航空 航天

CHINA AEROSPACE
STUDIES INSTITUTE

China's Aeroengine Industry

Prepared by TextOre, Inc.

Peter Wood, Alden Wahlstrom, Roger Cliff

March 2020

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

ISBN: 9798637786664

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

Design by Heisey-Grove Design

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

China Aerospace Studies Institute

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

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

- CASI primarily conducts open-source native-language research supporting its five main topic areas.
- CASI conducts conferences, workshops, roundtables, subject matter expert panels, and senior leader discussions to further its mission. CASI personnel attend such events, government, academic, and public, in support of its research and outreach efforts.
- CASI publishes research findings and papers, journal articles, monographs, and edited volumes for both public and government-only distribution as appropriate.
- CASI establishes and maintains institutional relationships with organizations and institutions in the PLA, the PRC writ large, and with partners and allies involved in the region.
- CASI maintains the ability to support senior leaders and policy decision makers across the full spectrum of topics and projects at all levels, related to Chinese aerospace.

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

Preface

As we move further into the era of 21st century great power competition, it is important to understand with whom we are competing. This report is our second in a 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 is our first case-study in this series. This paper focuses on the aeroengine industry within the PRC. As you might expect, engines are a critical component to any aerospace endeavor. Despite serious efforts on the part of the PRC, China still struggles with several key technologies for the most advanced aeroengines. In other areas, however, China has made significant progress, either through their own research or through co-opting foreign technology.

Part I of the study provides an overview of the R&D and acquisition ecosystem related to Chinese aeroengine development and a historical perspective on China's key advances in the field. Key research institutes, factories, government offices, and people involved in the development of Chinese aeroengines are profiled. As there is significant overlap in the materials, propulsion, and control systems design and engineering used for turbines meant for power generation and aeroengines, an examination of Chinese gas turbine development is crucial to understanding China's advances in aeroengines. Therefore, for the purposes of this study, we have also chosen to highlight the role of Chinese R&D institutes or breakthroughs related to power generation.

Part II of the study focuses on the development of four particular types of engines that represent the areas of greatest effort, highlighting the difficulties Chinese aviation engineers have faced and their progress toward overcoming challenges in this vital but complicated sector. These are fighter jet engines, turbofans for bombers and commercial aircraft, helicopter engines, and engines for unmanned aerial vehicles (UAVs) and cruise missiles.

- Fighter Jet Engines – analyzes the historical development of jet engines in China from the earliest rote copies of Russian designs to indigenous successes and cutting-edge research currently being incorporated into China's latest generation of stealth fighters.
- Bomber and Commercial Aircraft Turbofans – focuses on high-bypass turbofans under development for bombers like the H-6K and H-20 and for strategic transport, aerial refueling and airborne early warning and control aircraft (AEW&C) such as the Y-20 and its variants.
- Helicopter Engines – discusses China's path toward indigenized lines of turboshaft engines for the PLA's expanding range of rotary wing aircraft.
- UAVs and Cruise Missile Engines – looks at two areas with significant overlap: "micro and small" turbofan engines for the significant number of high-performance UAVs and advanced cruise missiles being developed for the PLA.

Drawing on Chinese-language government publications, news articles, authoritative writings on strategy and tactics, and academic studies, each section examines the history of declared priorities, strategy, and R&D in the field. Combined with contemporaneous reporting, each section gives an assessment of the current state of the respective field. Taken together, these provide a clear snapshot of the strategic requirements driving aeroengine R&D, the companies and research institutions carrying it out, and the relative trajectory of progress by these companies.

CASI would like to thank the team at TextOre for their continued work in helping us bring further clarity to the often murky world that is the aerospace sector in the PRC. We would also like to specifically thank Peter Wood, Roger Cliff, and all the others who contributed to completing this report. We hope you find this volume useful, and look forward to bringing you further reports in this series on the Chinese aerospace sector.

Brendan S. Mulvaney
Director, China Aerospace Studies Institute

Abbreviations

AECC	Aero Engine Corporation of China
AESA	Active Electronically Scanned Array (radar)
AEW&C	Airborne Early Warning & Control
AAM	Air-to-Air Missile
AM	Additive Manufacturing
AMS	Academy of Military Sciences
ASW	Anti-Submarine Warfare
AVIC	Aviation Industry Corporation of China
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CAAC	Civil Aviation Administration of China
CAD	Computer Aided Design
CAE	Chinese Aeronautical Establishment
CAIG	Chengdu Aircraft Industry Group
CASC	China Aerospace Science and Technology Corporation
CASIC	China Aerospace Science and Industry Corporation
CASS	Chinese Academy of Social Sciences
CCP	Chinese Communist Party
CFD	Computational Fluid Dynamics
CIMS	Computer Integrated Manufacturing Systems
COMAC	Commercial Aircraft Corporation of China
CMC	Central Military Commission
CNC	Computer Numerical Control
COSTIND	Commission for Science, Technology and Industry for National Defense
CSIC	China Shipbuilding Industry Corporation
DWP	Defense White Paper
ECM	Electronic Countermeasures
EDD	Equipment Development Department
EW	Early Warning
FADEC	Full Authority Digital Engine Control
FYP	Five Year Program

GAD	General Armament Department
HALE	High Altitude Long-Endurance
ISR	Intelligence, Surveillance, and Reconnaissance
LAM	Laser Additive Manufacturing
LRIP	Low-rate Initial Production
LSG	Leading small group
MCF	Military-Civilian Fusion
MIIT	Ministry of Industry and Information Technology
MOF	Ministry of Finance
MOST	Ministry of Science and Technology
NDU	National Defense University
NRDC	National Development and Reform Commission
NUDT	National University of Defense Technology
PAP	People's Armed Police
PBSC	Politburo Standing Committee
PLA	People's Liberation Army
PLAAF	People's Liberation Army Air Force
PLAN	People's Liberation Army Navy
PLASSF	People's Liberation Army Strategic Support Force
PRC	People's Republic of China
R&D	Research and development
RMB	Renminbi
STOL	Short Takeoff and Landing
SASAC	State-owned Assets Supervision and Administration Commission
SASTIND	State Administration for Science, Technology and Industry for National Defense
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle

Table of Contents

Part I

Introduction

The engines powering the multiplying types of modern Chinese fighters, surveillance, transport, and bomber aircraft represent the core problems of China's rise: increasing domestic strength in science and technology (S&T) and a persistent dependence on imported foreign technology.

For the Chinese military, improved engines are critical to its ability to perform more complex and demanding missions. Focuses of development include: advanced high bypass ratio turbofans for bombers and heavy transport aircraft; high-performance low bypass ratio turbofans and thrust vector control (TVC) for fighter aircraft; more-capable turboshaft engines for helicopters; and improved turboprop engines for tactical transport and maritime patrol aircraft.

At the strategic level, the shift from a mission of territorial air defense [国土防空] to preparing for both offensive and defensive operations [攻防兼备], and the resultant requirement to perform missions such as long-range strike [长途奔袭] and strategic force delivery [战略投送], are shaping Chinese requirements for more capable, long-range aircraft. At the tactical level, requirements for specialized missions such as close air support and anti-submarine warfare (ASW) are further driving requirements.

Chinese publications describe aeroengines as the "pearl in the crown" [皇冠上的明珠] of an aviation industry, the "heart of an aircraft" [飞机的心脏] and a "strategic guarantor" [战略保障] of national security. Despite this emphasis, China continues to struggle to develop its own aeroengines. The following section examines China's progress in the development of modern aeroengines and the challenges it has encountered.

Difficulties in Aeroengine Development

Across the world, aeroengines typically impose significant upfront costs in terms of technology development and prototype manufacturing and testing to ensure that designs meet requirements for power output, weight, fuel efficiency, lifespan, and maintenance. Chinese observers note that, in addition to high-performance materials, modern aeroengines require precision machining and lengthy and expensive periods of testing that requires specialized wind tunnels, atmospheric and environmental condition testing, and test-to-destruction procedures. This testing requires substantial investments in high-tech testing equipment.[1]

In the West, development of a new military turbofan engine has historically cost between $300 million and $4 billion and required up to seven years from the time of contract award to the initiation of low rate production. For example, the Pratt & Whitney F100, used in the F-16 and F-15 fighters, cost an estimated $2.26 billion (in 2018 dollars) and took 4.5 years to develop. The F119, used in the F-22, cost $3.94 billion to develop.[2]

Engines represent a significant portion of the overall cost of an aircraft, typically between 20-25 percent. Thus, aside from eliminating China's dependence on foreign suppliers for a critical element of its military power, the capability to produce aeroengines domestically would enable China to capture a significant portion of the production cost of military aircraft that would otherwise go to foreign suppliers.

Andrea and Mauro Gilli have noted that technologies such as aeroengines require so many different research, manufacturing and supply chain inputs that reverse-engineering of the technology is difficult or impossible to effect.[3] An example of the difficulty of the material science and precision machining key to producing quality aeroengines can be seen in China's multi-decade quest to precisely manufacture ball bearings smaller than 0.1 millimeter, such as those used in regular ballpoint pens. This effort only succeeded in 2017.[4]

The Chinese government's efforts to promote domestic aeroengine development over the past decade have included three major initiatives:

- Acceleration of state plans for aeroengine R&D
- Consolidation of the aeroengine industry
- Creation of new research institutes and test platforms

State-Sponsored Aeroengine R&D Efforts

China's goals for aeroengine development stem from both strategic and economic imperatives: the desire to dramatically increase China's overall military capability and to move Chinese manufacturing and exports further up the value chain. Manufacturing aeroengines, however, is a longstanding weakness in China. Although China was capable of producing a range of different types of aircraft, by the mid-1960s, making the engines for those aircraft posed problems. For instance, sufficiently powerful engines required hollow cast turbine blades that used advanced alloys. Metallurgy in China, however, was insufficiently advanced to produce these alloys.

As a result, over the years the Chinese government has launched a series of efforts to improve China's aeroengine manufacturing capabilities. In 1978, for example, it issued an "Aviation Industry Science and Technology Development Program for 1978-1985" [1978-1985年航空工业科学技术发展规划]that included, among eight key projects, development of a high thrust-to-weight ratio turbofan engine.[5] Described in greater detail below, this project, the WS-6 [涡扇-6], lasted until 1986, when it was canceled without a workable engine having been produced.

In the 21st Century, national development plans for industry and technology have consistently prioritized the development of aeroengine technology. The "Program for Developing Hi-Tech Industries During the 11th Five Year Program Period (FYP)"[a] [高技术产业发展 "十一五" 规划], for example, called for efforts to develop the aviation industry in general, with aeroengines being an area of specific emphasis.[6] Similarly, the "Program for the Development of Emerging Strategic National Industries During the 12th FYP Period"[b] ["十二五" 国家战略性新兴产业发展规划] listed the aviation equipment industry as the number one priority under the category of "high-end equipment manufacturing industries" [高端装备制造产业]. A development roadmap included in this document prioritized breakthroughs in core aeroengine technologies, including completing the development of turbofan engines for large commercial aircraft by 2020, strengthening research and development of critical technologies for new types of turboshaft engines, and improving China's overall capabilities to develop technologies for the research, development, testing, and evaluation of aeroengines.[7] Similarly, the "Program for National S&T Development During the 13th FYP Period"[c] [国家 "十三五" 科学技术发展规划] listed "aeroengines and gas turbines" first among major science and technology areas in which China should strive to achieve breakthroughs by 2030.[8] Likewise, the "Made in China 2025" [中国制造2025] program, promulgated in 2015, includes aerospace and aviation equipment as one of ten priority strategic sectors key to transforming China into a "manufacturing superpower." The plan specifically calls for breakthroughs in high thrust-to-weight ratio advanced turboprop engines and high bypass ratio turbofan engines.[d, 9]

Launch of the "Two Engines" Project

Perhaps the primary policy initiative driving aeroengine development in recent years has been the national-level technology project to indigenously develop and manufacture modern aeroengines and industrial gas turbines (which share many core technologies). In 2013, the State Council issued a decision "to concentrate all efforts on development of aeroengines" [下决心把航空发动机搞上去], launching feasibility studies for what was termed the "Two Engines" special project ["两机"专项].[10]

In early 2015, the Two Engines project was first written into the annual government work report. The report proposed that major projects such as aeroengines and gas turbines be implemented, and that national defense scientific research and high-tech weapons and equipment construction be strengthened. The "State Innovation-Driven Development Strategy Guidelines" ["国家创新驱动发展战略纲要"] issued by the Chinese Communist Party (CCP) Central Committee and the State Council in May 2016 called for the Two Engines project to be launched as quickly as possible.[11] The project was officially launched in August 2016 with a budgeted investment of 100 billion yuan (approximately $15 billion).[12] The level of official support, both politically and in terms of funding, when combined with across-the-board policy support, make the Two Engines project analogous to "Made in China 2025" in terms of its authority, scale, and impact.

In 2016, Ministry of Industry and Information Technology (MIIT) Minister Miao Wei [苗圩] emphasized that during the 13th FYP period, China would make major progress on the Two Engines project, with breakthroughs in key technologies. Within the aeroengine portion of the Two Engines project the focus is on turbofans and turbojets, while not neglecting turboshaft, turboprop, and piston engines. For gas turbines, China aims to achieve independent production of 300MW "F-class" gas turbines by 2020 and develop 400MW "H-class" gas turbines by 2030.[e] The Chinese government views gas turbines as a major market worth as much as $500 billion, with major applications for power generation as well as for the maritime and manufacturing sectors.[13]

Significance of Gas Turbine Development to Aeroengine Development

Most of China's aeroengine development plans include mention of industrial gas turbines. [燃气轮机]. While power-generating gas turbines do not face the same weight limitations that make aeroengine development so difficult, their expected lengthy runtimes and power output make precision, balancing and advanced thermodynamics necessary. Techniques developed for one sector are frequently flowed to others, leading to improvements in reliability and durability. Leaders in one sector are typically deeply involved in the other, as evidenced by GE and Rolls Royce's large power generation businesses.

In China, the QD128 12MW-class gas turbine, for example, was spun off the core design of the "Kunlun" [昆仑] aeroengine. Li Xiaotang [李孝堂], chief designer of the QD128 and deputy director of the AECC Shenyang Engine Research Institute [中国航发沈阳发动机研究所], also worked on maritime applications of the same engine as well as the R0110 heavy-duty gas turbine.5

In 2018, Chinese state-owned shipbuilder China Shipbuilding Industry Corporation (CSIC)

Government Bodies Overseeing Aeroengine Development

While the details are not always clear, a number of high-level government and military bodies appear to provide direction for and oversight over the Two Engines project and aeroengine development in general.

Two Engines Project Leading Small Group ["两机"专项领导小组]

The State Council has administrative authority through a directly subordinate leading small group (LSG) on the Two Engines project. The LSG's general office is housed within MIIT. Several related groups provide direction for the project, including the Two Engines project expert advisory committee ["两机" 专家咨询委员会][f] and the Two Engines project basic research committee ["两机" 基础研究委员会]. A Two Engines project basic research professional group ["两机" 基础研究专业组] was established in April 2017.[14]

Though the State Council typically issues an official notice outlining an LSG's purpose, responsibilities, and membership whenever one is established,[15] no such notice was issued for the Two Engines project LSG, an indication of the level

of sensitivity surrounding the project. While the group is alluded to in official media, the lack of an official State Council notice means that little insight can be gleaned about the officials or agencies that compose the LSG. Several official sources indicate that it was nominally led by Vice Premier Ma Kai [马凯] prior to his retirement.[16] At least some functions of the role now appear to be filled by MIIT Vice Minister Xin Guobin [辛国斌], who, though never explicitly named as the head or even a member of the LSG, is observed in official media appearing and speaking at significant events related to the Two Engines project.

Leading Small Group for Building a Manufacturing Power [国家制造强国建设领导小组]

Established in June 2016, the LSG for Building a Manufacturing Power is charged with coordination and planning for the implementation of the "Made in China 2025" program. The general office of this LSG is also housed within MIIT. Unlike the Two Engines project LSG, details about the group's composition were made public in a June 2015 State Council notice. Vice Premier Ma Kai initially headed the group, and MIIT Minister Miao Wei was initially listed as deputy head. Officials drawn from departments and agencies such as NDRC, the Ministry of Science and Technology (MOST), MOF, etc. make up the rest of the LSG.[17]

The Central Military-Civilian Fusion (MCF) Development Commission [中央军民融合发展委员会]

This commission, established in January 2017 and chaired by Xi Jinping, provides uniform leadership over MCF development and acts as the central coordinating body for policy and decision-making for key MCF issues.[18] China has prioritized coordination of military and civilian industries and research institutes to achieve faster breakthroughs in areas with implications for both sectors – aeroengines chief among them.[g]

In an indication of the commission's stake and interest in the Two Engines project and in aeroengine development more broadly, representatives of the commission have appeared at Two Engines project-related events, including at the establishment of Tsinghua University's Institute for Aero Engine (sic) [清华大学航空发动机研究院] in 2018.[19] While details of the plans are unclear, the commission has approved a series of MCF plans for defense, science, technology, and industry tied to the 13th FYP, including the "Program for National Defense Science, Technology, and Industry Development During the 13th FYP Period" ["十三五"国防科技工业发展规划], "Opinions on Promoting the In-Depth Development of Military-Civilian Fusion in National Defense Science, Technology and Industry" ["关于推动国防科技工业军民融合深度发展的意见"], and "Opinions on Implementing

g Military engine designs can be improved and spun off into civilian applications. In the U.S., the core of the F101 engine for the B-1 bomber was used in both the military F110, which powers many U.S.-made fighter aircraft, and in the French-U.S. CFM56, the most widely used engine on commercial jetliner.

In-Depth Development of Military-Civilian Fusion in Military Logistics During the 13th FYP Period" ["十三五"期间推进军事后勤军民融合深度发展的实施意见].[20] Given that the 13th FYP explicitly calls for major breakthroughs to be made in core aeroengine and gas turbine technologies,[21] the MCF plans adopted by the commission very likely address aeroengine development in greater depth.

Central Military Commission's Equipment Development Department [装备发展部]

The Equipment Development Department (EDD) is one of two bodies that provide oversight and direction for S&T development under the Central Military Commission (CMC), the top military organization in China. It is also one of the bodies through which the PLA sets priorities for equipment R&D. In a sign of the organization's involvement in the Two Engines project, representatives of the EDD attended the opening ceremony for Beihang University's Basic Research Science Center for Aeroengines and Gas Turbines [航空发动机及燃气轮机基础科学中心], an initiative under the Two Engines project dedicated to basic research.[22]

Central Military Commission's Science and Technology Commission [科学技术委员会]

The CMC Science and Technology Commission also provides oversight and direction for aeroengine development and plays an important role coordinating between the CMC, scientific organizations, the State Administration for Science, Technology and Industry for National Defense (SASTIND), SOEs and private industry. In August 2017, the Science and Technology Commission and MOST issued the "Plan for S&T Military-Civilian Fusion Development Special Projects During the 13th FYP Period" ["十三五"科技军民融合发展专项规划].[23] Again, though details of the plan are not public, it is likely that aeroengine development is a focus given the prioritization of aeroengine and gas turbine technologies during the 13th FYP period.

Equipment Development Department's Military Representative Bureaus [军事代表局]

For specific projects, the EDD's Military Representative Bureau has representative offices [代表处/办] at factories and research institutes to help guide work and ensure progress. Members of these offices occasionally publish in related journals. For example, personnel from the Shanghai Regional Military Aviation Representative Office under the PLA Army Equipment Department's Military Aviation Representative Bureau [陆军装备部航空军事代表局驻上海地区航空军事代表

室] recently contributed to a study on the containment structure of an unidentified engine's air turbine starter published in *Aeroengine* [航空发动机], a technical journal issued by the Aviation Industry Corporation of China (AVIC).[24]

Consolidation of the Aeroengine Industry

A basic feature of China's military-industrial complex is the division of research and manufacturing duties into discrete state-owned bodies. In the 1950s research institutes [设计研究院所] and manufacturers [主机生产企业] were separated. Primary responsibility for R&D of the J-10 fighter jet, for example, was divided between the Chengdu Aircraft Design Institute [成都飞机设计研究所] (611 Academy), with production handled by the Chengdu State Aircraft Factory No. 132 [国营132厂].

Particularly since 2010, China has undergone a series of reorganizations of its defense industry. These have increasingly combined formerly separate research institutes and manufacturers into single enterprises. This reorganization is meant to make the design and development process more efficient by forcing the organizations responsible for design to work more closely with those responsible for production.. The most important of these consolidations is the May 2016 creation of the Aero Engine Corporation of China [中国航空发动机集团] (AECC).

> **Aero Engine Corporation of China (AECC)**
> [中国航空发动机集团有限公司 (中国航发)]
>
> Headquarters: Dadong District, Shenyang, Liaoning Province
>
> Website: http://www.aecc.cn

AECC is China's primary developer and manufacturer of turbojet, turbofan, turboshaft, turboprop, and piston engines and gas turbines. It serves both the civilian and military sectors. AECC is partly owned by the State Council through the State-owned Assets Supervision and Administration Commission (SASAC), as well as by the Beijing government, AVIC, and the Commercial Aircraft Corporation of China (COMAC). Prior to the creation of AECC, aeroengine design, development, manufacturing, and overall was performed by numerous separate enterprises dispersed throughout AVIC's organizational structure. AECC represents several years of consolidation among the various engine-producing components of AVIC.[25] It brings together 27 companies and research institutes and employs roughly 84,000 people. The central government approved the creation of AECC to consolidate the resources available for the Two Engines special project.

Speaking during the March 2019 meetings of the National People's Congress and the Chinese People's Political Consultative Congress, Xiang Qiao [向巧], academician of the Chinese Academy of Engineering, and deputy director of the CMC Science and Technology Commission, emphasized that the combination of the Two Engines special project and the creation of AECC were specifically meant to consolidate resources.[26] Among AECC's projects is the AEF3500 turbofan for widebody aircraft. The largest aeroengine yet developed by China, the AEF3500 features will have a 35-ton thrust and is planned to enter service around 2030.[27] The engine was first unveiled at Airshow China 2018.[28]

Creation of New Research Institutes and Test Platforms

China has continued to face difficulty in manufacturing fan blades and housings capable of withstanding the extreme temperatures and pressures that occur in a modern jet engine. Chinese scholars and policymakers have identified the cause of these problems as redundancy in research and insufficient funding for basic materials science research. In 2012, for example, Xu Jianzhong [徐建中] of the Chinese Academy of Sciences [中国科学院] noted that "China is the only permanent member of the UN Security Council that cannot independently develop advanced aeroengines. This is extremely disproportionate to China's national security and status as a major power."[29] Xu asserted that a major cause of China's inability to develop advanced aeroengines was insufficient basic research. The Chinese government appears to be attempting to remedy this shortcoming in recent years.

Both national and provincial-level funds exist for research on particular topics, including aeroengine technology. For example, the Yunnan province funds a Basic Research Priorities Project [云南省基础研究重点项目] and numerous provinces have Department of Education Talent Projects [省教育厅人才项目]. At the national level, the National Natural Science Foundation of China [国家自然科学基金委员会] has its own programs to support aeroengine-related research in areas such as combustion and material science.[h]

h For example, a 2019 plan project funds research on combustion and turbulence for advanced aeroengines and lays out criteria for prospective applicants to follow. See: "面向发动机的湍流燃烧基础研究重大研究计划2019年度项目指南," National Natural Science Foundation of China (NSFC; [国家自然科学基金委员会]), 20 May 2019. http://www.nsfc.gov.cn/publish/portal0/tab568/info75968.htm

Aeroengine and Gas Turbine Basic Research Center
[航空发动机及燃气轮机基础科学中心]

The Aeroengine and Gas Turbine Basic Research Center [航空发动机及燃气轮机基础科学中心] was established in Beijing in 2018. The center is a collective effort that includes Beihang University, Tsinghua University, the Chinese Academy of Sciences, Northwestern Polytechnical University, AECC Engine Research Institute, and China United Heavy Duty Gas Turbine Co. [中国联合重型燃气轮机技术有限公司].[30]

AECC Beijing Institute of Aeronautical Materials
[中国航发北京航空材料研究院]

Location: Beijing

Website: http://www.biam.ac.cn/

The Beijing Institute of Aeronautical Materials was established in 1956. It conducts research on the development, engineering, and utilization of advanced aviation materials. It has a total staff of more than 2000 people, about half of whom are technical personnel. It operates nine national laboratories and engineering centers.[31]

AECC Aeroengine Control System Institute
[中国航发控制系统研究所]

Location: Wuxi, Jiangsu province

Website: http://camci.com.cn

The Aeroengine Control System Institute, also known as the 614 Institute [614所], was founded in 1974 in Wuxi, Jiangsu Province.[32] In 1991, it absorbed several related institutes to become what it is today. The institute is responsible for research, development and the manufacture and repair of aeroengine and gas turbine control systems for military and civil applications. It carries out digital simulation and environmental testing and is home to the only key laboratory on aeronautical power control systems [航空科技动力控制系统重点实验室]. The institute has also built full authority digital engine control (FADEC) systems for turboshaft engines, such as the WZ-16 jointly developed with France.[33] In 2015 it employed a staff of roughly 1,000 people.[34]

AECC Sichuan Gas Turbine Research Institute
[中国航发四川燃气涡轮研究院] (624 Institute)
Location: Jiangyou Mianyang, Sichuan Province [四川省绵阳市]
Website: http://www.cgte.com.cn/

AECC Sichuan Gas Turbine Research Institute, is one of China's three large aeroengine institutes.[35] Though ostensibly a gas turbine research institute, the overlap between gas turbine technology and aeroengines discussed earlier in the report makes the research institute one of China's key aeroengine R&D centers. It recently invested 13 billion RMB ($2 billion) to build an engineering research and development center [工程研发中心], an engineering simulation center [工程仿真中心], an "engineering synergy center" [工程协同中心], a military-civil fusion development center [军民融合发展中心], and a shared technical laboratory group[共用技术试验室群].[36]

AECC Aero Science and Technology Co, Ltd.
[中国航发航空科技股份有限公司 (航发科技)]
Location: Chengdu, Sichuan Province [四川省成都市]
Website: http://ast.aecc.cn

AECC Aero Science and Technology Co., Ltd. is a limited stock company jointly established in 1999 by AECC Chengdu Aero Engine Group Corporation, AECC Shenyang Liming Aero-Engine Co., Ltd., Beihang University, AECC's China Gas Turbine Establishment, and Chengdu Aeronautic Vocational and Technical College. It has a staff of over 4,100 and is engaged in development, production, and testing for aeroengines.[37]

AECC South Industry Co., Ltd.
(previously China National South Aviation Industry Co.)

[中国航发南方工业有限公司 (“航发南方”)]

Location: Zhuzhou, Hunan Province [湖南省株洲市]

Website: http://www.aeccsi.com/

AECC South Industry Co., Ltd. (previously named China National South Aviation Industry Co.) was established in 1951, shortly after the founding of the PRC, and produced the PRC's first aeroengines. Over time it has also developed and produced China's first heavy motorcycle engines, first industrial gas turbines, and first turboprop engines. It currently produces turboprops, turboshafts, and small turbojets.[38] The company has had extensive contacts with overseas businesses, including in the United States. As of 2014, AECC South Industry Co. was contracted to supply components to Pratt &Whitney Canada, Hamilton Sunstrand, and Turbomeca.[39]

Key Figures in Aeroengine R&D

Provided below are profiles of key figures in the development of aeroengines in China in recent years.

Zhang Enhe [张恩和]

Chief Designer of the WS-10/Taihang

Perhaps the biggest milestone of the 2000s for engine development was the successful production of the WS-10 [涡扇-10], also called the "Taihang" [太行]. Over the course of his career Zhang played important roles in the development of engines for fighter jets and transports, including the canceled J-9 fighter, the Y-7 turboprop transport, and the J-10 fighter.

Zhang graduated from the Harbin Institute of Technology in 1964 with a major in aeroengine design. He the WS-6 engine program, China's first effort to develop a turbofan, which was eventually canceled.[40] As a top technical talent, Zhang also spent some time studying in the United States. In 1981, he was sent to the New York Institute of Technology to study for two years.[41]

During the 1980s China relied on "second generation" [二代] turbojet engines, whereas the developed countries were already widely using "third generation" turbofan engines.[42] The "Taihang" program was launched in 1987 to address this problem. Zhang worked on preliminary research for the program when he returned to China following his studies in the United States. In 1991, he was named the project's lead engineer. China's relatively low starting point forced the engineering team to absorb the knowledge of how to use dozens of new materials and techniques. Problems continued to follow the project in 2003, with at least one major incident occurring during high altitude testing. The engine design eventually passed review in December 2005 and was finalized in March 2006.[43] Zhang died on 13 November 2016 at the age of 77.[44]

Liu Yongquan [刘永泉]

Chief Designer of China Aerospace Shenyang Engine Research Institute

Liu Yongquan, chief designer [总设计师] and deputy director of the China Aerospace Shenyang Engine Research Institute (often shortened to Power Institute) [沈阳发动机研究所 ("动力所")], has been a leading figure in China's aviation engine R&D and basic research.

Liu is credited as the chief designer of five key aeroengine models, including the WS-10B,[45] an enhanced version of the Taihang engine.[i]

Liu received an undergraduate degree in aeroengine design from Northwestern Polytechnical University in 1984.[46] In 1990, he received a master's in engineering[47] from the propulsion department at Beihang University.[48] Liu has also studied abroad.[49]

Liu joined Shenyang in the 1980s and worked on the "Kunlun" aeroengine for the J-7 and J-8 fighter jets. The Kunlun is claimed to be China's first indigenously designed jet engine.[50] Liu later worked on the Taihang engine. He and his team at the Power Institute focused on improving engine reliability. Liu was also the lead expert on the national defense project addressing engine vibration ["整机振动技术研究"课题], a problem which had plagued Chinese aeroengines.[51]

Liu is credited with helping China's aeroengine industry make a leap forward in overall engine performance, greatly enhancing China's indigenous national defense capability. This is said to have helped China overcome the negative effects of international technology embargoes and achieve the completely independent development of advanced core machine technology for the first time. Liu is a Chief Scientist for China's 973 Program and belongs to the expert group on aeroengines under the Central Military Commission's Equipment Development Department.[52]

Wang Haifeng [王海峰],
AVIC Chief Technical Expert and Chief Designer of Chengdu Aircraft Design Institute

On 6 November 2018, at the 12th Airshow China, the J-10B thrust vector technical demonstration project made its debut. The J-10B testbed's successful performance of technically demanding aerial maneuvers including the Pugachev Cobra, the Herbst maneuver and the falling leaf maneuver[53] showcased China's capabilities in thrust vectoring control (TVC) systems. Wang Haifeng, AVIC chief technical expert and chief designer at AVIC's Chengdu Aircraft Design Institute [航空工业成都飞机设计研究所], was the chief designer of the J-10B thrust vector technical demonstration project.

Wang majored in flight mechanics in the guided missile department of Northwestern Polytechnical University. He graduated in 1984 and was sent to the Chengdu Aircraft Design Institute, where he had the immediate opportunity to work on the development of the J-10. He returned to Northwestern Poly in 1987 and studied under Song Wencong [宋文骢], the J-10's lead designer. In 2000, Wang was accepted into the transportation planning and management program at Northwestern Poly's School of Aeronautics. He earned a doctorate in 2005.[54] In addition to the J-10, Wang has also participated in the development of the J-20 stealth fighter,[55] the J-10S (two-seat variant of the J-10), the FC-1 fighter co-produced with Pakistan, various UAVs and other technical research projects.[56] Wang is a noted academic. He and Chengdu Aircraft Industry Group (CAIG) deputy chief designer for flight control systems Yang Chaoxu along with Wang Chengliang previously wrote a paper in 2006 on high angles of attack for advanced fighters. It appears that some of the directions they were pursuing when writing the article have been incorporated into CAIG-produced aircraft.[57]

Having been assigned to different positions in various specialty fields over the course of his career, Wang is said to have gained expertise in and made significant contributions to areas such as aerodynamics, flight control, flight tests, after-sales support, and fault prediction and aircraft health management. The models for "Fault Prediction and Health Management System" [故障预测与健康管理系统] and "Independent Logistics Support Information System"[自主保障信息系统] Wang led the development of are said to have enabled the building of a layered diagnostic system that allows for analysis of the aircraft as a whole to predict and identify faults.[58]

In addition to the J-10B thrust vector technical demonstration project, Wang also oversees the Turbine-Based Combined Cycle Engine flight demonstration project, which completed a successful test in January 2019.[59] Wang also manages the R&D of China's next-generation fighter jets.[60]

International Cooperation

Given the difficulties China has encountered in manufacturing modern aeroengines, international cooperation represents a significant potential source of assistance in overcoming those difficulties. China received some assistance in this regard from the West during the 1970s and 1980s, but since the 1989 Tiananmen Square incident Western countries have restricted China's capability to acquire technologies that have potential military applications, including turbine engine technology. As a result, China's principal external source for aeroengine technology has been the countries of the former Soviet Union.

China-Russia Cooperation on Aeroengine Development

Russia was instrumental in the establishment of China's aviation industry, including the capability to manufacture aeroengines, during the 1950s. Russia withdrew its technical assistance in 1960, however, and since then has provided relatively little direct technical assistance to China's aeroengine sector, although there have been reports in recent years of plans to collaborate in the development of a high bypass-ratio turbofan for widebody airliners and a turboshaft engine for heavy lift helicopters. Russia has nonetheless been an important supplier of aeroengines for Chinese military aircraft in recent years, which has at least provided China with the opportunity to study, and potentially reverse-engineer, modern military aeroengines.

Russian sales of sophisticated weapons systems and components, such as turbofans, are part of a calculated move by the Kremlin. Western sanctions levied in response to the Ukraine crisis and other related political and economic fallout re-incentivized Russia to deepen its ties with China. According to Russian reports, Russian experts carried out extensive research to assess the potential threats that closer partnership with China could involve.[j] Russian expert thinking converged around the idea that China will depend increasingly less on imports from Russia, regardless of whether Russia continues to sell weapon systems and components over the short- to medium- term. This, coupled with a view that China will not threaten territory in the Russian Far East, underpins the rationale behind the sale of sophisticated Russian technology to China. Beyond the monetary benefits high value deals bring to the Russian arms industry, these sales are an integral part of the Russian strategy to build closer relations with China. In return, Russia seeks Chinese political and economic support as it weathers the effects of its increasingly strained relations with the West.[61]

In addition to sales of aircraft and components and the planned cooperation in the development and manufacturing of helicopters and the CR929 widebody airliner, there are a large number of ongoing academic exchanges between the Chinese and Russian aviation sectors. In 2014, for example, the Chinese Aeronautical Establishment (CAE) [中国航空研究院] signed a strategic cooperative agreement with the Russian Central Aerohydrodynamic Institute [Центра́льный аэрогидродинами́ческий институ́т] establishing high level exchanges and coordination. The two organizations hold an annual China-Russia Aviation Technology Exchange Conference.[62]

Similarly, in January 2017 a delegation from AECC's China Aero Engine Research Institute [中国航发研究院] signed a memorandum of cooperation with Russia's Central Institute of Aviation Motors (CIAM) [Центральный Институт Авиационного Моторостроения]. CIAM is Russia's sole specialized engine technology research center. The institute also plays a central role in Russia's study of hypersonic flight. Under the terms of the memorandum of cooperation, the two sides will advance technical research, experimental equipment construction, and aviation engine research and development. Specific areas of cooperation include improving aeroengine health management, distributed control systems, and aeroengine thermal management. A follow-up was set for April 2017, and both sides planned to jointly organize an aeroengine technology development forum to be held in Beijing later in 2017.[63]

China-Ukraine Cooperation

Another major input to Chinese aeroengine development, one whose importance has increased over the past decade, is China's deep relationship with Ukraine. Chinese companies have aggressively pursued Ukrainian engine technology, attempting to buy the Ivchenko-Progress AI-222-25F afterburning turbofan for trainer and light combat aircraft in 2009, and then bidding to buy another Ukrainian aeroengine manufacturer, Motor Sich, in 2017.[64] Though both deals were blocked by the Ukrainian government, Chinese investors were eventually able to acquire a stake in Motor Sich, allowing China to establish a direct relationship with a Ukrainian aeroengine company.[65] Chinese investment is so important to the company that the president of Motor Sich, Vyacheslav Boguslayev, recently stated that if the relationship was cut off, he would have to immediately "fire 10,000 people."[66]

In 2016, Chinese companies were licensed to produce Motor Sich's D-136 turboshaft (the world's most powerful helicopter engine), the MS-500V, TV3-117VMA-SBM1V and AI-450S turboprop engines, the D-436-148FM and D-18T high bypass-ratio turbofan engines, the D-27 counter-rotating propfan engine, and the AI-222 series low-bypass turbofans. The D-18T high bypass ratio turbofan engine is particularly significant, as it is used in the An-225 and An-124 strategic transport aircraft.[67]

At Airshow 2018, four aircraft engines were showcased by Beijing Skyrizon Aviation Industry Investment Co. Ltd. [北京天骄航空产业投资有限公司 (天骄航空)] and its subsidiary Chongqing Skyrizon Aviation Power Co., Ltd. [重庆天骄航空动力有限公司] in partnership with Motor Sich, including the AI-222 turbofan, the TV3-117VMA-SBM1V turboprop, the D-436-148FM turbofan, and the

MS-500V-S family of turboprops. The MS-500V-S family of engines was jointly developed, manufactured, assembled and tested by Skyrizon and Motor Sich; the engines are reportedly very similar to the Pratt & Whitney Canada PT6A . Skyrizon and Motor Sich developed MS-500V-S family of turboprops based on Motor Sich's MS-500V family of turboshafts.[68]

Part II

Four types of aeroengine have been the highest development priority in China: fighter jet engines, turbofans for bombers and commercial aircraft, helicopter engines, and engines for UAVs and cruise missiles. This section describes China's efforts in each area.

Fighter Jet Engine Research and Design

Perhaps the most significant focus of aeroengine development in China has been the effort to produce lighter, more powerful engines for its fighter aircraft. China has long possessed the capability to manufacture turbojets based on designs introduced by the Soviet Union during the 1950s but has struggled to produce the high thrust-to-weight-ratio turbofans used on modern fighter aircraft.

Challenges China's aeroengine industry has faced include inadequate basic research and a lack of sophisticated design and manufacturing tools. In some cases, development efforts have not been able to keep up with shifts in China's strategic environment. The WP-6Z turbojet program, for example, was canceled because the J-9 and Q-6 air superiority and ground attack aircraft it was to be installed in were canceled due to being obsolete before they had finished development.

Engine Development Milestones	
1954	First aeroengine factory built in Shenyang
1983	Taihang engine project chosen over improved WS-6 and WP-15 designs for new fighter
1984	Kunlun engine project established
1987	Taihang engine project begins R&D
1989	First Taihang live test
1991	Taihang passes first technical review
1992	Taihang engine passes first full-thrust test
2002	Kunlun engine design approved
2005	Taihang engine design finalized[69]

Even when the technology to produce a particular type of engine has been acquired, China's lower level of metallurgy capabilities and mastery of quality control have often prevented it from successfully manufacturing it. The "Qinling" [秦岭] engine used in the JH-7 aircraft, for example, is a licensed version of the Rolls Royce Spey engine. The license was acquired in 1974, but China was not able to actually produce these engines until 2013.

Another weakness of Chinese aeroengines has been their short service lives. The PLA aspires to achieve Western levels of proficiency in its pilot training. This requires that each aircraft be flown several hundred hours a year. Chinese-made engines based on Soviet designs and imported Russian-made engines, however, have very short service lives. Early versions of the Soviet-Russian AL-31F engine, for example, which powers most of China's J-11 and J-10 fighter aircraft, had a time-between-overhauls (TBO)[k] of 300 hours, whereas Western aeroengines typically have TBOs of 2,000 hours.[70] In addition, these engines can only be rebuilt three times, so they have a total service life of only 900 hours. As the PLA spends more time doing maritime training, moreover, considerations like seawater corrosion may further reduce engine lifespans. Reportedly the domestically-manufactured Taihang engine, however, has now reached a TBO of 500 hours. This is a major improvement from its previously reported TBO of 300 hours.

Key Institutes for Fighter Jet Engine Research and Design

Two key organizations for the design, development, and production of fighter jet engines in China are the Shenyang Engine Design Institute and AECC Shenyang Liming Aero Engine Co., Ltd. The Shenyang Engine Design Institute is responsible for designing aeroengines and other types of gas turbines, while Shenyang Liming is primarily responsible for production, although it has some degree of in-house design capability as well.

Shenyang Engine Design Institute (606 Institute)
[沈阳发动机设计研究所]
Location: Shenyang, Liaoning Province

The Shenyang Engine Design Institute, also known as the 606 Institute, is part of AECC. It was established in 1961 and as of 2011 had a staff of more than 2,500, including 1520 engineering and technical personnel. It was the PRC's first aeroengine design research institute. It is a center for research and development of medium and large turbojet and turbofan engines as well as industrial gas turbines. Over its history it has developed more than 10 types of turbojet and turbofan engines including the Kunlun and Taihang.[71]

AECC Shenyang Liming Aero Engine Co. Ltd.

[中国航发沈阳黎明航空发动机有限责任公司(黎明公司)]

Location: Shenyang, Liaoning Province

Website: http://slae.aecc.cn

Based in Shenyang's Dandong district, Liming, a subsidiary of AECC, has a staff of more than 12,000. While the company has its origins with Warlord Zhang Zuolin's Fengtian Armory in 1919, its modern incarnation as an aeroengine company began in April 1954, when it was tasked with producing China's first turbojets during the First FYP[l] (1953-1957).[72] Over the years it has been responsible for repairing, copy-producing, upgrading, researching, and producing multiple types of engines.[73] Liming produces both the Kunlun and the Taihang.[74]

Key Components and Technologies

The state of jet engine research and design in China is indicated by its progress in mastering key components and technologies for jet engine development.

Turbine Blades

A crucial technology for modern aeroengines lies in the light and high temperature-resistant materials used in the manufacture of turbine blades. Building on the foundation of aviation metallurgy built by Shi Changxu [师昌绪],[m] Chinese scientists and engineers have slowly begun to overcome the immense technological hurdles involved in their manufacture. The high temperatures and pressures involved in modern engines make use of advanced alloys a necessity. In March 2019, *China Aviation News* announced that Xu Qingyan [许庆彦], a researcher at Tsinghua University, and his team had independently developed a unique process for modelling monocrystalline growth in nickel-based superalloys a key technology in modern aeroengine turbine blades.[75] A 2016 overview of progress toward developing high temperature alloys by researchers from the Aviation Key Laboratory of Science and Technology on Advanced Titanium

l Specifically, the 156 项重点工程项目

m Shi Changxu received a Ph.D. from the University of Notre Dame before returning to China in 1955. He helped pioneer metallurgical work on aeroengine turbine blades, developing advanced alloys and casting techniques. See "师昌绪," China Academy of Sciences, [accessed June 2019] http://www.cas.cn/ky/kjjl/gjzgkxjsj/2010gjzgkxjsj/shichangxu/grjj/201102/t20110210_3070504.shtml

Alloys [先进钛合金航空科技重点实验室] at the Beijing Institute of Aeronautical Materials [北京航空材料研究院], however, made clear that while Chinese labs understood the technical steps to make titanium alloy heat resistant, they were still in the theoretical speculation, research, and lab test phase. The researchers admitted that more tests and experimentation are needed to build a sufficient data pool to move forward.

Blisk Technology

A further development of aeroengine turbine blades that has had a major impact in reducing weight and the number of compression stages and the engine's overall weight are integrally bladed rotors in which the turbine blades and the rotors they attach to are fused together into a single "bladed-disk" or "blisk" [整体叶盘]. According to Chinese sources, blisks can save more than 30 percent of the weight that results when the components are cast separately, decrease wear and tear, and improve efficiency.[76] Producing blisks, however, requires advanced manufacturing technology.

Progress is being made in producing better blisks using advanced techniques. The Beijing Iron and Steel Research Institute [北京钢铁研究总院] and Beihang University, for example, have successfully produced a two-layer titanium alloy blisk [双组织双性能钛合金整体叶盘] using laser additive manufacturing.[77]

Full Authority Digital Engine Control (FADEC) [全权限数字发动机控制]

FADEC systems improve engine performance, safety, and lifespan. FADEC represents a major improvement over the hydraulic systems of previous generations.[78] Just as modern flight control systems must constantly adjust the trim of an aircraft to keep it airborne, to the airflow, rate of combustion, and other parameters of an aeroengine must be constantly tuned and altered so that the engine will continue to run smoothly even as the aircraft's external environment, altitude, and attitude change.

In the West, FADEC systems first came into use in the 1980s.[79] In 2003, an indigenously-designed FADEC system developed by the AVIC Aerodynamic Control System Institute [中航工业航空动力控制系统研究所] (also known as the 614 Institute) was reported to have been accepted for use by the PLA Air Force Equipment Department.[80]

FADECs are complicated by the necessity of communicating engine data (often wirelessly) while withstanding the tremendous pressures and temperatures generated by aero engines. Over the course of the 12th FYP and 13th FYP periods

(2011-2015 and 2016-2020), the goal of China's aviation industry has been to gradually move from transitional, distributed structure [渡期分布式结构控制系统] FADECs to fully distributed FADECs by improving the temperature resistance of sensors, which must withstand temperatures in excess of 1800 degrees Celsius while continuing to function.[81]

Thrust Vector Control

Thrust Vector Control is an emerging technology primarily used on advanced fighter jets to give greater control and maneuverability by manipulating the direction of thrust itself, rather than relying on flight control surfaces such as ailerons, leading edge flaps and elevators. China's military aviation industry has been seeking to acquire this technology. Its progress in this area was displayed at Airshow China 2018, when a J-10B thrust vector demonstrator developed by AVIC successfully performed "post-stall" maneuvers. At a press conference jointly held by AVIC and AECC, Yang Wei [杨伟], Site Manager of the J-10B Thrust Vector Technical Demonstration Project and AVIC Vice President, asserted that China had become one of the few countries in the world possessing this key technology.[82]

Supercruise

Supercruise is sustained supersonic flight. In previous generations of aeroengines (with a few exceptions) supersonic flight was only achievable for short periods of time, typically through the use of afterburners. Afterburners inject additional fuel into the engine exhaust after it exits the turbine, leading to a large increase in thrust; however, this burns fuel rapidly. Supercruise engines, in contrast, can produce sufficient thrust to achieve and maintain speeds in excess of Mach 1 without the need of afterburners, reducing both fuel consumption and stress on the engines. Two examples of engines with supercruise capability include the F119 used in the F-22 and the AL-41F1S installed on the Sukhoi Su-35S and Su-57. (China is believed to have acquired the non-supercruise version of the latter with the Su-35 fighters it has imported from Russia.)

Supercruising has significant advantages for military aircraft, particularly for mission sets that the PLA has demonstrated an interest in, such as long-range bombing and defensive counterair operations to intercept and disrupt incoming air strikes.[83] There is significant evidence to suggest that China is currently attempting to build aeroengines capable of supercruise.

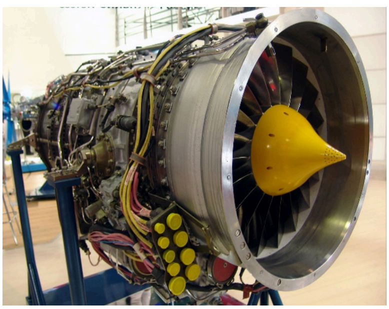
Fighter Jet Engines in Production or Development in China

The following are examples of engines that China has imported, and in many cases, replicated or developed itself.

WS-19 "Huangshan" [黄山] Engine

Chinese defense industries are claiming major progress in their capability to produce modern aeroengines.

The Guizhou Aeroengine Design Institute [贵州航空发动机研究所] (also known as the 649 Institute) is believed to be leading the design of a medium-thrust turbofan, the WS-19. The WS-19 is said to have a thrust-to-weight ratio of 11 and to produce more than 24,000 lbs of thrust (when afterburning, presumably). The engine is intended for the FC-31 medium-weight stealth fighter, which currently uses the Russian RD-33MK. The WS-13, with a thrust-to-weight ratio of 9 and thrust of 10,000kgs, which was also developed by the Guizhou Aeroengine Design Institute based on an earlier version of the RD-33, was judged to be insufficient.[84]



AI-222-25F

The L-15 [猎鹰] advanced fighter trainer produced by AVIC Hongdu [中航工业洪都] uses two AI-222-25F [АИ-222-25Ф] engines.[85] The AI-222-25F is a low-bypass afterburning turbofan manufactured by Ukraine's Motor Sich.[86] An earlier version of this engine is used on the Yakovlev Yak-130 [Як-130] jet trainer. A recent overhaul of the engine design gave it a service life of 3,000 hours, with maintenance at 1,500 hours, more than doubling the engine life.[87] China reportedly received a license to manufacture this engine in 2016.[88]

Bomber and Commercial Aircraft Engine Research and Design

In addition to high-performance jet engines, another priority specified for the Two Engines special project and other S&T development programs is high-bypass-ratio turbofan engines [大涵道比涡扇发动机]. These engines have greatly improved efficiency compared to ordinary turbojets, making them standard on passenger jets and long-haul, heavy-lift transports built during the past half-century. China's drive to create a "Strategic Air Force" [战略空军], which prioritizes acquiring a heavy bomber and strategic transport capability, also requires these types of engines.

Military High Bypass Turbofans

A core component of China's "Strategic Air Force" concept is the development of strategic transport aircraft. Although China is able to manufacture the turboprop engines used on tactical transport aircraft such as the Y-7, Y-8, and Y-9, high bypass-ratio turbofan engines are currently the most efficient way to power strategic transport aircraft like the Y-20. Other military applications for large turbofans include advanced bombers (such as the H-20 currently under development) and future aircraft such as the Y-20U aerial refueler, civilian Y-20F-100, and KJ-3000 AEW aircraft.

At present China is reliant on the Russian-made D-30KP-2 engine, which is being installed on the Y-20 transport and H-6K medium bomber currently being built in China.[89] Some Chinese aircraft have reportedly begun using a domestically-built engine called the WS-18, but Russian analysts believe that the WS-18 is simply a copy of the D-30KP-2. It is unclear if the WS-18 is intended to replace the D-30KP-2 or if it is meant to act as a stepping stone on the way to a more-advanced engine, the WS-20. In either case, while the development of the WS-18 began in 2007 and flight testing began in 2015, China has continued to purchase more D-30KP-2s. In 2016, China signed two contracts for a combined order of 224 D-30KP-2 engines to be delivered through 2020. Upon receipt of this order, China will have imported a total of 463 of these engines from Russia.[90] At the time of the 2016 order, some Russian analysts indicated that 170 of the 224 engines were for use on the Y-20; the remaining 54 engines were slated for China's Il-76 and Il-78 aircraft.[91]

The WS-20 "Huanghe" [黄河] engine is meant to replace both the imported D-30KP-2s and the WS-18. An article in the *Journal of Aerospace Power* [航空动力学报] in June 2008 provided an overview of China's progress and difficulties in large bypass turbofans. The article stated that China's goal for the WS-20 was to achieve a level of efficiency and power similar to the U.S.-French CFM56, used on narrow-body airliners, and superior to Russia's D-30KP engine.[92] Some Russian experts, however, have commented that the WS-20 would be a "weak link" in the Y-20, citing a previous history of Chinese engines having a more limited service life and being less reliable than Russian engines.[93]

Civilian High Bypass Turbofans

China has been attempting to build commercially viable jetliners and engines for them for almost 50 years. As noted above, the WS-6 project, China's first effort to develop a turbofan for fighter aircraft, ultimately proved to be a dead-end and was terminated in 1986.[94] During the 1970s China attempted to develop another turbofan engine, the WS-8, which was intended to power the Y-10 transport aircraft. The Y-10 was simply a copy of the Boeing 707 and the WS-8 was presumably a copy of the Pratt & Whitney JT3D-3B engines that powered it. In March 1971, the WS-8 design was declared essentially complete and development proceeded over the next decade, with the first successful 1000-hour endurance test in October 1977. The WS-8 was flight-tested in April 1982 on a Boeing 707. Chinese manufacturers experienced difficulties with the WS-8s engine's requirement for advanced precision ball bearings and extensive use of titanium, however, and the project was ultimately cancelled.[95]

China's most recent efforts to develop commercial jet aircraft include the COMAC ARJ21 twin-engine regional jet and the COMAC C919 narrow-body jetliner. Development of the ARJ21 began in 2003 and it began entering service in 2015. This aircraft was intended to compete internationally with comparable aircraft produced by Bombardier and Embraer, but all of its customers so far have been state-owned airlines and corporations within China.[96] COMAC did not attempt to source the engines for this aircraft locally; the ARJ21 relies on imported CF34-10A engines produced by GE.[97]

A subsequent project is the C919 narrow-body airliner, intended to compete with the Boeing 737 and Airbus A320 series. This aircraft, under development since 2008 and currently scheduled to enter service in 2021 or 2022, will initially be equipped with CFM International Leap-1C engines. AECC Commercial Aircraft Engine Company, however, is developing an alternative engine, the CJ-1000 [长江1000发动机], not only for installation on the C919, but hypothetically for 737s and A320s as well. Entry into service for the CJ-1000 is currently targeted for 2025.[98]

AECC Commercial Aircraft Engine Company is reportedly also developing a more-powerful turbofan, the AEF3500 (formerly known as the CJ-2000), that could be used to power the Sino-Russian CR929 widebody airliner currently under joint development. Chinese media have suggested that the AEF3500 could enter service by around 2030.[99] Russian industry officials, however, have stated that Russia and China will jointly develop an engine for the CR929, and Russian engine maker Aviadvigatel has also been developing an engine that could power the CR929.[100] Whether the Russian and Chinese efforts will be merged or the Chinese AEF3500 project will continue as a separate program is unclear.

International companies' eagerness to gain access to the Chinese market has also resulted in a large number of joint ventures and cooperative agreements between the aeroengine giants and AECC subsidiaries. Safran Aircraft Engines, formerly Snecma, has set up multiple facilities in China to manufacture parts for the CFM56 aeroengine, which is a product of CFM International, a joint venture between Safran and GE.[n] Additionally, CFM has a Fleet Support Center in Shanghai and an AOG (Aircraft on the Ground) spare parts center in Zhuhai. CFM also joined with Air China to set up Sichuan Services Aero Engines Maintenance Company (SSAMC), a 60/40 joint venture that performs overhauls for CFM56 and LEAP engines at a new maintenance and overhaul facility that opened in Chengdu in 2018.[101]

In 2008 Snecma Suzhou Co. Ltd., and Messier-Dowty Suzhou Co. Ltd., set up Snecma Xinyi Airfoil Castings Co. Ltd., a partnership between Snecma and Guizhou Xinyi Machinery Factory (a subsidiary of AVIC), in the Suzhou industrial park. This casting factory makes turbine parts for CFM56-2, -3, -5A, -5C and -7B engines.[102]

Key Institutes for Bomber and Commercial Aircraft Engine Research and Design

AECC Commercial Aircraft Engine Company
[中国航发商用航空发动机有限责任公司; 中国航发商发, AECC CAE]
Location: Shanghai
Website: http://www.acae.com.cn/

Originally created in 2009 as a subsidiary of AVIC, AVIC Commercial Aircraft Engine Co. Ltd. was transferred to AECC in 2016 and renamed AECC Commercial Aircraft Engine. AECC CAE is focused on commercial aeroengines and related products.[103] As such it has been the leader on R&D of the CJ-1000.[104]

Z-5 Helicopter

China's helicopter R&D program began with the duplication of the Mi-4 Soviet helicopter, which became the Z-5 in the 1950s. While helicopter R&D essentially languished throughout the 1960s, in the early 70s demand for capable attack helicopters to combat Soviet tanks, and later, for search and rescue (SAR) applications came to the fore. This coincided with the acquisition of China's first French helicopters and the beginning of a close ongoing relationship.

France has been China's most important source for helicopters and engines.[o] The Z-8, Z-9, Z-11 and their derivatives are all based on designs from Aerospatiale (now part of Airbus Helicopters), and Chinese enterprises received licenses to manufacture Turbomeca (now Safran Helicopter Engines) Turmo and Arriel turboshaft engines to power them. AECC has close relations with Safran, the French maker of aeroengines and other aerospace components. AECC and Safran have established a strategic cooperation committee and cooperate closely on engine components and production supply chains.[p]

AECC displayed its first "completely indigenously" [完全自主研制] turboshaft engine, the "Yulong" [玉龙] at an exhibition in 2017.[105] AECC South in Zhuzhou, Hunan, was the lead for R&D, with Yin Zeyong [尹泽勇] as chief designer. Development of the engine is said to have taken more than 23 years and posed numerous technical issues, such as cracking turbine blades in 2007.[106] An example of the progress and remaining problems with Chinese turboshaft development can be seen in the three-engine Z-8, a copy of the Aerospatiale Super Frelon transport helicopter. Older Z-8s use the WZ-6C engine, a Chinese-made version of the Turbomeca Turmo. The newer Z-8F, however, and civilian AC313 based on the Z-8, use the Canadian PT6B-67A turboshaft, presumably because the performance of the WZ-6C was inadequate.[107]

Evidence from Chinese state plans and R&D institutions indicate that improved turboshaft engines capable of operating at high altitudes and in marine environments are a high priority, as Chinese helicopters have seen increased

o The contours of this relationship are explored in greater depth in "Lumbering Forward, China's Aviation Industry" pp. 42-44.

p Underscoring the closeness of their cooperation, AECC Chairman Cao Jiandong [曹建国] and Safran CEO Philippe Petitcolin were both present at the first meeting of the two companies' strategic cooperation committee interest in and testing for mountain warfare and maritime roles. Both of these mission sets impose particular challenges for engine design and capability.

Mountain Warfare

In 2008 after the Wenchuan earthquake in Sichuan, civilian and military fixed wing and rotor wing aircraft from across China were rushed to the area to assist with the emergency response. Many commentators have since noted the severe deficiency of capable helicopters able to operate in mountainous areas. Moreover, the PLA needs capable helicopters for tactical movement and resupply in the terrain of the Tibetan plateau. Current helicopters, such the Z-8 and Z-9, are unable to operate at high enough altitudes. Recently, the Z-20, similar to the U.S. UH-60 "Blackhawk," has entered service.[q, 108] This medium-lift helicopter may help address China's deficiency in mountain warfare-capable helicopters. Limited information is available about the Z-20's engines at present, though there is speculation that it will use a domestically-developed engine called the "Yulong" [玉龙] or WZ-10 [涡轴-10].[109]

Maritime Helicopters

The PLA Navy has increasingly demonstrated a commitment to shipborne antisubmarine warfare and transport applications for helicopters, equipping most of its new destroyers and amphibious assault ships with Z-9, Z-8 or Ka-28 helicopters. More recently there has been an attempt to expand into direct attack roles, as evidenced by the testing of Z-9Cs firing light anti-ship cruise missiles and a series of landing tests for Z-10 attack helicopters. Effectively fulfilling these mission sets will require much greater thrust-to-weight ratios and ease of maintenance to deal with saltwater environments. Further evidence of this focus on maritime roles for helicopters includes China's apparent ongoing construction of a Type 075 amphibious assault ship that resembles the U.S. Navy's "Wasp" class of landing helicopter docks (LHDs), believed to be underway at the Hudong-Zhonghua Shipyard in Shanghai.[110]

AECC "Yulong" Turboshaft Engine
Source: http://www.stdaily.com/zhuanti01/hkfdj/2017-09/13/content_576649.shtml

Key Institutes for Helicopter Engine Research and Design

For historical reasons dating to the Third Line Policy of the 1960s, Chinese helicopter R&D, including helicopter engine R&D, is concentrated in Zhuzhou [株洲], Hunan province.

Hunan Aviation Powerplant Research Institute [湖南动力机械研究所] (608 Institute) Location: Zhuzhou Hunan [湖南株洲]

Established in March 1968, the Hunan Aviation Powerplant Research Institute is the primary executor of research on helicopter engines and transmissions in China.[111] It has played a key role in the development of many Chinese aeroengines (including the "Yulong") as well as gas turbines.

UAV and Cruise Missile Engines

Other applications for aeroengines that have received less publicity, but which will perform important missions for the PLA in the future, are high-efficiency small-diameter turbojet and turbofan engines for UAVs and cruise missiles.[r, s]

China apparently acquired its first such turbojet through U.S. Firebee surveillance drones that crashed or were shot down on Chinese territory during the 1960s and 1970s. Beihang University reverse-engineered the French/U.S. Teledyne CAE J69 on these drones, producing the WP-11 [涡喷-11]. Beihang has recently displayed an upgraded version, the WP-11C, as part of the "Cloud Shadow" UAV [云影], and a "D" variant has been said to be under development.[112] Imports and covert acquisition of Russian and Ukrainian cruise missile engines have also played an important role.

China also appears to have benefited from Soviet/Russian small turbofan designs. Russian experts have noted that China's CJ-10A cruise missile appears to be a copy of the Russian Kh-55.[113] Some stocks of Kh-55 cruise missiles intended for destruction or sale to Russia after the breakup of the Soviet Union appear to have been sold to other countries. Accounting discrepancies in the reporting from Ukraine have raised questions as to whether all the missiles were indeed transferred to Russia or liquidated. Information that has come to light in the years following the deal indicates that this was not the case. It is believed that up to 18 Kh-55 missiles were transferred abroad to China and Iran.[114] If this is accurate, the engines in the Kh-55 missiles that China received would be R95-300 engines produced by Motor Sich. This was the engine of choice for Soviet-produced variants, and Ukraine's Kh-55s were produced during the Soviet era.

Ukraine's Motor Sich has recently developed the MS400 engine, which is comparable to the R95-300 engines on the Kh-55.[115] Development of the MS400 has given Motor Sich an engine that it has the rights to sell abroad. This was essential, as 90% of the components for the R95-300 were produced by Russian defense enterprises, and Russia has developed its own engine, the TRDD-50, for installation on newly-made Kh-55s and their derivatives, depriving Motor Sich of its top customer.[116]

A Russian military expert associated with the Center for Analysis of Strategies and Technologies (CAST) has published a report indicating that Motor Sich sold China's Poly Technologies several MS400 engines, transferred in small batches in

r Note: some information regarding these programs will be presented in greater depth in subsequent publications in this series, focusing on Missiles and Guidance Systems, hypersonic systems, and persistent C4ISR projects.

s For an excellent study of China's cruise missiles and relevant organizations involved in R&D, see Dennis M. Gormley, Andrew S. Erickson, and Jingdong Yuan, A Low-Visibility Force Multiplier Assessing China's Cruise Missile Ambitions, NDU Press, 2014.
https://inss.ndu.edu/Portals/68/Documents/Books/force-multiplier.pdf

2003, 2004, and 2007.[117] Other reports have also suggested that the engines on China's CJ-10As are based on the MS400.[118]

Key Institutes for UAV and Cruise Missile Engine Research and Design

Major organizations involved in micro or small aeroengine [微小型航空发动机] R&D include the Institute of Engineering Thermophysics of the Chinese Academy of Sciences [中国科学院工程热物理研究所], Hunan Aviation Powerplant Research Institute (608 Institute), the Third Academy of China Aerospace Science and Industry Corporation (CASIC), [中国航天科工集团第三研究院], and the China Gas Turbine Establishment [中国燃气涡轮研究院].

UAVs

The number of UAVs produced by Chinese defense companies large and small has exploded in recent years. Several Chinese companies including Norinco and CAIG have produced traditional reconnaissance UAVs following the United States' Predator/MQ-1 UAV format. The "Yilong" [翼龙] II was the first Chinese UAV to use a turboprop engine.[119] As China seeks to acquire high performance HALE UAVs (covered in a later case study), it will need to develop lighter, more fuel-efficient engines capable of greater performance in low-oxygen environments. An example of one of the companies working in this sector is Star UAV System Co. Ltd [朗星无人机系统有限公司].

Star UAV System Co. Ltd
[朗星无人机系统有限公司])
Location: Shuangliu District, Chengdu, Sichuan Province [四川省成都市双流区]
Website: http://www.staruas.com/

Star UAV first came to attention when it tested the AT200 Air Truck, a modified utility aircraft touted as an unmanned transport UAV. The UAV is based on the P750XL aircraft, produced by Pacific Aerospace, Ltd., of New Zealand, whose long range (2000km) and short-takeoff and landing (STOL) capability make it possible to deliver supplies to remote bases, including China's occupied reefs in the South China Sea.[120] The Institute of Engineering Thermophysics of the Chinese Academy of Sciences, which has been a major collaborator with CIAM, also participated in the AT-200's development.[121]

Cruise Missiles

Many cruise missiles use small turbofans for propulsion due to their high efficiency, allowing them to fly at lower altitudes and much greater distances than their solid or liquid fueled counterparts. While details are scant compared to other engine projects, it is clear that China has had success copying American and Russian-Ukrainian turbojets and turbofans.

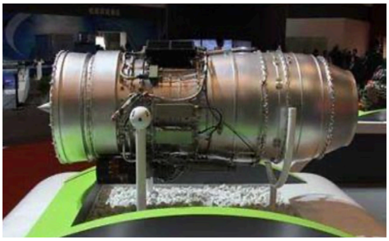
In 2018 a special test facility was set up to help accelerate the development of small and medium-sized aeroengines in Zhuzhou, the center of R&D for turbojets and turbofans for use in cruise missiles.[122]

Jiuzhai [九寨] Small Turbofan

The AECC Sichuan Gas Turbine Research Institute displayed a supercharged turbofan suitable for UAVs and cruise missiles first at Airshow 2012 and then again at the Entrepreneurship Expo in 2017.[123]

He Yuwei [何玉伟], a designer at the institute, told reporters at the 2017 exhibition that with 1000kg of thrust, the "Jiuzhai" [九寨] matched and in some cases exceeded the performance of equivalent American engines. The same article also speculated that the engine could be used on high altitude UAVs or in the next generation of YJ-62 ASMs.[124]

The "Jiuzhai" turbofan completed its first flight test in October 2017. It was designed and built by CASIC's Third Academy [中国航天科工三院]. The Institute of Engineering Thermophysics and Beihang University are also thought to have participated in the R&D.



Conclusion

In an interview, AVIC chief technology expert Wang Haifeng stated that the demands of China's situation are forcing aviation companies to "significantly shorten model development cycles and reduce the cost of R&D while, at the same time, [building aircraft] capable of responding to capable enemies."[125] The speed at which China has rolled out new aircraft and made notable achievements, such as the thrust-vectoring-capable J-10 on display in Zhuhai in 2018, are clear marks of progress in aeroengine development and lend credence to Wang's assertion.

However, it is important to note that aeroengine complexity does not increase linearly: a new engine or even a new variant may, in fact, be many times more complex than the previous one and may require many times more-precise tolerances or numbers of hours of simulation. Thus, while China's aeroengine industry has made significant progress, further progress will likely require increasing levels of effort and inputs of resources.

References

Referenced academic journals include:

- *Aeroengine*[126] [航空发动机] published by Shenyang Engine Design Institute
- *Journal of Aerospace Power*[127] [航空动力学报] published by Beihang University, AVIC and China Aviation Society [中国航空学会].[128]

Books and Studies

James Fallows, *China Airborne*. Knopf Doubleday Publishing Group, 2012. Kindle edition.

William C. Hannas, James Mulvenon, Anna B. Puglisi. *Chinese Industrial Espionage: Technology Acquisition and Military Modernization*, Routledge, 2013.

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

Tai Ming Cheung, , Ed. *Forging China's Military Might – A New Framework for Assessing Innovation*. Baltimore: Johns Hopkins University Press, 2014. Kindle Edition.

Evan S. Medeiros, Roger Cliff, Keith Crane, James C. Mulvenon, *A New Direction for China's Defense Industry*, Santa Monica, Calif. RAND Corporation, 2005.

Roger Cliff, Chad J.R. Ohlandt, David Yang. *Ready for Takeoff: China's Advancing Aerospace Industry*, Santa Monica, Calif.: RAND Corporation, 2011.

Roger Cliff, John F. Fei, Jeff Hagen, Elizabeth Hague, Eric Heginbotham, and John Stillion, *Shaking the Heavens and Splitting the Earth: Chinese Air Power Employment Concepts in the 21st Century*, Santa Monica, Calif.: RAND Corporation. 2010.

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

http://inss.ndu.edu/Portals/68/Documents/Books/force-multiplier.pdf

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

Wendell Minnick, ed. *Chinese Aircraft Engines*, self-published, 2016.

Wendell Minnick, *More Chinese Fixed Wing UAVs*, self-published, 2019.

中国航空工业史编修办公室, 编. [中国航空工业大事记（1951-2011)], 航空工业出版社, 2011.

Endnotes

1 "中航发的成立与涡扇6, 涡扇8发动机停产的悲剧," CWZG.cn [察网], 2 September 2016. http://www.cwzg.cn/politics/201609/30655.html

2 See Obaid Younossi et al., *Military Jet Engine Acquisition: Technology Basics and Cost-Estimating Methodology* (Santa Monica, CA: RAND Corporation, 2002), pp. 74, 75; Charles Skira, "Reducing Military Aircraft Engine Development Cost through Modeling and Simulation," Paper presented at the RTO A VT Symposium on "Reduction of Military Vehicle Acquisition Time and Cost through Advanced Modelling and Virtual Simulation," held in Paris, France, 22-25 April 2002, and published in RTO-MP-089 (as of February 26, 2020: https://apps.dtic.mil/dtic/tr/fulltext/u2/p014146.pdf). Development costs in these two studies were stated in 2001 dollars and 1996 dollars, respectively, and were converted into 2018 dollars based on [source].

3 Andrea Gilli and Mauro Gilli, "Why China Has Not Caught Up Yet - Military-Technological Superiority and the Limits of Imitation, Reverse Engineering, and Cyber Espionage," *International Security*, Vol. 43, No. 3 (Winter 2018/19), pp. 141–189

4 "China develops its own ballpoint pen tips," *Xinhua*, 10 January 2017. http://www.xinhuanet.com//english/2017-01/10/c_135970334_2.htm

5 "张新国在中国航空研究院重组成立会议上作重要讲话," *China Aviation News* [中国航空报], 24 October 2016. http://wap.cannews.com.cn/newwap/index.php?a=viewa&id=159729

6 "高技术产业发展 '十一五'规划," National Development and Reform Commission, April 28, 2007, https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/200705/W020190905497497838962.pdf

7 "务院关于印发'十二五'国家战略性新兴产业发展规划的通知," PRC Government, 20 July 2012. http://www.gov.cn/zwgk/2012-07/20/content_2187770.htm

8 " '十三五'国家科技创新规划," Central People's Government of the People's Republic of China, August 8, 2016. http://www.gov.cn/zhengce/content/2016-08/08/content_5098072.htm

9 "(中国制造 2025) 重点领域技术路线图," China Aeronautical Establishment, 29 October 2015. http://www.cae.cn/cae/html/files/2015-10/29/20151029105822561730637.pdf

10 "北京航空航天大学:聚焦国家重大任务, 推动行业自主发展," Ministry of Education, 16 August 2013. http://www.moe.gov.cn/s78/A16/A16_ztzl/ztzl_kjs2011/kjs2011_jyjl/201512/t20151202_222564.html

11 "中共中央 国务院印发 (国家创新驱动发展战略纲要)," *Xinhua News Agency*, 19 May 2016. http://www.xinhuanet.com//politics/2016-05/19/c_1118898033.htm

12 "中科航空动力抢滩中小型航空发动机研发," *China Aviation News*, 8 April 2018. http://www.cannews.com.cn/2018/0408/173590.shtml

13 "'两机'重大专项启动 高端装备制造产业带加速成型," 经济参考报, 25 November 2016. http://finance.people.com.cn/n1/2016/1125/c1004-28894606.html

14 "清华大学航空发动机研究院揭牌成立," Tsinghua University, 18 December 2018. http://news.tsinghua.edu.cn/publish/thunews/9658/2018/20181218231926267268505/20181218231926267268505_.html

15 For example: "国务院办公厅关于成立国家制造强国建设领导小组的通知," PRC Government, 24 June 2015. http://www.gov.cn/zhengce/content/2015-06/24/content_9972.htm

16 "计划6年走完发达国家20年走的路! '重型燃气轮机'将在上海诞生," *Shanghai Observer* [上观新闻, 17 December 2017. https://www.jfdaily.com/news/detail?id=74263

17 "国务院办公厅关于成立国家制造强国建设领导小组的通知," PRC Government, 24 June 2015. http://www.gov.cn/zhengce/content/2015-06/24/content_9972.htm

18 "习近平主持中共中央政治局会议 决定设立中央军民融合发展委员会," *Xinhua News Agency*, 23 January 2017. http://www.xinhuanet.com/mrdx/2017-01/23/c_136005188.htm

19 "为 '高, 远, 快, 智' 航空发动机提供基础理论和核心技术," Tsinghua University, 20 December 2018. http://news.tsinghua.edu.cn/publish/thunews/9650/2018/20181220165738431663417/20181220165738431663417_.html

20 "习近平: 向军民融合发展重点领域聚焦用力," *Xinhua*, 22 September 2017. http://www.xinhuanet.com//politics/2017-09/22/c_1121709932.htm

21 "The 13th Five-Year Plan for Economic and Social Development of the People's Republic of China," National Development and Reform Commission, March 2016. http://en.ndrc.gov.cn/newsrelease/201612/P020161207645765233498.pdf

22 "航空发动机及燃气轮机基础科学中心成立大会在北航召开," Beihang University, 31 July 2018. https://news.buaa.edu.cn/info/1002/44886.htm

23 ("十三五"科技军民融合发展专项规划) 热点问题权威解读, *Xinhua*, 23 August 2017. http://www.mod.gov.cn/regulatory/2017-08/23/content_4789748.htm

24 "航空发动机空气涡轮起动机包容结构研究," *Aeroengine* [航空发动机], No. 3, 2019. p.51-57.

25 "集团简介," AECC, [Accessed May 2019], http://www.aecc.cn/jqgk/jqjg/index.shtml

26 "航空人 '两会'上一道引人注目的风景线," *China Aviation News*, 4 March 2019. http://www.cannews.com.cn/2019/0304/190909.shtml

27 Alfred Chua, "Next-gen Chinese engines power down – but for how long?," *FlightGlobal*, October 22, 2019 (as of March 4, 2020: https://www.flightglobal.com/engines/next-gen-chinese-engines-power-down-but-for-how-long/134654.article)

28 "国产最大航空发动机亮相," *Beijing Daily* [北京日报, 9 November 2018, http://bjrb.bjd.com.cn/html/2018-11/09/content_294795.htm.

29 "航空发动机之痛," China Science and Technology Awards website [中国科技奖励], 25 July 2012. http://www.stawards.com/shownews.asp?id=2411&bigclassname=%CD%F9%C6%DA%BB%D8%B9%CB

30 "航空发动机及燃气轮机基础科学中心在京成立," ScienceNet.cn [科学网], 7 August 2018, http://news.sciencenet.cn/sbhtmlnews/2018/8/337869.shtm

31 "院情介绍," AECC Beijing Institute of Aeronautical Materials website [accessed March 2020], http://www.biam.ac.cn/tabid/87/Default.aspx

32 "关于我们," AECC Aero Engine Control System Institute Website, [Accessed May 2019], http://camci.com.cn/index.php/gywm.html

33 "涡轴发动机控制系统的发展," International Aviation Weixin Account [国际航空微信公号], 16 February 2016. http://www.cannews.com.cn/2016/0216/147828.shtml

34 "中航工业航空动力控制系统研究所 (无锡614所)," Harbin Institute of Technology, 21 September 2015. http://sa.hit.edu.cn/6a/80/c6582a158336/page.psp

35 "中国航发四川燃气涡轮研究院研发总部在成都开工建设," *Xinhua*, 12 December 2017. http://www.xinhuanet.com//fortune/2017-12/12/c_1122100079.htm

36 "中国航发四川燃气涡轮研究院研发总部项目开工," Chengdu Government, 14 December 2017 http://gk.chengdu.gov.cn/govInfoPub/detail.action?id=1839761&tn=2

37 "公司简介" AECC Aero Science and Technology Co, Ltd. website [accessed March 2020], http://ast.aecc.cn/enter_intro.

38 "企业概况," AECC South Industry Co., Ltd. website [accessed March 2020], http://www.aeccsi.com/CompanyProfile; Evan S. Medeiros et al., *A New Direction for China's Defense Industry* (Santa Monica, CA: RAND Corporation, 2005), pp. 170-174.

39 Wendell Minnick, ed. *Chinese Aircraft Engines*, 2014 Zhuhai Airshow brochure, 2016. p. 17.

40 "忆 '太行' 发动机总设计师张恩和," *China Aviation News*, 24 November 2016. http://www.cannews.com.cn/2016/1124/160978.shtml

41 "张恩和: 他留下一座巍峨的高山激励着后来人," *China Youth Online* [青年网], 18 January 2017. https://qclz.youth.cn/znl/201701/t20170118_9046359.htm

42 "张恩和:设计出'太行'发动机 这辈子值了," 81.cn, 18 January 2017. http://www.81.cn/jmywyl/2017-01/18/content_7456575.htm

43 "张恩和:他留下一座巍峨的高山激励着后来人," *China Youth Online*, 18 January 2017. https://qclz.youth.cn/znl/201701/t20170118_9046359.htm

44 "追记 '太行' 发动机总设计师张恩和," *China Youth Daily* [中国青年报], 17 January 2017. http://military.people.com.cn/n1/2017/0117/c1011-29030562.html

45 "铸国防空疆之重器——记中航工业发动机研究院, 动力所总设计师刘永泉," *China Aviation News*, 22 February 2016. http://www.cannews.com.cn/epaper/zghkb/2016/02/23/A02/story/823099.shtml

46 "刘永泉," Northwestern Poly School of Power and Energy, [Accessed June 2019]. https://dongneng.nwpu.edu.cn/info/1260/4549.htm

47 "校风风采," Behang University School of Energy and Power Engineering, 3 February 2016. http://sepe.buaa.edu.cn/rcpy/xyfc1/88645.htm

48 "沈阳发动机研究所刘永泉: 一颗 '中国心' 航空添动力," *China Aviation News*, 3 July 2018. http://www.cannews.com.cn/2018/0703/179122.shtml

49 "动力所总设计师刘永泉: 铸国疆空天之重器," *China Aviation News*, 28 August 2014. http://www.cannews.com.cn/2014/0828/103806.shtml

50 "新一代航空发动机的领军人——刘永泉," *China National Radio* [中央任命广播电台], 27 June 2018. http://www.cnr.cn/ln/jrln/20180627/t20180627_524283793.shtml

51 "我国自主创新某型航空发动机试验成功," *China Aviation News*, 24 February 2016. http://www.81.cn/jmywyl/2016-02/24/content_6926780_3.htm

52 "我国自主创新某型航空发动机试验成功," *China Aviation News*, 24 February 2016. http://www.81.cn/jmywyl/2016-02/24/content_6926780_3.htm

53 "我国已掌握推力矢量关键技术," *S&T Daily*, 7 November 2018. http://www.stdaily.com/kjrb/kjrbbm/2018-11/07/content_728406.shtml

54 "中航工业王海峰:用 '实' 和 '真' 设计起飞的轨迹, " *China Aviation News*, 5 September 2016. http://www.cannews.com.cn/2016/0905/158103.shtml

55 "China Eyes Building Next-Generation Fighter Jets by 2035," *Global Times*, 11 February 2019. http://www.globaltimes.cn/content/1138454.shtml

56 "中航工业王海峰:用 '实' 和 '真' 设计起飞的轨迹," *China Aviation News*, 5 September 2016. http://www.cannews.com.cn/2016/0905/158103.shtml

57 Wang Haifeng [王海峰], Yang Chaoxu [杨朝旭], Wang Chengliang [王成良], "先进战斗机大迎角运动特性分析和试验" (High Angles of Attack Character Analysis and Test for an Advanced Fighter) {飞行力学} [Flight Dynamics], No. 4, 2006. p.4.

58 "王海峰: 海纳百川攀高峰," Northwestern Polytechnical University, 23 September 2014. https://xyh.nwpu.edu.cn/info/1004/1247.htm

59 "China Successfully Completed Hypersonic Engine Test," *Global Times*, 17 January 2019. http://www.globaltimes.cn/content/1134932.shtml

60 "揭开歼20超短研发周期实现首飞'奇迹'的奥秘," Official WeChat Account of Chengdu Aircraft Design Institute, Accessed 4 June 2019, https://mp.weixin.qq.com/s/lgkYhxJsG_Tt-Cf5LlvOFQ

61 "Вооруженная Дружба: Как Россия и Китай Торгуют Оружием," Московский Центр Карнеги, November 2017, https://carnegieendowment.org/files/CP_Gabuev_Kashin_web.pdf

62 "中国航空研究院与俄罗斯中央空气流体动力学研究院签署战略合作协议," Chinese Aeronautical Establishment (CAE) [中国航空研究院], 12 September 2014. http://www.cae.ac.cn/Cn/html/5398604156.html

63 "中国航发研究院与俄罗斯中央发动机研究院在京签署合作备忘录", Hebei Industrial Bureau for National Defense Science and Technology [河北省国防科技工业局]," 25 January 2017, http://www.hbjg.gov.cn/index.do?id=11675&templet=content&cid=31.

64 “Китай просит Украину продать лицензию на двигатели к истребителям,” UNAIN, 25 July 2009, www.unian.net/world/248333-kitay-prosit-ukrainu-prodat-litsenziyu-na-dvigateli-k-istrebitelyam.html; “Chinese firm’s stake in Ukraine military aircraft engine maker ‘frozen’,” *South China Morning Post*, 16 September 2017. https://www.scmp.com/news/china/diplomacy-defence/article/2111493/chinese-firms-stake-ukraine-military-aircraft-engine

65 “Chinese to acquire stake in Ukraine’s Motor Sich, sign helicopter deal with Russia,” *Kyiv Post*, 26 February 2019. https://www.kyivpost.com/ukraine-politics/chinese-to-acquire-stake-in-ukrainian-motor-sich-sign-helicopter-deal-with-russia.html

66 Anton Troianovski, “China has what Ukraine wants: business for its military factories,” *Washington Post*, 20 May 2019. https://www.washingtonpost.com/world/europe/at-a-ukrainian-aircraft-engine-factory-chinas-military-finds-a-cash-hungry-partner/2019/05/20/ceb0a548-6042-11e9-bf24-db4b9fb62aa2_story.html

67 “我国获权生产乌克兰航空发动机意味着什么,” *S&T Daily* [科技日报], 25 November 2016. http://www.stdaily.com/index/kejixinwen/2016-11/25/content_345480.shtml

68 “Four Aircraft Engines Make Debut, Displaying New Results of Cooperation Between China and Ukraine on Aviation Power [4款航空发动机首次亮相 展现中乌航空动力合作新成果],” *Xinhua* [新华], 6 November 2018, http://www.xinhuanet.com/tech/2018-11/06/c_1123672718.htm.

69 “国产‘太行’航空发动机: 一颗强健的中国心,” *People.cn*, 25 February 2007. http://military.people.com.cn/GB/52934/67858/5413146.html

70 “中国太行发动机仍未超越俄AL31F 寿命仅为俄航发50%,” Sina Military [新浪军事], 5 July 2018. http://mil.news.sina.com.cn/jssd/2018-07-05/doc-ihevauxk7662325.shtml

71 “中国航空工业集团公司沈阳发动机设计研究所 (六O六所) 招聘,” Xi’an Jiaotong University School of Aerospace Engineering, October 10, 2011, http://sae.xjtu.edu.cn/info/1073/1098.htm

72 “中国航发黎明简介,” Shenyang Liming [Accessed May 2019], http://slae.aecc.cn:8080/default/cn.aecc.portal.contentDetailMult.flow?id=323&typeId=AECC_CONTENT_TYPE_50

73 “中国航发黎明公司简介,” Shenyang Liming Aero-Engine Co., Ltd. website (accessed March 2020), http://slae.aecc.cn:8080/default/cn.aecc.portal.contentDetailMult.flow?id=723&typeId=AECC_CONTENT_TYPE_50

74 “产品服务,” Shenyang Liming [Accessed May 2019], http://slae.aecc.cn:8080/default/cn.aecc.portal.contentDetailMult.flow?id=323&typeId=AECC_CONTENT_TYPE_50

75 “国产软件打破航空发动机单晶涡轮叶片研制国际垄断,” *China Aviation News*, 30 March 2019. http://ep.cannews.com.cn/publish/zghkb7/html/1615/node_068795.html

76 “中国航发:整体叶盘成发动机结构设计的新宠儿,” AVIC Weixin [中国航发微信公众号], 8 May 2019. http://www.cannews.com.cn/2019/0508/195340.shtm.

77 “航空发动机整体叶盘制造技术的变革创新!,” *China Aviation News*, 18 October 2018. http://www.cannews.com.cn/2018/1018/183653.shtml

78 “航空发动机 ‘大脑’进化简史,” *China Aviation News*, 10 April 2017. http://www.cannews.com.cn/2017/0410/163564.shtml

79 E.g., see “FADEC: The brains behind the brawn optimizing the world’s aircraft engines,” BAE Systems website (accessed March 2020), https://baesystems-ps.com/fadec.php

80 “中国发动机全权限数字电子控制系统通过验收,” *Sina.com*, 15 August 2003. http://mil.news.sina.com.cn/2003-08-15/143715.html; “姚华,” *AVIC News*, 4 May 2010. http://www.cannews.com.cn/zghkb/html/2010-05/04/content_7066.htm

81 “国外航空发动机分布式控制系统技术发展,” *AVIC News*, 27 December 2011. http://www.cannews.com.cn/zghkb/html/2011-12/27/content_30087.htm

82 “China has Mastered Key Thrust Vector Technology [我国已掌握推力矢量关键技术],” *S&T Daily* [科技日报], 7 November 2018, http://www.stdaily.com/kjrb/kjrbbm/2018-11/07/content_728406.shtml.

83 Zhang Yuliang, Yu Shusheng, and Zhou Xiaopeng, *Science of Campaigns* [战役学] (Beijing: National Defense Univ. Press [国防大学出版社], 2006). p.331.

84 “我国第二种五代机专用航空发动机曝光 或为涡扇19,” Sina Military [新浪军事], 20 October 2018. https://mil.news.sina.com.cn/jssd/2018-10-20/doc-ihmrasqs8867591.shtml

85 “蓝天三剑客: 中俄韩三国新型高教机,” *China Aviation News*, 24 April 2014. http://www.cannews.com.cn/2014/0424/90847.shtml; “Китай представил лёгкий боевой самолёт,” Военное Обозрение, 2 May 2017. https://topwar.ru/114731-kitay-predstavil-legkiy-boevoy-samolet.html

86 “АИ-222-25Ф/АИ-322Ф,” Мотор Сич, http://www.motorsich.com/rus/products/aircraft/tde/ai-222-25f/; “我国获权生产乌克兰航空发动机意味着什么,” *S&T Daily* [科技日报], 25 November 2016. http://www.stdaily.com/index/kejixinwen/2016-11/25/content_345480.shtml

87

88 “我国获权生产乌克兰航空发动机意味着什么,” *S&T Daily,* 25 November 2016. http://www.stdaily.com/index/kejixinwen/2016-11/25/content_345480.shtml

89 “Контракты НПО "Сатурн" на поставку 224 двигателей Д-30КП2 в Китай," BMPD Blog, 28 October 2016 https://bmpd.livejournal.com/2212133.html; “Китайская копия советского Ту-16 впервые примет участие в «Авиадартсе»" ТВ Звезда, 13 July 2018 https://tvzvezda.ru/news/vstrane_i_mire/content/201807131252-ih01.htm

90 “Контракты НПО "Сатурн" на поставку 224 двигателей Д-30КП2 в Китай,” BMPD Blog, 28 October 2016 https://bmpd.livejournal.com/2212133.html; “НПО "Сатурн" поставило в Китай первую партию двигателей Д-30КП-2" ТАСС, 18 October 2012 https://tass.ru/politika/642623; «НПО «Сатурн» поставит двигатели для транспортных самолетов в Китай за $658 млн," *Rambler*, 27 October 2016 https://news.rambler.ru/world/35111334-npo-saturn-postavit-dvigateli-dlya-transportnyh-samoletov-v-kitay-za-658-mln/

91 “Контракты НПО ‘Сатурн’ на поставку 224 двигателей Д-30КП2 в Китай,” BMPD Blog, 28 October 2016, https://bmpd.livejournal.com/2212133.html

92 刘大响, 金捷, 彭友梅, 胡晓煜 “大型飞机冬季的发展现状和关键技术分析,” *Aerospace Power* [航空动力学报] , Vol. 23, No. 6, June 2008.

93 “Российско-украинская оборонка на службе у Поднебесной,” Независимая газета, 21 March 2013. http://www.ng.ru/armies/2013-03-21/1_rf_ua_china.html

94 “中航发的成立与涡扇6, 涡扇8发动机停产的悲剧,” *CWZG.cn* [察网], 2 September 2016. http://www.cwzg.cn/politics/201609/30655.html

95 “中航发的成立与涡扇6, 涡扇8发动机停产的悲剧,” *CWZG.cn* [察网], 2 September 2016. http://www.cwzg.cn/politics/201609/30655.html

96 “COMAC ARJ21 Production List,” Planespotters.net, (accessed March 2020), https://www.planespotters.net/production-listCJ-1000AX COMAC/ARJ21?sort=dd

97 “China ACAC Selects General Electric to Power ARJ21 Regional Jet; Selection Represents Potential $3 Billion Engine Market," GE website, 4 November 2002. https://www.geaviation.com/press-release/cf34-engine-family/china-acac-selects-general-electric-power-arj21-regional-jet

98 Stella Qiu, Tim Hepher, “China's bid to challenge Boeing and Airbus falters,” *Reuters*, January 9, 2020. https://www.reuters.com/article/us-china-aviation-comac-insight/chinas-bid-to-challenge-boeing-and-airbus-falters-idUSKBN1Z905N; Alfred Chua, “Next-gen Chinese engines power down – but for how long?” *FlightGlobal*, 22 October 2019. https://www.flightglobal.com/engines/next-gen-chinese-engines-power-down-but-for-how-long/134654.article

99 Chua, “Next-gen Chinese engines power down.”

100 “CR929 engine set for joint development,” *China Daily*, 15 November 2018. http://www.chinadaily.com.cn/a/201811/15/WS5becb760a310eff303288c36.html

101 “Flying with the Dragon: CFM Celebrates 30 Years in China," Safran, 29 October 2015. https://www.safran-aircraft-engines.com/media/flying-dragon-cfm-celebrates-30-years-china-20151029; “SSMC Inaugurates New Mro Facility, Adds Leap Capability,” CFM, 23 March, 2018. https://www.cfmaeroengines.com/press-articles/ssamc-inaugurates-new-mro-facility-adds-leap-capability/

102 “Two new facilities in China,” Safran, 8 April 2008. https://www.safran-aircraft-engines.com/media/two-new-facilities-china-20080408

103 “公司概况,” AECC CAE, Accessed May 2019. http://www.acae.com.cn/portal/About/Index_1.aspx

104 “产品介绍,” AECC CAE, Accessed May 2019. http://www.acae.com.cn/portal/Engine/Index_2.aspx

105 "我国第一型自主研制涡轴发动机 '玉龙' 参展," *S&T Daily*, 13 September 2017. http://www.stdaily.com/zhuanti01/hkfdj/2017-09/13/content_576649.shtml

106 "记 '玉龙' 发动机研制团队: 登顶 '玉龙'山高人为峰," *China Aviation News*, 9 June 2017. http://www.cannews.com.cn/2017/0609/164723.shtml

107 "三军急需的新一代通用直升机直8宽," *Sina*, 30 December 2018. http://k.sina.com.cn/article_2149981442_80261d02027011qem.html?from=mil

108 "China: Opening Doors to Western Military Imports, An Intelligence Assessment," CIA CREST, October 1984. p. 4. https://www.cia.gov/library/readingroom/docs/CIA-RDP85T00310R000200160003-5.pdf

109 "直-20:海军大型水面舰艇航空反潜的利器," (环球人物) 杂志, 8 April, 2014. http://www.81.cn/bqtd/2014-04/08/content_5843429_4.htm

110 See satellite imagery via Andreas Rupprecht on Twitter, 14 June 2019. https://twitter.com/RupprechtDeino/status/1139496417406459905

111 "中国航发湖南动力机械研究所," Hunan Provincial Society of Aeronautics and Astronautics [湖南省航空学会], 4 May 2017. http://hnshkxh.com/ArticleDetail-I32.html

112 "国产无人机发动机白菜化, 4家机构齐推自家1吨级涡扇," *EastDay*, 13 December 2017. http://mil.eastday.com/a/171213073529233.html

113 "Китайский «Барсук» с советской родословной," Военно-промышленный курьер, 24 May 2011 https://www.vpk-news.ru/articles/7703

114 "Приключения дозвуковых крылатых ракет в Незалежной," Независимая газета, 23 December 2011 http://nvo.ng.ru/armament/2011-12-23/12_rockets.html; Куда долетит ракета из Киева?," Известия, 3 July 2006, https://iz.ru/news/315079

115 See "МС400," Мотор Сич, http://www.motorsich.com/rus/products/aircraft/tde/ms400/

116 Igor Bilyk and Konstantin Stepanov, *Motor Sich: Facts Support Strong Prospects*, November 2008, http://www.motorsich.com/files/933-11.2008.pdf

117 "Все течет с Украины," Военно-Промышленный Курьер," 7 July 2014, https://www.vpk-news.ru/articles/20972

118 "Он улетел, но самолет оставил. Проблемы украинского авиапроизводителя," *Корреспондент.net*, 12 July 2018, https://korrespondent.net/business/economics/3989296-on-uletel-no-samolet-ostavyl-problemy-ukraynskoho-avyaproyzvodytelia

119 "中国航空工业察打一体无人机"翼龙" II 首飞成功," *China Aviation News*, 28 February 2017. http://www.cannews.com.cn/2017/0228/162531.shtml

120 "Could drone that can deliver cargo to islets in South China Sea secure presence in disputed waters?," *South China Morning Post*, 28 October 2017. https://www.scmp.com/news/china/diplomacy-defence/article/2117438/drone-could-deliver-cargo-islets-south-china-sea-makes

121 "China's AT200 cargo drone makes maiden flight," *Xinhua*, 27 October 2017. http://www.xinhuanet.com//english/2017-10/27/c_136710480.htm

122 "中科航空动力抢滩中小型航空发动机研发," *China Aviation News*, 8 April 2018. http://www.cannews.com.cn/2018/0408/173590.shtml

123 "'岷山', '九寨' 发动机亮相中航工业产品将再添新动力," *China Aviation News*, 20 November 2012. http://www.cannews.com.cn/epaper/zghkb/2012/11/15/A03/story/329268.shtml; "首款中国造1吨级航空发动机亮相 可配10吨无人机," *China Youth Daily* [中国青年报], 12 December 2017. http://www.chinanews.com/mil/2017/12-12/8398082.shtml

124 "首款 '中国造' 1000kg级航空发动机亮相创博会," *China Youth Online*, 11 December 2017. http://www.comac.cc/xwzx/cyzx/201712/11/t20171211_5932228.shtml

125 "揭开歼20超短研发周期实现首飞 '奇迹'的奥秘," *Aircraft Manufacturing Technology Magazine* [航空制造技术], 3 January 2019. https://mp.weixin.qq.com/s/lgkYhxJsG_Tt-Cf5LlvOFQ

126 Website: http://www.avicaeroengine.com/hkfdj/ch/index.aspx

127 Website: http://www.jasp.com.cn/ch/index.aspx

128 “本刊介绍,” *Journal of Aerospace Power*, [Accessed March 2019], http://www.jasp.com.cn/ch/common_item.aspx?parent_id=20110419163711001&menu_id=20110419163854001&is_three_menu=0