Aerospace Precision Electromechanical Institute [西安航天精密机电研究所] / Shaanxi Cangsong Machinery Co., Ltd. / Factory 7171 [7171厂] – Based in Xi'an, the 16th

RI is China's preeminent institution producing inertial guidance systems, it was founded in 1966 to produce liquid floating gyroscopes [液浮陀螺].[167] It is involved in the development of fiber-optic gyroscopes [光纤陀螺] and strapdown inertial systems.[168]

- 704th RI [704所] – This institute is involved in inter-satellite datalink and communication applications that may be relevant to missile navigation.[169] It has been described as responsible for 80 percent of the LM-3A rockets' measurement and communication equipment [测量和通信].[170]
- 771st Research Institute [771所] – This institute is responsible for onboard computers [火箭"大脑"] used in the Long March-3A series rocket.[171]
- 772nd RI [772所] – This institute appears to be involved in development of circuits for satellites, and presumably other aerospace-specific microchips and other components.[172]
- Factory 7107 [7107厂] / Shaanxi Aerospace Navigation Equipment Company Ltd [陕西航天导航设备有限公司] / China Academy of Aerospace Electronics [中国航天电子技术研究院] – based in Baoji [宝鸡], Shaanxi.

- CASIC 4th Academy

  - 17th RI [17 所] / Beijing Institute of Control and Electronic Technology [北京控制与电子技术研究所] – Founded in 1968, this institute is involved in R&D of automatic control systems, guidance and control and tactical C4ISR systems and precision guidance. Affiliated experts include Academicians of the CAE Chen Shinian [陈世年] Chen Deren [陈德仁],[173] and Luan Enjie [栾恩杰].[174] Luan directed work on the JL-2 and DF-21 and has been a key figure in the development of long-range mobile missiles. It is located in Beijing's Muxidi neighborhood [北京木樨地].

Two additional institutions formerly under the 9th Academy are now under CASIC 4th Academy:

- Xianfeng Factory [险峰厂] / Institute of Microwave and Guidance Technology [微波与制导技术研究所], – This factory is involved in production of missile guidance radars.
- Hongfeng Factory [红峰厂], / Control Equipment Research Institute [控制设备研究所] – This factory is involved in inertial systems.

2.4 Reentry Vehicles

2.4.1 Overview

The payload, or carrying capacity of the missile, can include a single warhead or specialized "post-boost vehicle" (PBV) carrying multiple warheads. The warhead itself is typically protected in a reentry vehicle (RV), a specialized and above all heat-resistant design to allow the sensitive electronics and warhead to survive the transit back into the atmosphere. An ICBM's reentry vehicle can reenter the atmosphere at roughly 7,200 m/second and experience more than 50 g from aerodynamic drag.[175] Developing components capable of withstanding these conditions requires its own specialized R&D cycle with high-temperature materials and material light yet strong enough to withstand the g forces.

Additionally, to survive ballistic missile defenses, many reentry vehicles incorporate penetration aids or mask their observability in a range of electromagnetic wavelengths from the visual spectrum to radio waves to decrease the likelihood of interception. Many reentry vehicles also now have terminal maneuverability to hit moving targets or avoid defenses.

During the boost phase, the rocket booster lifts the RV to the desired altitude, before separating. In the case of multi-stage missiles, the second booster then ignites. Those with PBVs, which may include engines for course corrections, as well as a guidance, navigation, and control system, are last to separate and can make the required adjustments to put reentry vehicles on course for different targets.

During the subsequent mid-course phase, the RV makes course corrections and orients itself for reentry. In the case of a missile with a post-boost vehicle, such as an ICBM with MIRVs, the PBV may spin or otherwise change course and release its RVs to direct them toward different targets.

The bus or reentry vehicle may also include decoys and other "penetration aids" (see below) to reduce the likelihood of a successful interception by an antiballistic missile. The DF-5C and DF-41 are believed to employ PBVs.[176]

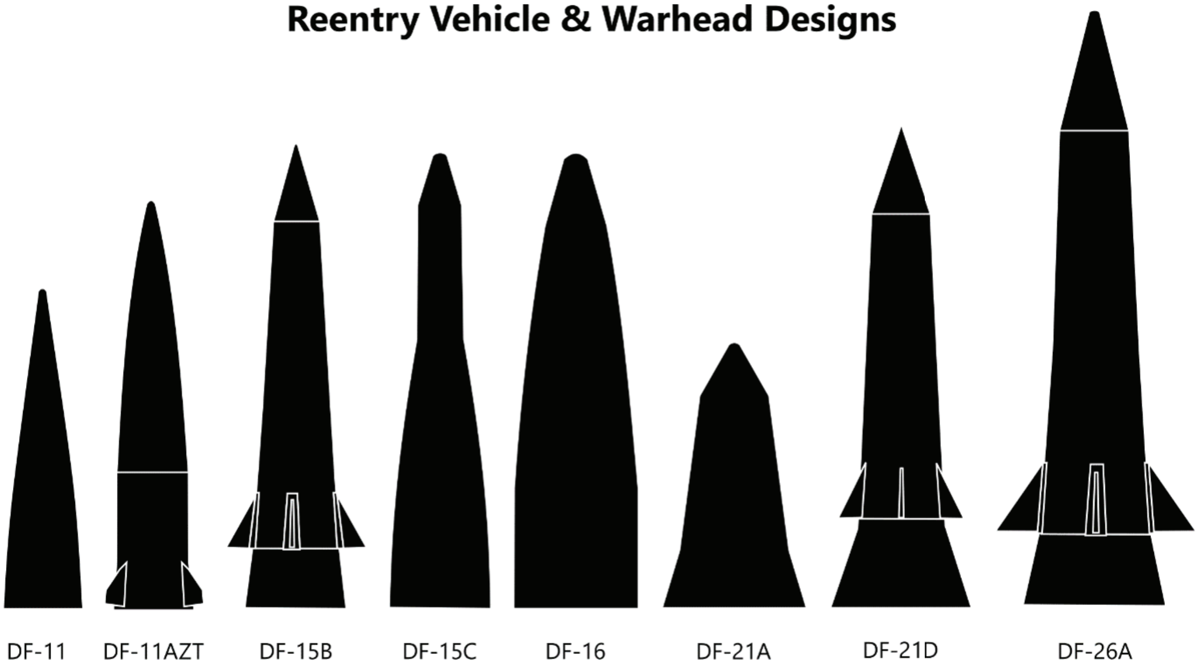
Russian / Soviet countermeasures / penetration aids

In the terminal phase, the RVs reenter the atmosphere. Depending on the type of RV, it may engage in a pull-up maneuver for additional distance and to allow time to orient itself toward its target. It may also begin terminal maneuvers to guide itself toward its target and help evade defenses. The warheads themselves can be broken down into conventional and nuclear types. Conventional warheads include, among others, 'bunker busters' capable of penetrating tens of meters of reinforced concrete as well as cluster munitions intended to deliver small bomblets to crater runways or destroy multiple targets over a large area.

While few details are available, general designs observable from photographs of missiles and other evidence suggest that a wide range of conventional warhead designs have been tested, from bunker busters to specialized submunitions to attack runways (See Section 2.6 for more detail). Some "bunker-busting" [钻地] variants have been developed including the DF-11AZT, DF-15C, and an unidentified DF-16 warhead variant.[177] Estimates in Chinese media put these as being able to penetrate 25 meters of reinforced concrete in the case of the DF-15C and 40-50 meters in the case of the DF-16.

Since the mid-2000s China has fielded an increasing number of missiles with maneuverable reentry vehicles (MaRVs), most notably the DF-21D and anti-ship variant of the DF-26 "carrier killers." The missiles were tested against a maneuvering target vessel in August 2020.[178]

Example Chinese Ballistic Missile Reentry Vehicle & Warhead Designs



Graphic by Peter Wood

Nuclear Warheads

With the development of the JL-2 and DF-31 China renewed emphasis on miniaturization of nuclear warheads. At the same time work on improvements to existing ICBMs appears to have continued. In January 2017, a claim of a test of "DF-5C" with multiple reentry vehicles was announced in a 2017 article, citing unnamed U.S. sources. While this claim was reproduced widely and commented on, there are no additional sources substantiating this designation.[179]

Since the 1990s there appears to have been an additional emphasis placed on developing countermeasures to defeat anti-ballistic missile defense systems and ensure that China's limited arsenal posed a credible threat. The proliferation of early warning systems, such as Taiwan's purchase of a PAVE PAWS early warning radar in 2000, deployment of additional advanced radars such as the Sea-Based X-Band Radar in 2006, and the deployment of Terminal High Altitude Area Defense (THAAD) radars to South Korea in 2017 (which China regards as targeting itself) have likely further incentivized China to continue development of countering technologies.

This also matches comments from Chinese experts. Speaking about changes in warhead development Chinese missile expert Huang Chunping [黄春平] noted that the major shift he observed throughout his career was the increased focus on penetrating missile defenses and that the older types he had worked on could not change orbits, deploy decoys, deploy MIRVs or employ stealth coatings.[180] More modern warheads must have multi-spectral stealth characteristics and use a range of deceptive methods to fool defenses including enhancing radar returns (for decoys), faking infrared signatures, or electronic jamming.[181] Other efforts include improving the lift-to-drag ratio of the warhead design to increase range beyond what additional propulsion can add and improve maneuverability to avoid countermeasures. In testimony in 2020, Gen. O'Shaughnessy the commander of NORTHCOM, testified that China is testing is an intercontinental range hypersonic glide vehicle.[182]

Summing up China's level compared to the United States and Russia, Huang said that "overall we lag behind…but not in every respect…We have second-mover advantage, and, given time, we can catch up and surpass them in many ways."

2.4.2 Relevant Institutions and Notable Developments:

- China Academy of Engineering Physics (CAEP) [中国工程物理研究院], in Mianyang, Sichuan, is responsible for the development of nuclear weapons.
- CASC 1st Academy
    - 14th RI [一院十四所], Beijing Institute of Space Long March Vehicle [北京航天长征飞行器研究所], involved in development of re-entry vehicles.
    - Hubei Spaceflight Vehicle Research Institute [湖北航天飞行器研究所]
- CASIC 4th Academy
    - Ninth Design Department [九部] / Hubei Space Vehicle Research Institute [湖北航天飞行器研究所] / Conventional Warhead Research Institute [常规弹头研究所]/ Space Vehicle Research Institute, located in Wuhan, Hubei Province. Involved in overall missile design, including design of the DF-11.
    - Honglin Factory [红林厂] /Missile Fuse Institute [导弹引信研究所] / Hubei Sanjiang Aerospace Honglin [湖北三江航天红林探控有限公司] formerly part of the 9th Academy.

2.5 Materials

Materials science plays a crucial role in rocketry, from the high-temperature-resistant materials used in the combustion chamber and reentry vehicle to high-strength metal alloys, aramid fibers, and composites used in the body and internal structural components.

2.5.1 Overview

While this tends not to be thought of as its own sub-system, the airframe of the missile requires rigidity while being lightweight. Producing these shells for the rest of the missile often involves advanced metallurgy for lightweight alloys. For rockets, the weight of the structure is 50 percent of the unfueled rocket, so cutting structural weight is a key part of improving performance. In the case of solid-propellant missiles, the composite-motor casing is made using filament winding machines that wrap high-tensile strength fibers to create a lightweight but strong body for the rocket motor or other components. Liquid-fueled missiles appear to use mostly lightweight alloys, though the lower and upper stages of missiles sometimes different materials. The DF-21 for example has been described as using a high-strength steel first stage and a fiberglass reinforced plastic composite upper stage.[183]

Other considerations include the wide range of environmental conditions encountered in wartime launch scenarios (rain, sand, snow, or wind) requiring casings need to withstand environmental effects, in addition to the stress of being launched into space.

Another focus area for material science is the manufacture of engine nozzles, which must be lightweight and heat resistant. Chinese companies are beginning to apply laser sintering and other new additive techniques to the production of these parts, speeding production while improving the effectiveness of the engine itself.


Examples of missile bodies made by filament winding

2.5.2 Relevant Institutions and Notable Developments:

- CASC 1st Academy
  - 702nd RI [702所] / Beijing Institute of Structural and Environmental Engineering [北京强度环境研究所]. Located in Beijing's Fengtai district, the institute was founded in 1956 is involved in static and thermal testing of rocket and missile components.[184]
  - 703rd RI [703所] / Aerospace Research Institute of Materials & Processing Technology [航天材料及工艺研究所]. The institute has made improvements in the manufacturing of orbital adjustment engines used in rocket second and third stages.[185]

Alloys

Alloys are used for the lower stages of liquid fuel rockets and missiles and for internal structures. The DF-5 for example used Aluminum-copper [铝铜合金] and Aluminum-magnesium [铝镁合金] alloys.

- CASC 8th Academy's 800th RI [800所] in Nantong [南通市], Jiangsu Province has made breakthroughs in the production of high-strength, lightweight alloys and expanding production to reduce costs.186 In 2019, for example, the 800th RI managed to reduce the weight of an unidentified rocket's structure by 10 percent by developing an aluminum-lithium alloy for the fuel tanks.187

Fibers and Composites

Solid rocket motor cases, in particular, appear to primarily use composites and fiber-wound materials. New composites and large-scale manufacturing techniques involving these technologies have seen some significant developments:

- CASC 4th Academy - The Academy announced that it had made a breakthrough in carbon-fiber winding for solid-propellant rocket motor bodies. Applied to the LM-11, it will also allow for lighter cases for the 4.2m-diameter Kuaizhou 21 and -31 rockets.188
  - 43rd RI, Xi'an Aerospace Composite Materials Research Institute [西安航天复合材料研究所], composite materials research and production
- CASIC 6th Academy
  - Ma Yanli [冯艳丽], a scientist at the 46th RI [46所][189] is involved in the development of F-12, an aramid fiber which is described as having use in missile bodies [导弹壳体], specifically for solid-propellant missiles.[190]

Manufacturing Techniques

The manufacturing techniques used to produce a rocket's structure can significantly affect its total weight. Reducing the number of fasteners connecting components, or increasing rigidity while decreasing overall weight can lead to better performance. The introduction of new welding techniques which reduce the amount of material used appears to be a significant breakthrough in worldwide aerospace production since the mid-1990s.

Capital Aerospace Machinery Co., Ltd. (Factory 211) in particular appears to have made significant improvements in the production of storage tank technology due to this development. This apparently involved acquisition of friction stir welding technology, which was prioritized in 1997 and saw domestic breakthroughs in 2004 before successful application in domestic Long March rockets in 2009.[191] Presumably, this technology would have been made available for the upgraded DF-5 and other missiles. An article in the *Journal of Materials Science & Technology* by scientists working at CALT and Capital Aerospace Machinery Company, described the technology as "having enormously improved the fabrication ability of Chinese aerospace industry."[192]

Commercial launch company Landspace has begun using automated laser sintering to produce rocket nozzles for its TQ-12 LOX/methane engine that is capable of producing 80-tons of thrust.[193] Using this technique means that lighter, stronger designs with better heat dissipation characteristics can be created at higher speeds than before.

2.6 Testing

2.6.1 Overview

Missile R&D of course requires extensive testing facilities, rocket engine test stands, drop test facilities, wind tunnels, and live missile testing, and impact ranges. This is primarily broken into wind tunnel testing, ground testing, and flight testing phases. Unsurprisingly few details of individual warhead designs are available, but some of the infrastructure needed to support this research and involved institutions have been identified.

JF-12 Hypersonic Shockwave Duplication Windtunnel

2.6.2 Wind tunnel testing

Reentry vehicle designs and associated materials are tested through the use of hypersonic wind tunnels which simulate the speed of airflow at speeds over five times the speed of sound (Mach 5).

Reentry vehicle test body being lifted into a hypersonic wind tunnel (FL22)

- JF-10 - China's first hydrogen-oxygen detonation wind tunnel, was completed in 1998.[194]
- JF-12 – Hypersonic Shockwave Duplication Windtunnel [复现高超声速激波风洞]. Located in Beijing's Huairou district [怀柔区], the tunnel is some 265 meters long and weighing over 1,000 tons, Chinese media has nicknamed the JF-12 the Hyper-Dragon [超级巨龙].[195] Work on the JF-12 began in 2008; it came online for the first time in 2012. It was completed in 2017 after 16 years of development.[196] The 2.5-meter diameter wind tunnel allows researchers at the Institute of Mechanics (Chinese Academy of Sciences) to replicate conditions at altitudes of 25-40 kilometers (roughly 82,000-164,000 feet) and speeds of Mach 5-10.[197, xviii] The JF-12 is also significantly more capable in terms of simulating high temperatures and can simulate 3500K (3226 degrees Celsius), compared to conventional hypersonic wind tunnels which typically can only reach 1000K. Perhaps most important is the fact that it can maintain these conditions for test times of over 100 milliseconds.[198] Jointly supported by the Ministry of Finance and the Chinese Academy of Sciences, the wind tunnel is one of eight major R&D areas under the National Medium- and Long-Term Science and Technology Development Plan (2006-2020) [《国家中长期科学技术发展规划纲要（2006—2020年）》].[199] According to Hong Kong-based Wen Wei Po, construction of the wind tunnel cost 46 million RMB (roughly $6.6 million).[200]
- JF-22 – China's newest-large scale wind tunnel, JF-22 is capable of testing speeds between Mach 7-30.[201] State television coverage of the wind tunnel showed what appears to be a reentry vehicle being hoisted into the wind tunnel (left).[202]

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xviii For context, the "Kármán line" typically used to denote the altitude where space begins is an altitude of 100 kilometers (62 miles).

2.6.3 Ground Testing

This phase includes static tests of rocket engines and drop testing of reentry vehicles.

During the Third Front period in the 1960s the 6th Academy test site in Fenzhou, Baoji, Shaanxi was China's only aerospace liquid power research and development base.[203]

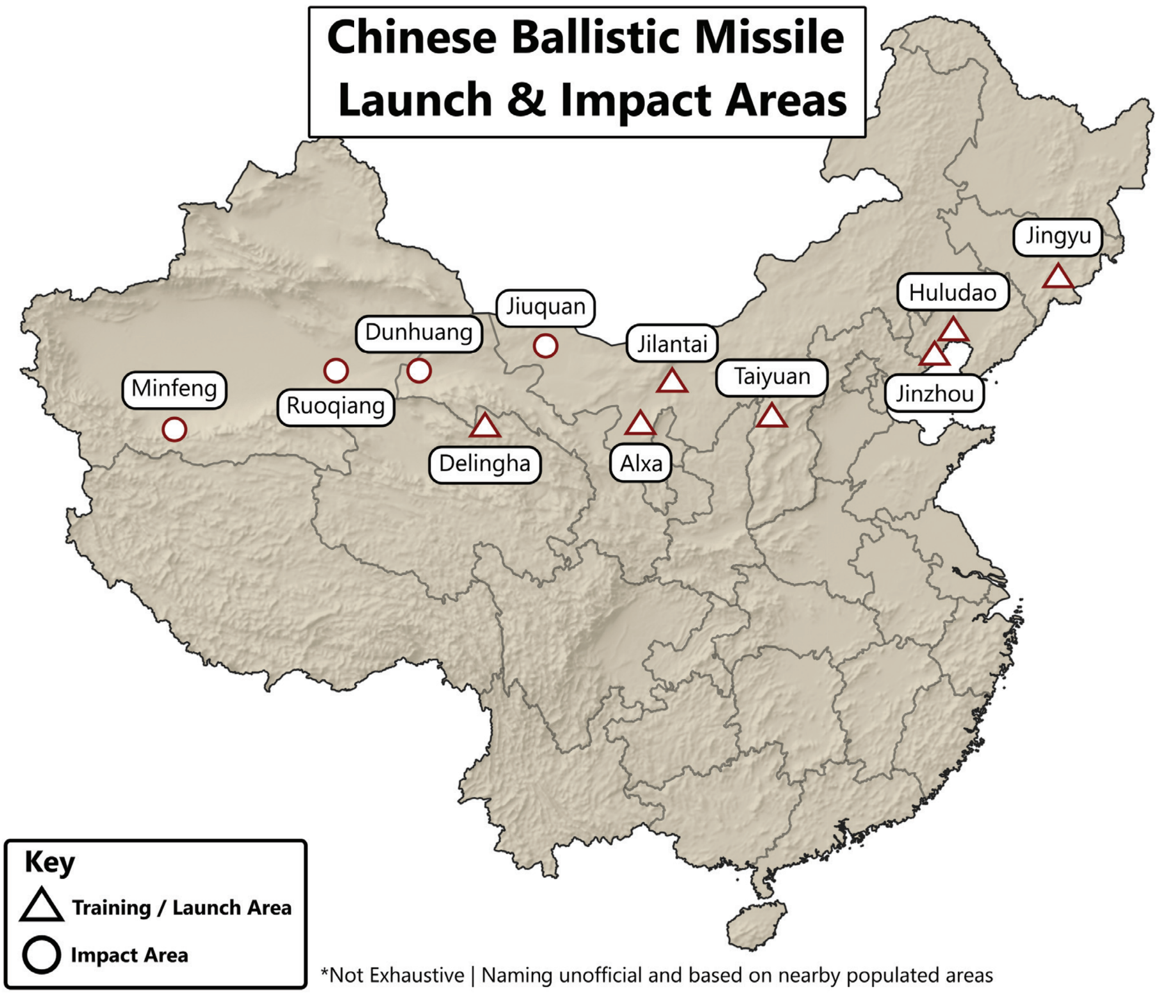
Liquid propellant rocket test stand under the 165th RI

- CASC 6th Academy
    - 101st RI [101所] /Beijing Institute of Aerospace Experimental Technology [北京航天试验技术研究所]. Founded in 1958, it specializes in engine testing, including second- and third-stage engines and satellite attitude control systems. It is located in Beijing's Fengtai District [丰台区].
    - 165th Institute [航天科技集团六院165所], also known as the Xi'an Aerospace Propulsion Testing Technology Institute [西安航天动力试验技术研究所] is the largest liquid rocket engine testing base in Asia and plays an important role in ground testing liquid oxygen/kerosene engines for China's next-generation space launch vehicles.[204] In 1992, the 165 Institute relocated to Xi'an, and in 1998, the Qingshuitou testing site [清水头试验区] was completed there. In 2003, the Balongyu 901 test stand [抱龙峪901考台] was successfully tested. In 2018, the Fengzhou special material industrial park was inaugurated [凤州试验区特种材料产业园]. In 2019, construction began on a new rocket engine testing platform.[205]

Firing test of 3m-diameter two-stage solid rocket motor in 2016

2.6.4 Flight Testing

This phase includes launches of the rockets and requires dedicated impact ranges and telemetry support stations to analyze flight characteristics. China has typically used flights from Jiuquan. Some are fired to the east, to impact in Bohai, where RVs are easily recoverable from the shallow waters. Others use test ranges to the west in Gansu, which, due to the earth's rotation, allow simulation of much longer-range tests. Based on public safety alerts or notices to airmen (NOTAMS) from Jiuquan and other launch sites, China maintains a busy schedule of tests for its missiles, including new and improved variants of older systems such as the DF-11.[207] Henri Kenhmann's research provides one snapshot of the rapidity of these launches, noting that available data suggests that between mid-November 2012 and mid-September 2017, Taiyuan Space Launch Center, just one of China's missile test launch sites, conducted no fewer than 66 military test launches, or once every 27 days.[208] China also uses an area of the South China Sea between the Spratly and Paracel islands for testing anti-ship ballistic missiles, as seen in July 2019 and August 2020. [209]



Key launch testing sites include the following:

- Jiuquan Satellite Launch Center (JSLC) [酒泉卫星发射中心] – The birthplace of modern Chinese rocketry and China's space program, the Jiuquan Satellite Launch Center was established in 1958 as the Northwest Comprehensive Missile Testing Facility [西北综合导弹试验基地] with the aid of Soviet technicians and R-2 missiles provided by Moscow.[210] The center is located Buge Yin'a Rila [布格音阿

日拉], in the western part of Inner Mongolia.[211] The Center has also been known as the 20th (Testing and Training) Base [第20 (试验训练) 基地], Dongfeng Aerospace City [东风航天城], and in the West as the Shuang Cheng-Tzu Missile Test Center.[212] The Center is subordinate to the PLA SSF Space Systems Department and uses the MUCD 63600.[213] As of April 2020, its commander is Zhang Zhifen [张志芬], and political commissar is Ji Duo [纪多] (both as of April 2020).[214] Continuing its historical role, the Center also carries out short-range ballistic missile, land-attack cruise missile, and ballistic missile defense system testing.[215]

- Taiyuan Satellite Launch Center (TSLC) [太原卫星发射中心] - Established in 1967, the Taiyuan Center is also known as the 25th Testing and Training Base [第25试验训练基地].[216] The Center is involved in testing medium- and intermediate-range ballistic missiles, including the DF-21.[217] While referred to in English and Chinese as Taiyuan, it is located over 150km away from Taiyuan, the provincial capital of Shanxi. Historically the launch center has been referred to as the Wuzhai Space and Missile Test Center by Western analysts after the county to the northeast. The Center is subordinate to the PLA SSF Space Systems Department [航天系统部] and has an assigned MUCD of 63710. As of September 2020, its commander is Major General Li Zongli [李宗利],[218] and political commissar is Wan Minggui [万明贵] (October 2019).[219]

2.6.5 Warhead Impact Test Sites

Ballistic missile impact test sites identified in Western China for example make it clear that these missiles are being used on a variety of test objects including simulated fuel tanks, runways, electrical substations, and hardened bunkers.[220] One site in Xinjiang's Ruoqiang County [若羌县] for example includes a complete 1,900m runway and mock F-35s.[221] Evidence of older tests such from the 1970s can still be seen in Minfeng County [民丰县][222] and Pishan County [皮山县][223], Xinjiang.

2.7 Launch Vehicles and Support Equipment

2.7.1 Overview

Launching a ballistic missile is a complex process. It involves a large support staff that readies the launch vehicle, arm the missile, and ensures the various subsystems are calibrated and target coordinates are uploaded to the guidance computers. In the case of the DF-31 for example this appears to include some 8-10 support vehicles.

DF-16 TEL

In the cases of SRBMs and even some of the long-range IRBMs like the DF-26, Chinese media has shown off the missiles' ability to relocate, rearm the missile, and fire another salvo.

China in particular has placed increasing emphasis on developing specialized vehicles to increase the mobility of its nuclear and conventional arsenal to ensure their ability to rapidly deploy and disperse after launch.

DF-26 reloading operations

A DF-21 missile is lifted from a support vehicle in preparation for reloading operations.

While less complex than the missiles they carry, this capability is no less important. The earliest generations of China's ballistic missiles required hours of prep-time to roll-out, fuel, and alignment. While they were dispersed to hardened positions and hidden in the mountains, if discovered they were not likely survivable and China's early warning network would not have provided sufficient warning.[224]

This included the DF-3, which used a Transporter-Erector (TE) to be wheeled into position and then erected for launch but which did not have a dedicated engine to move the missile itself, and needed to be separated from the missile before launch.[225] Later generations of missiles like the first versions of the DF-31 were road-mobile but incapable of real off-road operations.

Chinese Ballistic Missile Transporter-Erector Launchers

Producer	Chassis	Axels	Missile System
Wanshan	WAS2400	4	BP-12A
			DF-11
	U/I	4	DF-15B
	WS2500	5	DF-16
	WS2600	5	DC-21C/D
CASC/ Tai'an Special Vehicle Company	HTF5680A1	6	DF-26
	HTF59305	8	DF-31AG
	HTF5980A	8	DF-41
Hanvang	HY4330	8	DF-31A

Other support vehicles may transport personnel for security, provide obscurants, and other camouflage operations or other support. TEs and Mobile Erector Launchers (MELs), motorized trailers, have since been replaced by integrated systems: Transporter-Erector Launchers (TELs).

In addition to being rugged enough to sustain long-distance operations over rough terrain, these chassis are also used as the basis of other Chinese mobile weapon systems.[226] While most TELs use a cold-launch system, which pressurizes gas to propel the missile into the air before ignition, similar to SLBM launches, they must also be capable of handling the exhaust from the rocket launch.

There appears to be continuing reliance on imported engines and other components for these systems. Trade materials about Wanshan chassis note that the engines are imported, and appear to be German models. Other aspects of the design appear to draw from or even be done in cooperation with other countries such as Belarus.[xix] Space Sanjiang's Hubei Astronautics Shuanglong Special Car Limited Company [湖北航天双龙专用汽车有限公司] for example is believed to have a joint venture with Belarus Minsk Automobile Plant (MAZ). The gearboxes for the Hanyang chassis used to transport the DF-31 are produced by ZF Friedrichshafen AG.[227] The HY-480 chassis used as the basis for the HY-4330 uses a V-12 engine produced by Huachai Deutz [华柴道依茨公司], a licensed producer of Deutz engines and subsidiary of Chinese defense company NORINCO.[228] Wanshan vehicles such as the WS2900 rely on imported engines from Cummins (U.S.), and hydraulic torque converters, and transmission cases from ZF (Germany).[229]

Similar equipment is being used by OneSpace and ExPace [航天科工火箭技术有限公司] for their rapid-launch space launch vehicles.

The civilian space launcher Kuaizhou 1A, for example, uses a 7-axel TEL.

xix Companies that appear to be engaged in similar or related production include two Belarusian companies, Minsk Automobile Plant (MAZ) and Minsk Wheeled Tractor Plant (MZKT) produce specialized vehicles used for surface-to-air missiles, ballistic missiles and support vehicles for the Russian federation. KAMAZ, a Russian vehicle manufacturer, produces off-road vehicles that serve in support functions for various Russian military systems.

3.7.2 Relevant Institutions and Notable Developments:

The following are the key institutions involved in the production of TELs and related support vehicles for ballistic missile transport and launch operations:

- CASC 1st Academy / CALT has several subsidiaries and subordinate institutes involved in the production of TELs and associated vehicles that have been successively consolidated under the Aerospace Launch Technology and Special Vehicles Division [航天发射技术及特种车事业部], which was established in 2006.230 This includes the 15th RI [15所] /Beijing Aerospace Launch Technology Research Institute [北京航天发射技术研究所] which itself had absorbed the Tai'an Aerospace Special Vehicle Company and Factory 519 in 2004. As of 2018 the Aerospace Launch Technology and Special Vehicles Division had over 6,000 employees.
    - Factory 519 [519 厂] / Changzhi Qinghua Machinery Plant [长治清华机械厂], located in Changzhi [长治市], Shanxi, is responsible for final assembly of TELs and related vehicles. It was founded in 1964 and originally part of the 7th Machine Building Department. It works for both the 1st and 5th Academies and has locations in both Beijing and Changzhi, Shanxi [山西省长治市]
    - Tai'an Aerospace Special Vehicle Company [泰安航天特种车有限公司], in Tai'an, Shandong, is a subsidiary of CASC's Aerospace Launch Technology and Special Vehicles Division. The company dates to 1952 but its current organization was created in 2004 when it underwent a reorganization to establish its current organization under CASC.[231] It produces the "HTF-series" chassis used in ballistic missile TELs and support equipment. A new facility constructed to the south in Tai'an's Daiyue District sometime between 2009-2013 greatly expanded its production capacity.[232]

- Hubei Tri-Ring Hanyang Special Vehicle Company [湖北三环汉阳特种有限公司] (or Hanyang), is a heavy vehicle producer based in Wuhan involved in chassis production for the PLA, including the TEL used for the DF-31AG. It was formerly Hanyang Special Vehicle Manufacturing [汉阳特种汽车制造厂].233
- CASIC's 4th Academy has several subordinate organizations formerly under the 9th Academy involved in TEL production including the following:
    - Nanjing Chenguang Group Co. Ltd. [南京晨光集团有限责任公司], also known as Factory 307 [307厂]. Established in 1964 under the Seventh Ministry of Machine Building, it is involved in the production of ground vehicles. It appears to be involved in the production of the DF-21C and D.
    - Wanfeng Factory [万峰厂] located in Xiaogan [孝感市], Hubei, produces missile ground equipment and launch equipment
    - Wanshan Factory [万山厂], also located in Xiaogan, produces missile transport vehicles. Commercial imagery indicates that additional construction at Wanshan's older facility saw roughly a 70 percent increase in factory floor space and the construction of additional multi-floor office buildings between June 2005 and June 2013.[234] A new group of facilities to the east constructed between 2008 and 2014, covers an area of over four square kilometers.[235]

2.8 Final Assembly

2.8.1 Overview

Final assembly for missiles is a complicated process involving large factories, typically with access to rail connections to transport the large subassemblies. The assembly process appears to involve multiple steps, with the missiles themselves completed in one factory but mating with the TEL or other equipment happening at another facility.

After completion, the missiles are transported to checkout facilities belonging to each PLA Rocket Force Base, and then onward to the operational units, they will serve with.

Factory 211 Carrier Rocket Assembly Floor

2.8.2 Relevant Institutions and Notable Developments:

Assembly Facilities for Chinese Ballistic Missiles			
SOE	**Factory**	**Location**	**Missiles**
CASC	Factory 211 Capital Aerospace Machinery Company[236]	Nanyuan, Beijing	DF-5
CASIC	Nanjing Chenguang Group Corporation / Factory 307	Nanjing	JL-1, DF-21
	U/I	Nanjing[237]	
CASIC	U/I, possibly "Changyang Aerospace City"	Fangshan District [房山区], Beijing	DF-21, DF-26

CASC 1st Academy's Capital Aerospace Machinery Company [首都航天机械], also known as Factory 211 [211厂], is China's largest carrier rocket production and assembly plant. Factory 211 has been involved in missile production since 1958 when it produced copies of designs from the Soviet Union. In addition to handling final assembly for most of China's ballistic missiles, it specializes in the production of cryogenic storage tanks, liquid fuel engines, and rocket bodies.[238] According to an article from November 2018, the factory had 6,800 employees.[239]

Few details about missile assembly are available in public sources, but there are several notable themes in reporting on known facilities involved in missile and satellite launch vehicles, such as the increasing use of computer numerical control (CNC) machines and other automation techniques to speed production and improve precision:

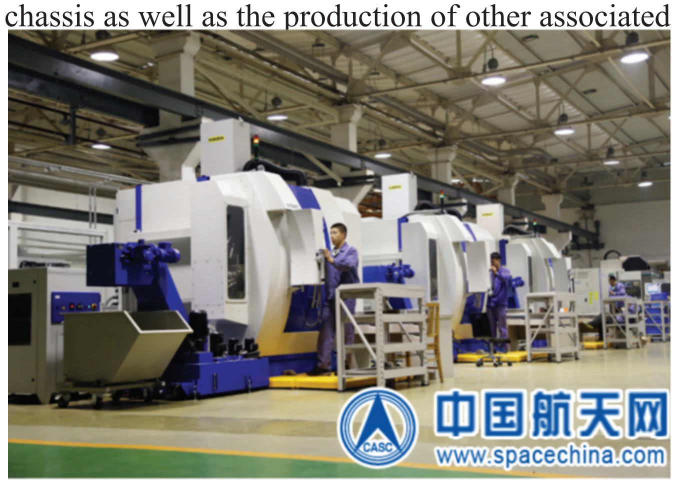
- Factory 211 has introduced automated connection processes for the Long March-3B rocket core stages, meaning that the factory can now automatically dock stages for rockets with diameters of 3.35 meters.[240] This technology could increase the speed and precision of rocket final assembly, including for classes of rockets that include ballistic missiles.
- One article in 2019 noted that Factory 211 had set a new record for the production of propellant storage tanks, due to increased efficiency.[241]
- Around early September 2018, Factory 211 set up a production problem guidance database system [生产问题导向库系统] which serves as a central repository for scientific research and production problems and solutions.[242] The database covers the 211 Factory and all of its research and production sections,

workshops, functional departments, and subsidiary companies.

- An article detailing Factory 211's work on the LM-2F for example emphasized increasing quality control and use of digital or automated techniques in production.[243]
- CASIC 4th Academy
    - Nanjing Chenguang Group Corporation [晨光集团] / Factory 307 [307厂] was responsible for final assembly of the JL-1 and DF-21A and appears to be involved in the production of the DF-21C and D variants.
- Another possible assembly facility was built in Nanjing's Jiangning District [江宁区] in the early 2000s.[244] It roughly doubled in size between 2007 and 2010 and underwent further significant expansion during 2018.

Another facility under CASIC that appears to be involved in the final assembly of missiles is "Changyang Aerospace City" [长阳航天城]. In 2013 CASIC established the "City" in Changyang, Fangshan District, Beijing [北京房山区长阳].[245] Separately, FAS researcher Hans M. Kristensen has identified a facility in the same area as involved in the completion of DF-26 missiles, support vehicles. In the case of the DF-26, the chassis is produced elsewhere so this likely involves connecting the missile and chassis as well as the production of other associated systems.[246] Work appears to have begun sometime in 2004 and proceeded through roughly 2012 when the first phase was complete. A second phase of expansion began in 2013, absorbing a former radar test area to the east. As of August 2020, the expanded facility now covers an area of over four square kilometers.

Notably, another company with large-scale facilities in the area, Beijing Anlong Technology Group [北京安龙科技集团], signed a strategic cooperation agreement with CASIC 4th Academy 4th Department in December 2018.[247] Beijing Anlong Technology group [北京安龙科技集团有限公司] is involved in research and production of equipment for the PLA, and People's Armed Police (PAP), and Ministry of Public Security.[248] The facility is located just south of CASC 6th Academy's 101st RI.



CNC machines at Factory 211

Conclusion

Since 2000, China has significantly increased the size of its ballistic missile forces. Looking ahead, given its strategic environment, the PRC leadership's focus on improving its nuclear deterrent and long-range strike capabilities will likely continue to drive the development of mobile ballistic missiles.

While the structure of the industry supporting that expansion has been re-arranged, it remains largely the same as even 40 years ago. Multiple rounds of reorganization have consolidated "silos of expertise" and greater consolidation is likely. From a technical standpoint, there is a clear trend of steady improvements. Superior design tools and manufacturing techniques that were less available through the mid-2010s appear to have been more thoroughly adopted in the past five years. Since the early 2010s, the size of manufacturing facilities has expanded and the techniques needed to produce large-scale rocket bodies or solid-rocket motors appear to have made breakthroughs.

While the Chinese ballistic missile industry has significantly modernized over the past twenty years, the rapid tempo of testing there appears to have shown incremental and iterative progress rather than radical breakthroughs. Advancements touted by Chinese media remain primarily significant in a Chinese context, and, likely, China is actually falling behind its competitors in terms of overall rocket development. We echo the conclusions of the 2005 RAND study in noting that the ballistic missile industry remains a mixed picture and it is clear that structural and technical limitations remain. China's ongoing economic transformation will pose significant challenges for the manufacturing industry which is racing to improve automation but also facing talent attraction and retention problems. In the past two decades, multiple technical bottlenecks appear to have held up the development of new systems until the acquisition of foreign technology allowed a breakthrough.

However, despite the remaining problems, the overall increase in capability and production capacity may be sufficient for China's defense needs going into the next decade and will continue to improve its overall conventional and nuclear capabilities.

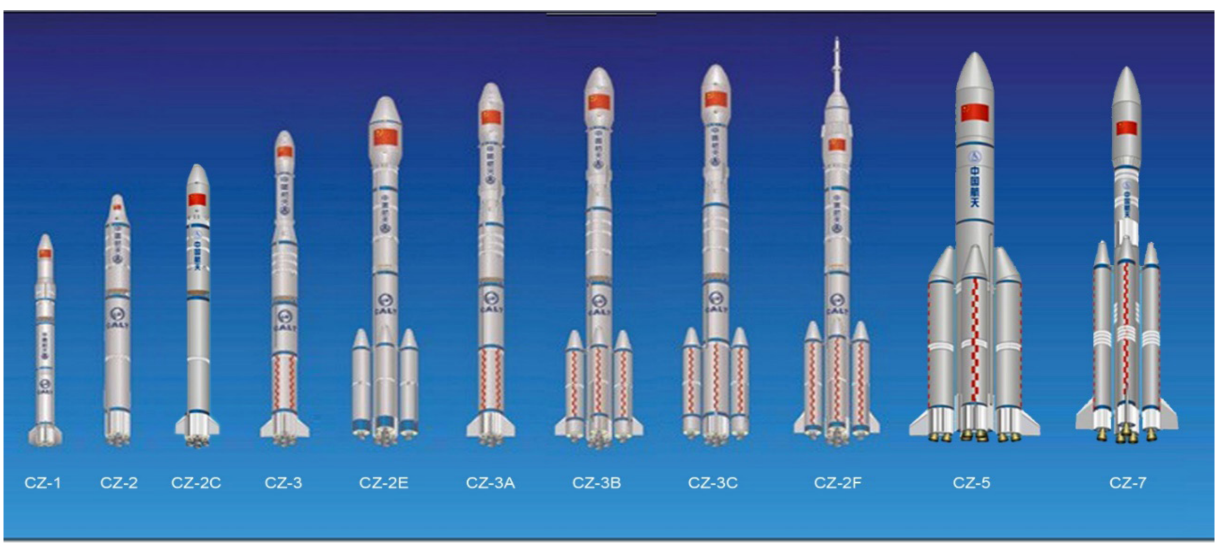
Appendix 1: Profiles of the "Small Core"

CASC 1st Academy

Academy	Name	Headquarters	Core Competency	Missiles Developed
CASC 1st Academy	China Academy of Launch Vehicle Technology (CALT) [中国运载火箭技术研究院]	Beijing	Lead system integrator, Launch vehicles, ballistic missiles	DF-4 DF-5 DF-5B DF-41 DF-15 SRBM DF-31/DF-31A ICBM DF-31AG JL-2 SLBM JL-3* SLBM DF-26 DF-41

Originally established in 1957 as the First Sub Academy under the Fifth Academy of the Ministry of National Defense, China Academy of Launch Vehicle Technology (CALT), also known as the CASC 1st Academy, was the birthplace of China's aerospace industry. It was approved to be the PLA's prime contractor for all tactical surface-to-surface ballistic missiles in May 1984 and remains the nation's sole provider of nuclear ICBMs.[249] It is responsible for R&D of the DF-15, DF-31, JL-2, DF-26, and DF-41. CALT has served as the lead systems integrator for six of the eight systems and/or variants outlined above. It cooperates with CASC 8th Academy on ICBMs.

On the civilian side, it is most well known as the developer and manufacturer of the Long March family of rockets.



Long March (aka CZ) Rockets developed by CALT

According to its official website, CALT is comprised of 22 departments, 13 subsidiaries, multiple wholly-owned companies, and holding companies. It covers an area of ~1,981 acres and a gross floor area of about 2.2 million square meters and employs 33,000 people. It is headquartered in the Nanyuan Residential District in

Beijing's Fengtai District and operates three production bases [产品基地], a comprehensive base [综合基地] in Gu'an, Hebei [河北固安], as well as several industrial bases promoting Military-Civil Fusion and aerospace technology commercialization.

CALT described itself as a major practitioner of the Military-Civil Fusion development strategy and its website kept a running record of its cooperation programs with civilian entities—universities, research institutions, enterprises, local governments within China and abroad.[250]

CALT is headquartered in Beijing's Fengtai District [丰台区], where a great number of players in China's defense industrial base are clustered including the CASIC 3rd Academy. According to a Beijing Daily article from June 2017, this area is home to 27 defense S&T research institutes, 125 state key labs, and over 30,000 advanced S&T research equipment.[251] Together these organizations employ 26 academicians and 70,000 R&D personnel, making it a "military-civil fusion innovation highland" [军民融合创新高地].[252]

CASC 4th Academy

Academy	Name	Alternate Name	Headquarters	Core Competency
CASC 4th Academy	Academy of Aerospace Solid Propulsion Technology (AASPT) [航天动力技术研究院]	Shaanxi Aerospace Science and Technology Corporation [陕西航天科技集团有限公司]	Xi'an [西安]	Large solid rocket motors

CASC 4th Academy is China's largest developer of solid rocket motors, responsible for the development, production, and testing of solid rocket motors for launch vehicles, strategic and tactical missiles, satellites, and manned spacecraft. It also takes on pre-research tasks for some of China's largest R&D megaprojects.

What would later become CASC 4th Academy began as the Defense Ministry's Fifth Academy's Solid Engine Research Institute [国防部五院固体发动机研究所] created in Luzhou [泸州], Sichuan Province in July 1962. In 1965, it was moved to Hohhot, the capital of Inner Mongolia, and became known as the Fourth Academy of the Seventh Ministry. In November 1966, the Fourth Academy began R&D on the third-stage solid rocket engine to be used on the Long March 1 that sent China's first man-made satellite, the "Dongfanghong-1" into orbit. In the 1970s, as part of the Third Front Movement, a decision was made to relocate the majority of the key equipment and R&D workforce to Lantian County, Xi'an, Shaanxi Province, the new Fourth Academy headquarters with the new designation Base 063. What was left of the Hohhot establishment was labeled the Fourth Academy's Inner Mongolia Headquarters [四院驻内蒙古指挥部], and remained a CASC 4th Academy subsidiary until 2002, when it was spun off from CASC and re-established itself as the CASIC 6th Academy.

According to data from 2019, CASC 4th Academy has a workforce size of more than 12,000 employees spread across six research institutes, two production plants, and 18 subsidiary companies that primarily produce civilian products.[253] It largely operates out of Xi'an, Shaanxi province, with a few satellite facilities in Hubei and Jiangsu provinces. AASPT and Northwestern Polytechnical University (NWPU), an MIIT affiliated university with a strong defense research focus that is also located in Xi'an, are close collaborators. AASPT and NWPU jointly built the Key Laboratory for Combustion, Thermal Structure and Internal Flow [燃烧、热结构与内流场重点实验室], the only national key laboratory in the field of solid rocket propulsion in China.[254]

Since its inception, the 4th Academy has developed over 100 types of solid rocket engines. AASPT describes its core competitiveness as centering on the research and development of advanced technologies such as rocket propulsion, polymer chemistry, explosives, and non-metallic composite materials.

CASC 6th Academy

Academy	Name	Alternate Name	Headquarters	Core Competency
CASC 6th Academy	Academy of Aerospace Propulsion Technology (AALPT) [航天推进技术研究院]	Base 067	Xi'an 西安	Liquid propulsion systems

CASC Sixth Academy traces its roots to the establishment of Base 067 in the Qinling Mountains west of Xi'an in 1968 by the First Sub Academy as part of the Third Front Movement.

Base 067, located in Fengzhou Town, Feng County, Baoji City, Shaanxi Province [陕西省宝鸡市凤县凤州镇], was the only aerospace liquid-fuel propulsion research and development base during China's Third Front construction period.[255] In June 1969, Base 067 was completed and put into operation, becoming the first Third Front base of China's aerospace system. In 1993, Base 067 was moved to Xi'an and officially renamed the Sixth Academy of CASC [航天科技集团六院] in 2001.

Its current form, the Academy of Aerospace Propulsion Technology, was created in 2008 as part of a reorganization within CASC that consolidated China's R&D workforces for liquid-fueled propulsion systems located in Xi'an, Beijing, and Shanghai. When it comes to space liquid-fueled propulsion technologies, the Sixth Academy is the only research institute in China capable of integrating the research, design, production, and testing of launch vehicle main propulsion systems thrust vectoring, divert and attitude control systems, and space flight vehicle propulsion systems.

Headquartered in Xi'an, the Sixth Academy employs around 17,000 people in its subsidiaries, out of which seven are based in Xi'an, two in Beijing, one in Shanghai, and one in Wuhan. The Sixth Academy is home to Asia's largest liquid rocket engine test stand [液体火箭发动机试车台] and largest turbopump performance laboratory [泵性能试验室], as well as China's only basic theory research office [国内唯一的基础理论研究室], and the only liquid propellant research center [液体推进剂研究中心]. It also established China's first cryogenic technology research center [低温技术研究中心], a national-level scientific research infrastructure.

CASIC 4th Academy

Academy	Name	Alternate Names	Headquarters	Core Competency	Missiles Developed
(New) CASIC 4th Academy	CASIC Academy of Launch Technology [航天科工运载技术研究院]	China Space Sanjiang Group [中国航天三江集团公司]; Formerly Base 066	Wuhan [武汉]	Tactical ballistic missile system integrator	DF-11[256] DF-16* JL-1/DF-21

The current form of CASIC's 4th Academy—often referred to as the "new 4th Academy" [新四院] or China Space Sanjiang—was created out of a merger that took place in December 2011 that reorganized and consolidated the former CASIC 4th Academy, which specialized in the development, and manufacturing of solid-fuel missiles, including the JL-1/DF-21,[257] and the former CASIC 9th Academy (also known as Base 066), a producer of ballistic missile systems such as the DF-11 series.[258]

The former 4th Academy was created in July 2002, when CASIC pulled together the various organizations under China Aerospace Corporation that have been responsible for the R&D and production of the JL-1/DF-21 missile and created the new CASIC 4th Academy. The CASIC 4th Academy absorbed, among others, the following key institutions located in Beijing and Nanjing:

- Former Fourth Sub Academy's Fourth Overall Design Department [第四总体设计部], the unit responsible for the overall design of the JL-1 missile.
- The 17th Research Institute, or Beijing Institute of Control Electronic Technology [北京控制与电子技术研究所], that specializes in the overall design of control systems and precision-guidance technologies.259 The 17th RI was originally created in 1968 under the First sub-Academy and stayed a First Academy subsidiary until the 1980s when it was resubordinated under the Second Academy.260
- Command Automation Technology R&D and Application Center [指挥自动化技术研发与应用中心], or 401st RI [401所];
- At least three entities belonging to the Nanjing Chenguang Group Corporation [晨光集团] headquartered in Nanjing, Jiangsu Province:
    - A missile general assembly and testing factory also known as Factory 307 [307厂] or Nanjing Chenguang Factory, which traces its history back to the Jinling Machinery Bureau [金陵机器制造局] established in 1865;
    - A large comprehensive equipment manufacturing enterprise called Aerosun Corporation [航天晨光股份有限公司];
    - Nanjing Chenguang Hi-tech Venture Capital Co., Ltd. [南京晨光投资高科技投资有限公司].

The former 9th Academy traces its history back to Base 066, a defense industrial base built by the Third Sub Academy in the 1960s in Yuan'an County, Xiaogan, Hubei Province. In the mid-1980s, Base 066 started research and development of the M-11/DF-11 SRBM, and in the late 1980s, it was split off from the Third Academy as an independent missile research and industrial complex.[261]

The new CASIC 4th Academy was established in Wuhan, Hubei Province, with total assets of 50 billion yuan, approximately 18,000 employees, and 32 member units. It operates out of Wuhan, Xiaogan [孝感], and Yuan'an County [远安县] in Hubei Province, as well as Beijing, Nanjing, and Chengdu. Research facilities housed under the Fourth Academy include one national-level enterprise technology center [国家级企业技术中心], 14 provincial-level enterprise technology centers [省级企业技术中心], one national-level engineering laboratory [国家级工程实验室], one national-level engineering research center [国家级工程研究中心], 13 provincial and ministerial key laboratories and engineering research centers, three academician expert workstations, and three post-doctoral research workstations. It has won more than 800 scientific and technological progress awards at or above the provincial and ministerial level and has more than 3,000 valid authorized patents.

CASIC 6th Academy

Academy	Name	Alternate Names	Headquarters	Core Competency
CASIC 6th Academy	Academy of Propulsion Technology [航天科工动力技术研究院]	Hexi Machinery Corporation [中国河西化工机械公司]	Baotou [包头]	Tactical solid rocket motors

The CASIC 6th Academy was created in 2002 by spinning off CASC 4th Academy's solid rocket motor research establishment in Hohhot. In addition to contributions to the Dongfanghong satellite program, the 6th Academy is known for the development of the 1.4-meter diameter solid rocket motors used in the JL-1 SLBM / DF-21 MRBM.[262]

The 6th Academy now has China's largest comprehensive testing facilities for solid-fuel engines, allowing new generations of large-scale solid fuel engines [大推力大型全尺寸固体发动机] to be tested. It is a provider of various equipment and systems for solid-propulsion engines for strategic and tactical missiles and space launch vehicles.[263]

Appendix 2: Chinese Ballistic Missiles – Definitions and Key Facts

Chinese Definitions of Missile Types and Ranges[264]		
English	**Chinese**	**Range (km)**
Short-range missile	近程导弹	<1000
Medium-range missile	中程导弹	1000-5000
Intermediate-long-range missile	中远程导弹	1500-5500
Long-range missile	远程导弹	5000-8000
Intercontinental missile	洲际导弹	>8000

Name*	Launch Prep Time (minutes)	Estimated CEP (meters)	No. /Brigade or Submarine	No. of Units	Total launchers	Total missiles†
DF-3	120-150	1000-4000	10	–	–	–
DF-4	60-120	1400-3500	10	1	–	–
DF-5	30-60	800-500	6	3	18	18
DF-10	30	15	–	2	–	–
DF-11	30	600 (2004); 200	10	2	20	80-120
DF-15	30	200-300	10	2	20	80-120
DF-15A	–	30-45	10	–	–	–
DF-16	10-15	–	–	–	–	–
DF-17	–	–	–	1	–	–
DF-21	10-15	100-300	10	6	60	200+
DF-26	–	–	–	–	–	–
DF-31	10-15+	5-10	8-10	7	56-70	32+
DF-41	–	–	–	1	–	16+
JL-1	30	1500-2000	12	–	–	–
JL-2	30	300-500	12	4	4	48
***Red indicates retired | †4-6 reloads are assumed for conventional ballistic missiles | – Unknown or N/A**						
Sources: Janes Strategic Weapons 2004, 2011; Lewis and Hua (1999); IISS, 2019; DOD Report to Congress, 2020.						

Appendix 3: Estimated Numbers of Missiles and Operational Brigades

	Name	No. /unit*	No. of Units (2020)	Total launchers	Total missiles†	DOD Estimates	
						2019	2020
SRBM	DF-11	10	2	20	80-120	250/750-1500	250/600+
	DF-15	10	2	20	80-120		
	DF-16	–	2	–	–		
MRBM	DF-21	10	6	60	240-360	150/150-450	150/150+
IRBM	DF-26	12	4+	48?		80/80-160	200/200+
ICBM	DF-5	6	3	18	18	90/90	100/100
	DF-31	8-10	7	56-70	56-70		

This chart uses two major assumptions: 1. (*) That the number of missiles (and thus launchers) per unit is correct and 2. (†) That there are 4-6 reloads for conventional (non-ICBM) ballistic missiles. DF-26s have been shown reloading in December 2018 so there should be at least be one additional reload. Note: ICBM estimates do not include JL-2. Source: Annual Report to Congress: Military and Security Developments Involving the People's Republic of China, Office of the Secretary of Defense, 2019; 2020.

PLA Rocket Forces Brigades by Assigned Missile Type				
Type	**Total**	**Type**	**No.**	**Brigade Number and Variant Type**
Nuclear	16	DF-4	1	662
		DF-5	3	631 (B), 633 (A), 661 (B)
		DF-21A	3	611, 612, 651
		DF-31	8	622 (A), 632 (AG), 641, 642 (AG), 643 (A/AG), 652, 663 (A), 664 (AG)
		DF-41	1	644
		JL-2	-	Four active Jin-class submarines each with 12 launch tubes
Conventional	9	DF-10*	2	623 (A), 635
		DF-11	2	614, 615 (A)
		DF-15	2	613 (B), 616 (A/B/C)
		DF-16	2	617 (A), 636 (A)
		DF-17	1	627
	10	DF-21	3	624 (D), 653 (D)
Dual	6	DF-26	6	621, 625, 626, 646, 654, 666
U/I	6	U/I	6	634, 645, 647, 655, 656, 665
Total No. of Operational Brigades: 40				
*: Ground Launched Cruise Missile				Source: BluePath Labs analysis October 2020

Appendix 4: Chinese Ballistic Missile & Rocket Designers

As highlighted in Section 1, CASC's 1st Academy (CALT) and its 1st Design Bureau have led work on the vast majority of Chinese ballistic missiles and space launch vehicles (see inset chart). While CASC has traditionally focused on liquid-fueled missiles and space launch vehicles, CALT's 1st Design Bureau appears to have taken on much more involvement in recent generations of solid-fueled missiles as well.

* Chief designer [总设计师] [xx]		† Deputy Chief Designer [副总设计师]	
Designer		**Program**	**Affiliation**
Qi Faren[265]	戚发轫	DF-1 (copy of Soviet R-2), SZ-series*	CALT
Qian Xuesen	钱学森	DF-3*	CALT
Tu Shou'e	屠守锷	DF-2, DF-3, DF-5*, LM-2	CALT
Liang Sili[266]	梁思礼	DF-2A, DF-5†, LM-2	CALT
Wang Zhenhua[267]	王振华	DF-11	CASIC 4th
Liu Baoyong	刘宝镛	DF-31*	CALT 1st Design Dept.
Wang Yongzhi[268]	王永志	DF-5, DF-15, DF-31, SZ-5, SZ-6	CALT
Hou Shiming	侯世明	JL-1†	CASIC 4th
Huang Weilu	黄纬禄	JL-1/DF-21*	CASIC 4th
Zhu Xuejun[269]	祝学军	U/I boost-glide tactical ballistic missile	CALT
Zhang Zhi	张智	LM-2F*	CALT
Jing Muchun	荆木春	LM-2F†	CALT
Long Donghao	龙东豪	LM-3A*	CALT
Jiang Jie	姜杰	LM-3A*	CALT
Wang Weibin	王维彬	LM-5†	CALT
Li Dong	李东	LM-5B*	CALT
Cheng Tangming	程堂明	LM-7†	CALT
Peng Kunya	彭昆雅	LM-11*	CALT
Guan Hongren	管洪仁	LM-11†	CALT

xx In the Chinese industrial system, the lead or chief designer [总设计师] is in charge of project coordination and design work, and is supported by several Deputy Chief Designer [副总设计师] which may support design work or be involved in leading work on a subsystem such as propulsion or guidance.

Chinese Nuclear Weapons and Warhead Designers		
Deng Jiaxian	邓稼先	Father of China's nuclear weapons program
Feng Yufang[270]	冯煜芳	Chinese Academy of Engineering Academician and researcher at the Rocket Force Research Institute involved in work on several unidentified nuclear warheads.
Huang Chunping	黄春平	He participated in the development of five types of nuclear warheads as well as multiple conventional types, serving as a chief director [总指挥]. Other work included contributions to the LM-3, LM-2E [长征-二戊], and LM-2F [长征-二已].
Li Xu'e	李绪鄂	Worked on U/I ICBM JL-1 SLBM warhead; led research on miniaturized warheads for ballistic missiles and SLBMs
Liu Lianyuan	刘连元	Warhead systems designer responsible for multiple warhead designs. He was deputy head of 1st Academy's (CALT) 14th Institute and Academician of the Chinese Academy of Engineering (CAE).[271]
Yu Min	于敏	Lead nuclear weapon designer in the Ninth Academy

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