Lifting the Veil

Major investments, test facilities and swift achievements underpin China's rapid rise in hypersonics

China has revealed the first known images of an indigenous scramjet test that it says was successfully conducted at speeds up to Mach 7 and altitudes up to 30 km, in December 2015.

NATIONAL NATURAL SCIENCE FOUNDATION OF CHINA

Guy Norris **Xiamen, China**

For many years, any coherent view of China's highly ambitious hypersonic research program, just like its mist-shrouded coastline, has been all but impossible to see from the outside world.

However, following the apparent decision to reveal more about its latest hypersonic research activities, the fog is lifting for the first time over at least some of China's test and development efforts in high-speed flight.

What has come into view is a cohesive, nationwide hypersonic research and technology program that not only shows astonishing depth and breadth, but has also produced a bewildering number of major accomplishments in a relatively short period. The new picture emerged in early March at the 21st International Space Plane and Hypersonic Systems and Technology conference held here, where China's top academic and government research units presented progress in unprecedented detail, on everything from hypersonic missions and vehicles to the latest on new test facilities and development of propulsion, power and control systems.

The event marked the first international hypersonic conference held in China, as well as the first meeting to be organized in the country by the American Institute of Aeronautics and Astronautics, in association with the China Academy of Engineering. Aimed at providing a domestic forum for China to internationally showcase its growing prowess in hypersonics, the conference promoted the open exchange of academic research while attempting to skirt the more sensitive defense-related aspects.

The conference, which gave many Chinese researchers their first opportunity to display many years' worth of research to a wider Western audience, underlined the nation's impressive overall advances in all areas of high-speed flight research for defense, transport and space access. While progress in some specific defense areas—most notably the recent flight tests of the DF-ZF/WU-14 hypersonic glide vehicles—was not discussed, the progress indicated by the underlying research makes it readily apparent that China is making strides in hypersonic capability much faster than previously thought.

The scope of high-speed technology activity, added to evidence shown at the conference of large-scale government investment in comprehensive test facilities, appears to support recent assertions made in the U.S. that China is on track to quickly overtake America's hard-won leadership in the field. The claim, made in 2016 by the U.S. National Academy of Sciences and by think tanks such as the Arlington, Virginia-based Mitchell Institute for Aerospace Studies, comes as both China and Russia conduct demonstration flights of air-breathing and boost-glide hypersonic weapon systems. Both nations are believed to be targeting 2020 for deployment of the first operational units (*AW&ST* Feb. 20-March 5, p. 20)

A major revelation early on at the conference was the first formal acknowledgement of a Chinese scramjet flight test in December 2015. It is highly likely, though not yet confirmed, that the milestone achievement is associated with the same program for which the Feng Ru Aviation Science & Technology Elite trophy (Feng Ru was a Chinese aviation pioneer) was presented in 2015 to Zhenguo Wang, a professor at the National University of Defense Technology (NUDT) in Changsha. The award, presented by the Chinese Society of Aeronautics and Astronautics at the 2nd China Aeronautical Science and Technology Conference, gave no details other than that it was for the successful development of a kerosene-fueled scramjet.

Showing images at the March hypersonic conference of the scramjet being ground-launched on a rocket booster, Chinese Academy of Sciences professor Lihong Chen said: "We also developed a low cost near-space science and technology flight test platform. The first flight test was successfully carried out, and key issues of the scramjet were demonstrated at Mach 3.5-7 and at altitudes of 15-30 km [9-18 mi.]." Offering no further details, Chen says the flight test was targeted at fundamental research under a program that she likened to the Australian-U.S. Hypersonic International Flight Research Experimentation (HIFiRE) effort.

HYPERSONICS RESEARCH PLAN

Many of the achievements outlined at the conference, including the scramjet test, have emerged from a multiyear national "near-space" research initiative supported by the National Natural Science Foundation of China. "The focus is on long-range hypersonic maneuverable aircraft flying at altitudes of 30-70 km," says Chen. The 150 million yuan ($22 million) project, which ran in 2007-16, was targeted at three key areas: developing theory and methods to guide relevant hypersonic technology research and development; driving innovative breakthroughs for "leap-forward" technology developments; and, lastly, fostering a team of outstanding researchers to support the sustained development of technology for near-space vehicles in China.

Within these broad research groups, "funding was given to fostering early concepts and key and integrated projects," says Chen. Topic areas included: aerodynamics, thermal environment, scramjet propulsion, coupling mechanisms and prediction methods for gas and turbulence effects, computational and numerical simulation, materials and structures, thermal protection and intelligent, autonomous control.

Over the life of the various projects, the road map covered three periods, she adds: "These were the 'sowing' period, where all areas were funded for the first four years. The second covered years five and six and included follow-on funding, particularly for programs with multidisciplinary optimization. The final phase, covering the seventh to ninth years, funded the integrated projects."

Key accomplishments include development of a theory for hypersonic unsteady flow, as well as understanding of complex flow mechanisms and advances in numerical simulation. "We improved the understanding of coupled-physical effects and found new flow phenomena," says Chen. "We also established optimal design methods for high-lift/drag-ratio hypersonic aircraft and methods to reduce heat flux and drag as well as developed technology for no-ablation, active cooling. A proposed active thermal protection system [TPS] without ablation was demonstrated in the JF12 shock tunnel." The JF12 is a detonation-driven shock tunnel in the State Key Laboratory of High Temperature Gas Dynamics in Beijing's Chinese Academy of Sciences.

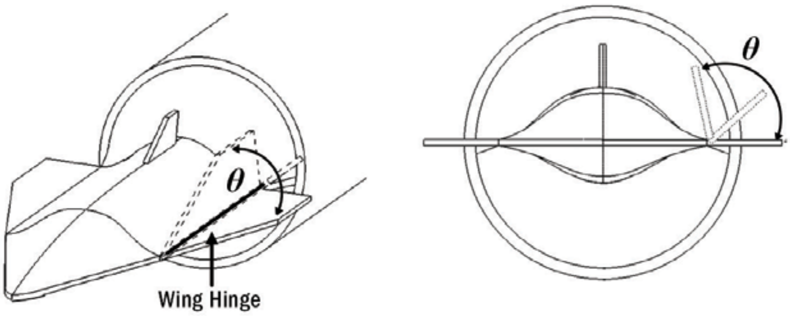
Propulsion highlights outlined by Chen, in addition to the scramjet flight test, included the identification of blowout limits of supersonic combustion with hydrocarbon fuel—vital to knowing the operability range of a scramjet. Researchers also proposed a new design method for hypersonic inlets, including a concept based on a curved compression face.

Chen says accomplishments in lightweight and heat-resistant materials, including structural TPS, include the development of materials in which resistance to thermal shock was enhanced by '"bionic" (biologically inspired) design of a ceramic surface structure. The result "increased thermal resistance by nearly 10,000 times," she adds. Researchers also developed advanced TPS deigns to provide more options for hypersonic vehicle design, using a variety of carbon foams, ceramic coverings and sandwich insulation, as well as combinations of corrugated sandwich materials and insulation.

Chinese developers have also perfected a manufacturing process for heat-resistant structures that combines fiber bundles made by an interpenetrating weaving method with a secondary layering process. The combined effect creates a 3D lattice composite structure "to solve the problem of low interfacial strength of panels and cores," says Chen. "Based on this technology, a new aerospace industry standard has been established and applied to a new generation of rockets and reusable space vehicles."

Chen also highlighted flight control, and described development of a new design method for fine attitude controlthat "has been applied to a waverider hypersonic vehicle to ensure efficient operation of the scramjet engine," she says. "Flight test results show the control system can ensure an angle of attack below 1.5 deg." Chen also described development of an active control law using an adaptive structural filter designed to improve flutter boundary and suppress flutter. "We have also developed a ground flutter simulation system for the rudder, which has been applied to research of the aerodynamic elasticity of hypersonic vehicles," she adds.

"There are also a lot of programs I cannot show here," says Chen, who also declined to discuss the scramjet

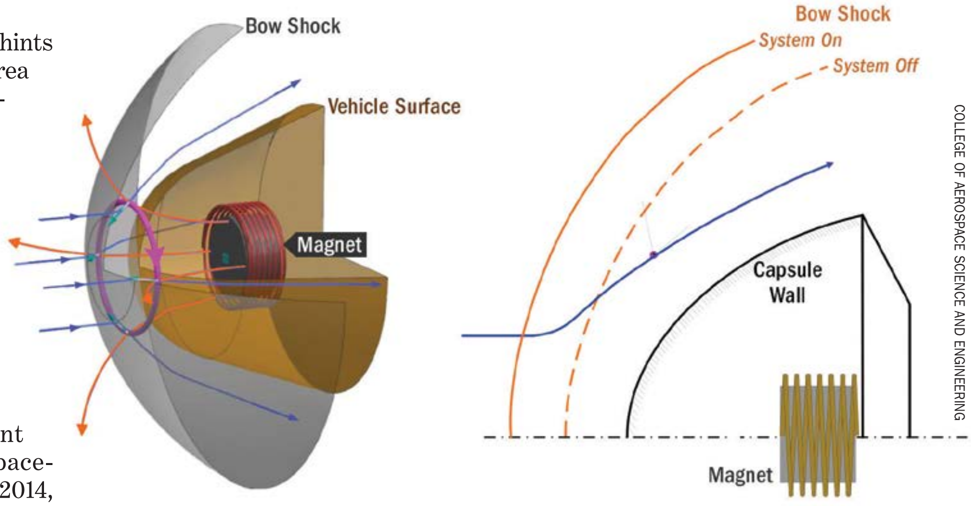


Studies of a folding-wing hypersonic boost-glide vehicle designed for deployment from a launcher at Mach 5 and 30-km altitude show dramatic changes in the center of pressure on release.

CHINA ACADEMY OF LAUNCH VEHICLE TECHNOLOGY flight test in further detail. More hints about progress in this classified area came from Yancheng You, conference co-chair and a Xiamen University hypersonics specialist. Believed to be referencing NUDT's scramjet pioneer Zhenguo Wang, You says: "From the very beginning we wanted to invite another keynote speaker, a [big name in hypersonics] from China. But it was a little bit difficult because the topic is sensitive."

Compared to the most recent U.S.-hosted hypersonics and spaceplanes conference in Atlanta in 2014, when just 89 papers were presented, a record 347 were shown in Xiamen—of which 272 were from China. Hypersonics is "definitely a very hot topic here," says You, who cites the explosive growth of academic papers on the topic as evidence.

Between 2002 and 2015, more than 33,300 papers were published in the Chinese language with "hypersonic/space planes" in the title, while 3,582 journal papers with the same keywords were published in Chinese over the same span. The trend is seen globally as well, says You. Of more than 1,660 academic papers published in English on hypersonics in 2011-15, some 627, or 38%, were from China. The U.S. accounted for 25%, with 422, with the remainder produced by nations including France, Germany, Italy, India, Japan, Russia and the UK.



Tests of a magneto-hydrodynamic heat shield system showed performance could be boosted by seeding the flow with potassium particles.

COMBINED-CYCLE CONCEPTS

Highlighted presentations at Xiamen on missions and vehicles included an integrated design method for an adaptable hypersonic dual waverider with twin scramjets fed by two 3D inward-turning inlets. The paper, from researchers at Avic, indicated the sharply swept delta-winged design with bifurcated inlets would have "satisfactory" performance at different angles of attack across a speed range of Mach 4-6.

A second highlighted vehicles study, presented by Yuan Yu of the Beijing-based China Academy of Launch Vehicle Technology, evaluated a reconfigurable waverider that would unfold its wings following deployment from beneath the shroud of a launch vehicle. While the details of the application were not discussed, the study appears to be clearly aimed at increasing the potential size—and therefore capability—of hypersonic glide vehicles that could be boosted into the upper atmosphere by intermediate or large ballistic missiles.

Ground tests of a hydrogen-fueled continuous-rotating detonation ramjet at Mach 4.5 and simulated 18.5-km altitude indicated positive thrust was obtained (see page 54).

The papers also reveal a major Chinese focus on advanced combined-cycle propulsion systems for two-stage orbital vehicles, including precooling hypersonic air-breathing engines as well as a variety of turbine-based combined-cycle (TBCC) and rocket-based combined-cycle engines. Researchers from the Beijing Institute of Aerospace Technology also provided one of the most startling revelations of the conference, of significant progress on a hybrid engine dubbed the turbo-aided rocket-augmented ramjet (TRRE) combined-cycle engine (see page 55).

Under testing and development for more than two years by the Beijing Power Machinery Research Institute, the TRRE is designed to operate from a standing start to Mach 6+ and from sea level to 33-km altitude. The propulsion system combines a turbine engine, rocket and ramjet with a common, adaptable inlet and exhaust and is in the first of three planned development phases. Developers plan to conduct the first tests of the prototype engine up to Mach 6 in a free-jet facility later this year. Initial flight tests of a TRRE subscale demonstrator are planned by

2025 and full-scale envelope expansion by 2030.

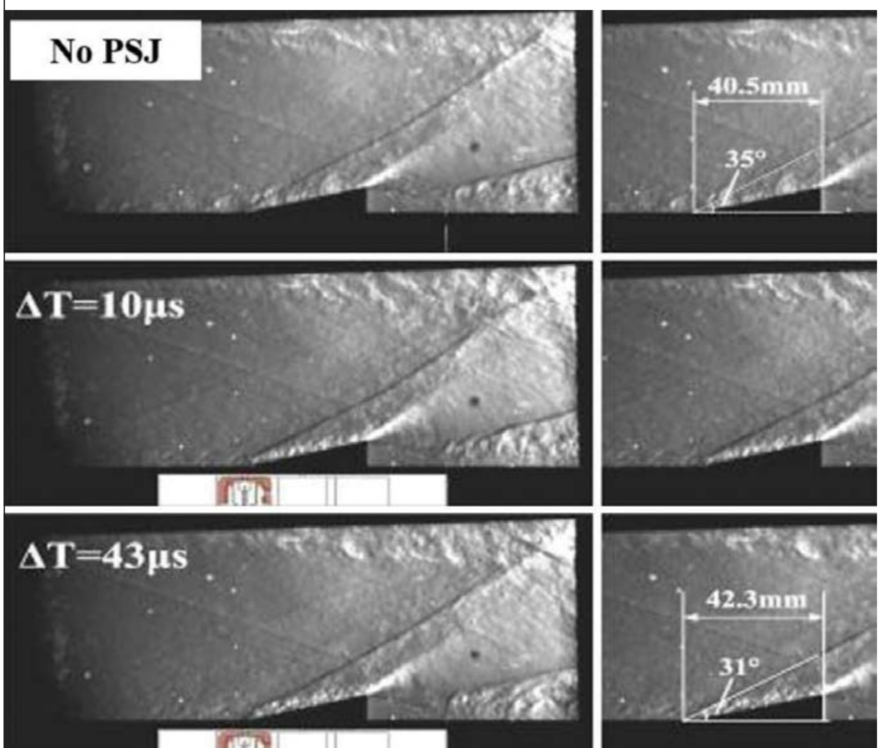
Another combined-cycle concept, the Xiamen Turbine Ejector-Ramjet Combined Cycle (XTER), is being studied by Xiamen University's School of Aerospace Engineering as a research training project. The propulsion system is another variation on the TriJet combined cycle outlined by Aerojet Rocketdyne in 2011, and combines a turbine, rocket-ejector and supersonic ramjet in a compact tandem/over-under hybrid flowpath arrangement.

"We know there is a lot of work to be done, but the XTER engine could satisfy the thrust requirements of future hypersonic vehicles over a wide range of Mach numbers up to Mach 6. The propulsion components, including an inward-turning TBCC-inlet, scramjet combustor, ejector ramjet and expansion ramp nozzle have been preliminarily studied," says Yin Zeyong, dean of the School of Aeronautics and Astronautics at Xiamen University.

Thermal management system concepts unveiled at the event included a magneto-hydrodynamic (MHD) heat shield system that uses a solenoid magnet in the nosecone to push the hypersonic bow shock away from the surface of the vehicle during reentry. The study, by researchers at the NUDT, found the shock standoff distance could be increased twentyfold by using MHD. It also found that shock control and thermal protection at lower Mach numbers could be significantly improved by seeding the inflow with particles of potassium to increase ionization.

Another thermal management system study that closely resembles the precooler work undertaken by the Japanese Aerospace Exploration Agency in the air turbo ramjet engine expander cycle program, and by UK-based Reaction Engines for its synergistic air-breathing rocket engine system, is a compact heat exchanger under test by a team at Beihang University in Beijing. The system, which would be used to precool air for the turbine in a combined-cycle engine, consists of tightly bundled tubes through which an unspecified coolant is pumped. The system produced "excellent performance" in early tests, say the researchers, who plan additional evaluations.

Several papers focused on ramjet and scramjet developments, with a heavy emphasis on mixing, injection and ignition, all of which are important for combustion. Working with the State Key Laboratory of Laser Propulsion and Application in Beijing, researchers from NUDT looked into the fundamentals of scramjet combustion, and in particular investigated auto-ignition caused by an oblique shock in a flow field at Mach 2.5. Using an imaging technique called nanoparticle-based planar laser scattering, they discovered that auto-ignition performance can be extended by increasing fuel injection pressure and the temperature of the airflow. They also found a longer flame cavity aids combustion.



AIR FORCE ENGINEERING UNIVERSITY

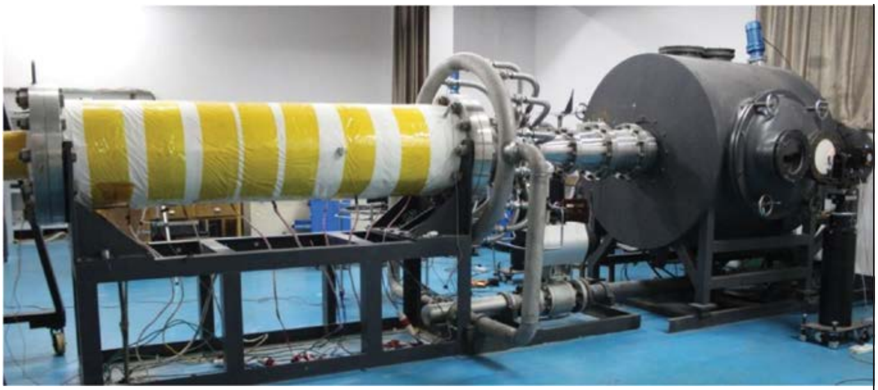
Experiments showed supersonic shockwaves could be controlled with an arc-driven plasma synthetic jet (PSJ) actuator.

Another group from the same university has also studied the use of successive laser shots to ignite ethylene fuel in a scramjet combustor at Mach 2.52. They found that increasing the energy of the laser shortened ignition time and increased the size of the initial flame but that plasma ignition could fail altogether if the gap between laser pulses exceeded 50 microsec.

China's early flight test success of a hydrocarbon-fueled (kerosene) scramjet in 2015 has prompted follow-on research into better combustion systems for dual-mode scramjets capable of operating over a broader speed range up to Mach 10. Researchers from Northwestern Polytechnical University in Xian tested a scramjet combustor made up of two flameholder cavities mounted in tandem. The direct-connect tests, which were conducted at Mach 2 and at a set inlet temperature, showed the flameholding capacity increased with higher inlet pressures and that combustion stability moved from the upstream to the downstream cavity as pressure decreased.

PROPULSION RESEARCH

Recent advances in propulsion component research include studies of an over-under TBCC exhaust system incorporating a moveable ramp for adjusting throat area ratio. Developed by Nanjing University of Aeronautics and Astronautics' (NUAA) Jiangsu Province Key Laboratory of Aerospace Power Systems, in collaboration with Avic's Shenyang Aircraft Design and Research Institute, the new configuration is aimed at smoothing the transition from turbojet to ramjet. The device was tested on an experimental TBCC nozzle in NUAA's blowdown wind tunnel and showed that while the two flowpaths interacted, the ramjet flow had a greater impact on the inter-



NATIONAL UNIVERSITY OF DEFENSE TECHNOLOGY

Latest hypersonic test assets now being commissioned in China include a Mach 6 quiet wind tunnel in Changsha, Hunan.

nal flow of the turbojet nozzle.

In other hypersonic propulsion studies, NUDT's detonation research group from Changsha revealed details of work underway since 2009 on a continuous rotating detonation ramjet engine (CRDRE). Operating on the same basic principle as the pulse-detonation engine, the CRDRE incorporates an annular combustor, into which propellants are fed axially to produce detonation waves that rotate circumferentially around the chamber.

Continuous rotating detonation is a form of pressure-gain propulsion that is gaining increasing interest for potential application in high-speed weapons and vehicles, largely because the air-breathing concept is highly efficient and mechanically simple and can be applied to either turbojets or ramjets. The NUDT team built and tested a 660-mm-long detonation wave ramjet in both direct-connect and free-jet conditions using both hydrogen and ethylene fuels. Positive thrust was measured with the hydrogen fuel-led version in free-jet tests representing Mach 4.5 and 18.5 km (see photos on page 52), and researchers say nozzle-area contraction ratio is a key factor for propulsive performance and altering combustor pressure.

In the power and control systems area, a team from the Xian-based Air Force Engineering University and the School of Electrical Engineering at Xian Jiaotong University, is evaluating the potential application of arc-driven plasma synthetic jets to control the angle and position of supersonic shockwaves. The study recommends further work to improve control intensity and stability, as well as possible use to reduce heat flux and flow separation.

Other areas of advancement include studies of stiffened carbon composite structures for space vehicles and research into silicon nitride/silica composites for potential use for spacecraft thermal protection. Several research facilities also unveiled results of flow and gas physics experiments in hypersonic fundamentals, and 45 papers were presented on advances in hypersonics studies using computational methods.

China's hypersonics initiative is grounded in a vast—and still expanding—nationwide network of test and evaluation facilities, the most notable of which is the Chinese Academy of Sciences' JF12 detonation-driven shock tunnel. With a 99-m-long (324-ft-long) detonation chamber and a nozzle exit diameter of 2.5 m, the JF12 is currently the largest shock tunnel in the world and capable of replicating flight conditions at altitudes of 25-50 km and speeds of Mach 5-9. Opened in 2012, the JF12 can put test specimens through hypersonic conditions for more than 100 millisec.

However, China is still adding to its suite of large-scale test sites, and engineers at the China Academy of Aerospace Aerodynamics in Beijing are currently completing commissioning of a new large-scale free-piston shock tunnel that is designed to test from Mach 10-15. Built in 2016, the FD21 is 170 m long overall, eclipsing even the mighty JF12. The facility can be operated as a conventional shock tunnel, a high-enthalpy tunnel with a test time of 5 millisec. or a moderate-enthalpy tunnel with a 50-millisec. test time.

Other new additions to the suite of test facilities include a Mach 6 hypersonic quiet tunnel built in 2016 at NUDT. Configured with a nozzle exit diameter of 300 mm and producing an operating time of more than 15 sec., the tunnel is still undergoing commissioning but has already shown that interference from the sidewalls, or "noise," is as low as 0.1% with pressures at or below 0.5 megapascals (MPa). Scramjet researchers based at the Hypervelocity Aerodynamics Institute at the China Aerodynamics Research and Development Center in Mianyang have meanwhile developed a combustion-heated facility capable of simulating flight conditions of Mach 4-7 with run durations of up to 600 millisec.

The 170-m-long FD21 free-piston shock tunnel in Beijing, opening soon, is the largest test facility of its type in the world.

CHINA ACADEMY OF AEROSPACE AERODYNAMICS

Hyper Hybrid

Chinese engineers say ambitious turbo-aided rocket and scramjet are on track for 2025 flight tests

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Chinese engineers will test a prototype combined-cycle hypersonic engine later this year that they hope will pave the way for the first demonstration flight of a full-scale propulsion system by 2025. If successful, the engine could be the first of its type in the world to power a hypersonic vehicle or the first stage of a two-stage-to-orbit spaceplane.

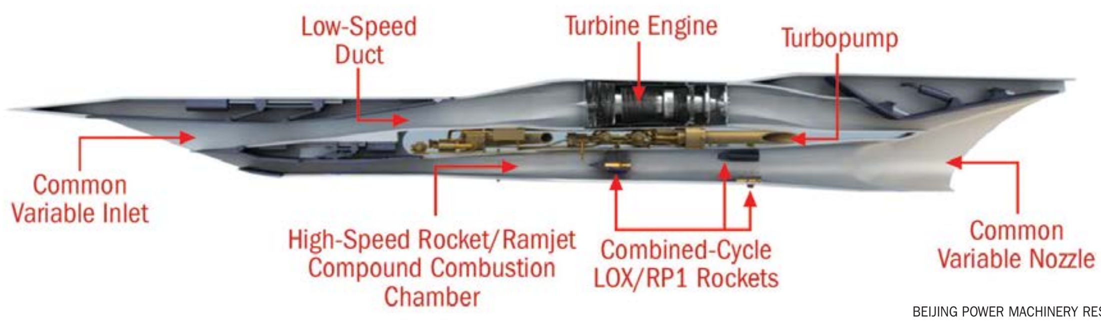
Combined-cycle systems have long been studied as a potential means to access to space and long-range hypersonic vehicles because they use both air-breathing and rocket engines to enable aircraft-like operations from a standing start to cover a wide range of speeds and altitudes. Such systems also take advantage of using atmospheric oxygen for fuel.

Various turbine, rocket and ramjet combinations have been studied in the West for decades, but it seems that a new Chinese-developed variation on this theme—the turbo-aided rocket-augmented ram/scramjet engine (TRRE)—appears to be closest to becoming the first practical combined-cycle propulsion system. Developers at the Beijing Power Machinery Research Institute say the engine will have sufficient capability to power horizontal-takeoff-and-landing hypersonic "near-space reconnaissance-and-strike" vehicles, two-stage-to-orbit and even the single-stage-to-orbit vehicles.

Although similar to several earlier combined-cycle concepts, including the Trijet proposed by Aerojet Rocketdyne in 2008, the TRRE incorporates the three main propulsion systems in just two main ducts. The TRRE consists of a turbine, liquid oxygen/kerosene-liquid-fueled rockets and a kerosene-fueled ram/scramjet combined with a common inlet and exhaust and is designed to operate from a standing start to Mach 6+. The turbine, which operates from takeoff to Mach 2, is housed in an upper low-speed duct, while the ramjet and rockets are located in the lower high-speed duct. Two rockets are mounted in the duct; an aft-mounted rocket for transonic acceleration and mode transition, and a main rocket mounted farther forward in the duct for flame stabilization during acceleration through to scramjet transition at Mach 6.

Updating test progress on the TRRE at the AIAA/China Academy of Engineering International Space Planes and Hypersonic Systems conference in Xiamen, Wei Baoxi of the Beijing Power Machinery Research Institute says simulations and experiments over the past two years have "validated its comprehensive advantages for acceleration, cruise, mobility and other aspects. The results show that the TRRE engine can reconcile the demands of high thrust at lower Mach numbers and high specific impulse at a Mach number of 6.0."

For a typical cycle, the TRRE would operate in the turbine mode for takeoff with both ejector rockets in the high-speed duct, or channel, augmenting thrust to overcome transonic drag. Around Mach 2, the low-speed duct is closed and the engine transitions to using the ramjet and rocket/ramjets in the high-speed duct. From Mach 3 to Mach 6, the engine operates in ram mode and rocket ram mode using both the high-speed inlet and the forward-mounted ejector rocket in tandem. The engine enters scramjet mode with the activation of the rocket/ramjet compound combustion chamber at Mach 6.



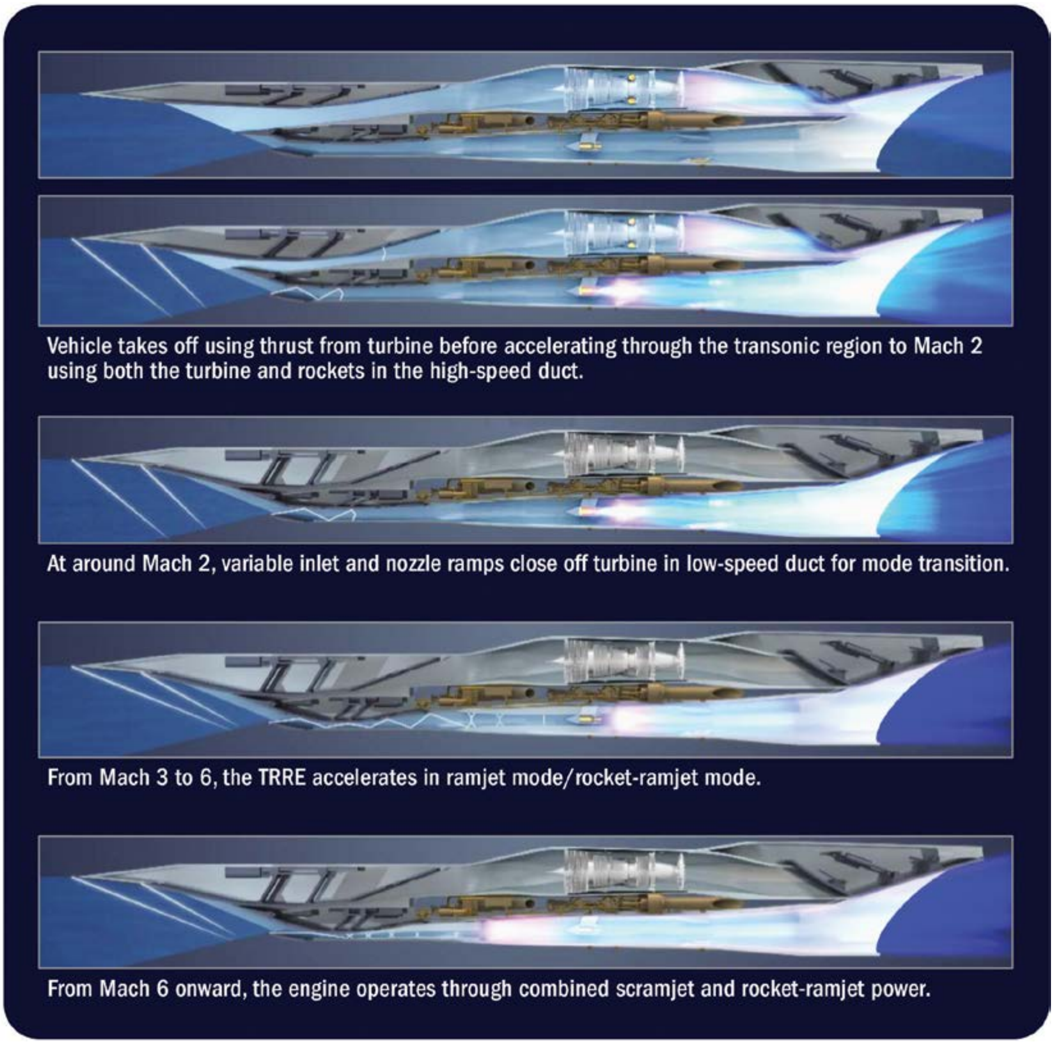
BEIJING POWER MACHINERY RESEARCH INSTITUTE

The TRRE combined-cycle system integrates a high-speed turbine, rockets and ramjets in an "over-under" two-duct configuration.

"The main advantage of the TRRE is that it can solve the problems of an RBCC at low thrust and low speed by using the turbine engine for takeoff and landing as well as low-speed flight," says Baoxi. "The second advantage is that with the rocket engine it solves the problem of the TBCC transition thrust 'pinch,' and it can also achieve a high specific thrust from Mach 3 to Mach 10. If integrated well, it will provide smooth mode transition and solve the thrust gap between the turbine and ramjet as well as provide a wide range of thrust capability between subsonic, supersonic and hypersonic conditions. It will also be good for acceleration and maneuvering. The configuration will also enhance the stability of engine operation under extreme conditions using the combustion and steady flame effect of the rocket gas jet. Using these, we can expand the boundaries of stable operation," he adds.

Numerical test results of the TRRE prototype show it can "operate in the full flight envelope of Mach 0-6+ and have demonstrated the integrated high- and low-speed channels work cooperatively," says Baoxi. "They also show reliable power-mode transition and the feasibility of the rocket/ramjet working in cooperation in the high-speed channel over an extremely wide speed range between Mach 1.5 and 7."

In 2016, developers completed inlet and nozzle wind-tunnel experiments as well as direct-connect test rig evaluations of power-mode transitions at Mach 1.8. Testing in the direct-connect rig was also performed to assess steady state performance between Mach 2 and 6. "The results verified the design methods of the TRRE inlet, nozzle and combustor. And the thrust performance obtained by the power mode transition experiments show the engine can achieve a reliable shift from the turbine mode to the rocket-ramjet mode," says Baoxi. "When the scale effect is taken into account, thrust at the power mode shift state can reach around 16,000 lb. [8 tons] for an engine with the capture area of 1 m^2, which basically meets the requirement of the vehicle design," he adds.



Vehicle takes off using thrust from turbine before accelerating through the transonic region to Mach 2 using both the turbine and rockets in the high-speed duct.

At around Mach 2, variable inlet and nozzle ramps close off turbine in low-speed duct for mode transition.

From Mach 3 to 6, the TRRE accelerates in ramjet mode/rocket-ramjet mode.

From Mach 6 onward, the engine operates through combined scramjet and rocket-ramjet power.

BEIJING POWER MACHINERY RESEARCH INSTITUTE

One of the biggest milestones for the program will occur later this year, when developers plan to conduct free jet tests of the engine for the first time. The work will evaluate the TRRE through power-mode transitions and steady state operation at Mach 2-6 and forms the heart of the first development phase, which is focused on proving core technologies and overall operations. During this phase, which runs through 2020, Baoxi says: "We plan to adopt a small turbine for the prototype to verify the working principle."

Baoxi indicates that the turbine for the ground prototype will be an off-the-shelf, low-bypass engine which is capable of around Mach 0.8. However, he adds that the engine will be adapted through unspecified means to represent conditions at Mach 1.8, which is the lowest mode transition speed already tested in the direct connect rig. "So it can be used to validate our operating principle," he notes.

For the follow-on flying demonstrator, Baoxi says the turbine will likely be based on the WS-15, a super-cruising turbofan under development by Xian Aero Engine Corp. for later production versions of the twin-engine Chengdu J-20 stealth fighter. However, even though the initial batch of J-20s entered service early this year with the People's Liberation Air Force, they are believed to be powered by an interim variant of the Russian-made Saturn AL-31 rather than the WS-15. An official quoted on the website China Military Online on March 13 commented that although WS-15 development is proceeding well, overall progress for production readiness has been hampered by quality control issues with relatively recently developed areas of advanced engine technology for China, specifically single-crystal superalloy turbine blades and powder metallurgy superalloy turbine disks.

It is unclear if the targeted thrust of the WS-15 (believed to be more than 40,000 lb. when installed in the J-20) is suited to the transition Mach numbers aimed at for the flying demonstrator planned for the second development phase in the 2020-25 time frame. "Before 2025, an in-service mature turbine engine will be adopted to form the engineering program and support completion of the small horizontal-takeoff-and-landing free-flight test vehicle," says Baoxi, who confirms the aircraft will conduct the tests from a runway rather than being air-dropped from a carrier aircraft.

Phase three, running from 2025-30, will focus on development and integration of an advanced high-speed turbine engine into the TRRE. Program success will also hinge on parallel breakthroughs in "the operation of the scramjet at higher Mach numbers, particularly in technology areas such as the adjustable combustion chamber ramjet suitable for a wide range of work," says Baoxi. In addition, development of a high-efficiency precooling system will be required. Preliminary work to support this is underway at various sites in China. Once combined with these enhancements, he adds, "the operating range of the TRRE engine can be further expanded."