AVIATION WEEK
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SPECIAL TOPIC

HYPERSONICS

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The Need For Speed

Hypersonics is the future and always will be. For decades this joke has, perhaps unfairly at times, characterized the stop-start pattern of progress towards U.S. operational capability in air-breathing powered flight at speeds up to Mach 5 and above.

But as 2018 gets underway there are clear signs of change as research into hypersonic propulsion and vehicles accelerates, funding increases and the biggest players in aerospace promote their plans for high-speed aircraft, missiles and spaceplanes. Not including 'black budget' funding and the likely existence of a number of classified hypersonic missile projects currently underway in the U.S., the uptick in support for high-speed research was already becoming visible by mid-2017. Compared to 2012 when the Air Force spent just under $79 million on hypersonic science and technology programs, the service requested over $292 million for the same areas in the 2018 Presidential budget. Of this $90 million was requested for prototyping.

So why now? What has changed to disrupt the pattern of the past 50 years? Just like the 1950s and 1960s when American leadership in space was propelled by the race to the Moon against the Soviet Union, the field of hypersonics is becoming crucial to national security. Hypersonics research and development has been galvanized by the growing awareness that China is on track to quickly overtake the U.S's hard-won leadership in the field. The clarion call, made in 2016 by the National Academies of Science and backed-up by think tanks like the Virginia-based Mitchell Institute for Aerospace Studies, came as both China and Russia conducted 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.

Hypersonic technology is a fundamental enabler towards the development of non-nuclear weapons that can strike distant targets in a short period, as well as high speed penetrating aircraft that can perform intelligence, reconnaissance and strike roles. As pointed out by Lockheed Martin, which in 2013, revealed to Aviation Week its plan to develop the SR-72, a Mach 6 successor to the SR-71 spyplane, there are far-reaching impacts of this capability. Ranging from preventing a new proliferator the ability to employ its nuclear weapons to countering sophisticated defensive systems, air-breathing hypersonic systems could also ultimately counter antisatellite weapons and provide a viable alternate path towards reusable space access.

The stories in this package trace the most recent highlights of this dramatic turnaround including the National Academies alarm call to the U.S.; an in-depth report on China's hypersonic research and development activities; and the formation of the U.S. Air Force's hypersonic road map:

It also includes updates on Lockheed Martin's progress towards the SR-72 and provides first details of a reusable hypersonic demonstrator concept unveiled by Boeing in January 2018.

Guy Norris
Senior Editor, Propulsion
Aviation Week & Space Technology

Classified Report On Hypersonics Says U.S. Lacking Urgency

Guy Norris

Less than four years ago, it seemed that the U.S. Air Force was on the brink of developing the first generation of air-breathing high-speed strike weapons following the success of the experimental scramjet-powered Boeing X-51A. Now a classified report warns that the U.S. may be losing its lead in hypersonics to China and Russia.

Although parallel research on hypersonic glide vehicles under DARPA's HTV-2 program suffered failures in 2010 and 2011, the Air Force by 2013 appeared enthusiastic about weaponizing the maturing air-breathing technology demonstrated in the X-51A flight tests. After more than five decades of development and testing in high-speed flight, the U.S. finally looked set to become the undisputed leader in hypersonics.

But as China and Russia demonstrate dramatic strides in the technology, the U.S. is in danger of falling behind, warns a classified report by the National Academies of Sciences, Engineering and Medicine now being briefed to senior Pentagon officials. Unless greater urgency and cohesiveness are injected into this crucial area of defense technology, the report says, the U.S. will become vulnerable to the threat from a new class of superior high-speed maneuvering weapons.

AW&ST ART DEPT CONCEPT

Are China and Russia threatening the U.S. lead in hypersonic propulsion?

The report, commissioned by the Air Force in early 2015, was published late last year and has already been reviewed by the Air Force Research Laboratory and defense acquisition officials. "The good news is that everyone who has seen it so far says it makes sense," says Mark Lewis, chairman of the National Academies' Committee on Future Air Force Needs for Defense Against High-Speed Weapon Systems, which produced the report.

"We are briefing it around town," adds Lewis, who explains that although the committee's charter was to focus on defense, the report also discusses developing offensive capabilities for both a counter and a defensive response. "You really cannot talk about defensive capabilities without linking them to offensive components. We were not making recommendations on what the Air Force should do in terms of developing its own hypersonic systems per se, but embedded in the report is the notion that you need to have your own developmental efforts," he says.

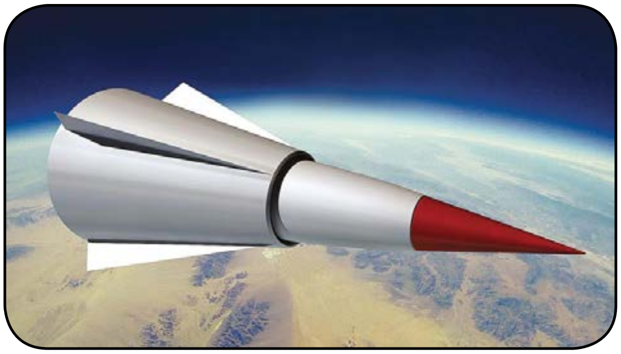
The U.S. is currently pursuing two main hypersonic development paths led by DARPA, with the Air Force, aimed at flight tests by 2019. Under the first initiative, Lockheed Martin and Raytheon are working competitively on an air-launched, rocket-boosted and scramjet-powered successor to the X-51A dubbed the Hypersonic Air-breathing Weapon Concept (HAWC). The second path is the Tactical Boost Glide (TBG) program under which Lockheed Martin is developing an unpowered hypersonic vehicle that will detach from the air-launched rocket stage in the upper stratosphere and glide to its target.

LOCKHEED MARTIN

The DARPA/Air Force HAWC program will not fly a scramjet-powered missile demonstrator until 2019, six years after the last X-51A flight.

Unlike a conventional ballistic-missile reentry vehicle, the hypersonic glide vehicle will be capable of aggressive maneuvers on its run to the target, making interception by even such advanced surface-to-air missile systems as the recently tested Raytheon Standard Missile-3 Block IIA guided missile more difficult. In addition, because the weapon is injected at high speed into the stratosphere, anti-missile defense systems will have much less time to respond.

China and Russia are accelerating development of air-breathing and boost-glide hypersonic weapon systems, and both are believed to be targeting 2020 for deployment of the first operational units. The alarm at the Pentagon was first sounded in early 2014 when U.S. space-based sensors detected Chinese tests of a hypersonic glider boosted by a DF-21 medium-range ballistic missile. Dubbed the DF-ZF by China and the WU-14 by the U.S, the vehicle has since been tested several times on a variety of both solid- and liquid-fueled ballistic missiles.



DANIEL TOSCHLAGER AND JAY MANTRI/WIKIMEDIA

Notional artist's impression of China's DF-ZF hypersonic glide vehicle, which is boosted to its high cruise speed by a ballistic missile.

In October 2015, it also emerged that China had successfully tested a scramjet-powered hypersonic vehicle when the project's leader, Wang Zhenguo, a professor at the National University of Defense Technology, was recognized for the achievement.

Russia is developing a series of hypersonic glide vehicles under its Project 4202 weapons program. Initial flights of the experimental Yu-71 atop an SS-19 missile took place in 2015 from Dombarovsky missile base in Orenburg, close to the border with Kazakhstan in southern Russia. Tests of a more advanced vehicle, the Yu-74, were observed in 2016. The newer vehicle was launched from Orenburg on an RS-18A ballistic missile and targeted at Russia's Kura test range in Kamchatka. The program's stated aim is development of conventional or nuclear-armed hypersonic glide warheads for the Makayev-designed RS-28 Sarmat next-generation ICBM, which is due to enter service around the end of the decade.

Although Russia has also researched and developed air-breathing hypersonic vehicles for many decades, including the Kh-90 (AS-19 Koala) high-speed cruise missile, it also appears to have been making steady progress in tests of a variety of hydrogen-fueled scramjet-powered experimental waverider-type vehicles developed by the Gromov Flight Research Institute. The latest of these, the GLL-AP-02, is provisionally targeted for test flights in 2018-19.

In light of these advances, the National Academy report warns that U.S. efforts, in contrast, appear to be losing momentum and focus. "We also wanted to communicate a sense of urgency," says Lewis. "Even the programs that we have underway do not seem to be demonstrating that sense. If HAWC flies when it is supposed to fly, that is 2019. That's almost a decade after the first flight of X-51. You hear things such as, 'We will develop in 2030, 2040.' For crying out loud, what's taking so long?"

But why the urgency? Other nations, says an unclassified, redacted version of the report, "have taken advantage of data and lessons learned from the U.S. and have been helped by the start-stop approach to technology development (including canceling programs even after major successes) and inefficiencies in the U.S. acquisition processes." As a result, the committee concluded, the U.S. "may be facing a threat from a new class of weapons that will effectively combine speed, maneuverability and altitude in ways that could challenge this nation's tenets of global vigilance, reach, and power."

"We pointed out that if you have maneuvering, high-speed systems available, you can now take on the world's greatest military with a lesser navy and a lesser air force," says Lewis. "You don't need to go ship-to-ship if you can hold the Navy at risk with a new weapon and can produce these effects without investing in a comparable military force. That was part of our warning to the Air Force as well." Referring to the greater long-range threat posed by these weapons, Lewis adds, "If we are forced to stay farther and farther away, it absolutely changes the way we do things."

Hypersonic development also needs to be focused and organized as a national priority, says the report. "The com-

mittee overall realized the programs just are not coherent. There are projects and concepts, but the field would benefit from more national-level direction," says Lewis. With technologies already well advanced, the report recommends that more leadership should be shown by the services, rather than leaving this role to research organizations such as DARPA. "The Air Force hasn't really taken ownership. One of the things we have been asking about is plans for an analysis of alternatives [AoA], so why isn't an AoA being done now?," says Lewis. We call this out in the report, but it is out of our scope to make that level of recommendation. We also believe the Air Force should be doing its own experimentation."


DARPA

Two flights of DARPA's HTV-2 high lift/drag hypersonic glider ended after 9 min. when the vehicles were lost after pull-up from reentry.

Others involved in U.S. hypersonics support the report's recommendations. Kevin Bowcutt, senior technical fellow and chief scientist for hypersonics at Boeing Research and Technology, says "many lessons on the path to X-51A success were hard-earned. Given the criticality of hypersonics as articulated in the report and with X-51A under our belt, there would be obvious value in leveraging this extensive experience and know-how to accelerate full-scale development of an operational hypersonic vehicle or weapon."

Bowcutt also believes the U.S. needs to create "a comprehensive national plan with adequate funding that fields offensive and defensive hypersonic capabilities as quickly as technology maturation, system integration and capability demonstration allow."

"It is a big problem for us. We have been kind of resting on our laurels," says Leon McKinney, president of McKinney Associates and former executive director of the U.S. hypersonics industry team. "The U.S. has been fighting wars and terrorism, so that is one of the reasons why we have not seen a burst of capability developments. But it seems our adversaries are catching up."

McKinney backs a three-phased approach to spurring development of a boost-glide capability, starting with a focus on an offensive hypersonic system that he believes could still be fielded within three years. Development of a defensive system, which McKinney says is "tough," would aim at characterizing Chinese and Russian vehicle maneuvering capabilities to produce a "threat tube," to enable effective interdiction. A third element would include development of a maneuvering target vehicle "which we could engage as a simulated threat."

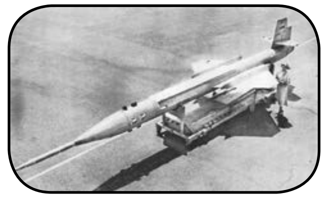
The report does not specify that current programs should be abandoned, "but we think there are some programmatic changes we need to see," says Lewis. "We just say, step on the gas and move these programs forward. If you want to map out a strategy to get you from the things we have tested to an operational system, one would argue we are not on that track."

A U.S. Timeline Of Hypersonics Starts And Stops

Guy Norris

The U.S. has had several opportunities over the past 50-plus years to move beyond experimentation and demonstration in hypersonics into research and development of operational systems. But technical challenges and test failures, start-stop funding and the absence of clear and consistent requirements from government customers have put the country at risk of losing its hard-earned leadership in hypersonics.

1947	National Advisory Committee for Aeronautics 11-in. hypersonic research wind tunnel opens at Langley, Virginia.
1949	German V-2-boosted WAC Corporal rocket becomes first vehicle to exceed Mach 5.
1951	First flight of X-7 ramjet high-speed research vehicle.
1956	Lockheed X-17 reentry test vehicle flight tests begin.
1958	First hypersonic research wind tunnel opens at Arnold Engineering Development Complex, Tennessee.
1959	First flight of rocket-powered X-15 hypersonic research aircraft.
1959	Launch of Boeing X-20 Dyna-Soar manned boost-glide vehicle project, not flown and canceled in 1963.
1959	U.S. Air Force Alpha Draco boost-glide experimental test vehicle flight tests.
1963	First flight of Air Force ASSET (Aerothermodynamic/elastic Structural Systems Environmental Tests) boost-glide test vehicle.
1964	NASA Hypersonic Research Engine (HRE) ramjet/scramjet project launched, ground tested.
1965	Aerojet ground-tests air turbo ramjet combined cycle engine.
1966	First flight of Air Force PRIME (Precision Recovery Including Maneuvering Entry) reentry flight vehicle.
1968	Atlas-boosted Air Force Boost Glide Reentry Vehicle flight test.


AW&ST ARCHIVES
1951


U.S. DEPARTMENT OF DEFENSE
1956


NATIONAL ARCHIVES
1959


NASA
1959


U.S. AIR FORCE MUSEUM
1963

1978 Air Force classified Advanced Manned Spaceflight Capability piloted-rocketplane program, later became TransAtmospheric Vehicle. Not flown; canceled in 1986.

1979 First test flight of Minuteman ICBM-boosted Advanced Maneuverable Reentry Vehicle, paving way for Sandia Winged Energetic Reentry Vehicle Experiment tests in 1980s and Advanced Hypersonic Weapon test in 2011.

1981 Space shuttle first orbital flight and hypersonic reentry.

1982 Start of classified DARPA Copper Canyon air-breathing single-stage-to-orbit project, evolved into X-30 National Aerospace Plane in 1986. Not flown; canceled in 1990s with termination of follow-on Hypersonic Systems Technology Program in 1995.

1995 Orbital Sciences selected by NASA for X-34 orbital launch vehicle. Not flown; canceled in 2001.

1996 NASA begins X-33 single-stage-to-orbit rocketplane to be built by Lockheed Martin. Not flown; canceled in 2001.

2001 First flight of scramjet-powered X-43/Hyper-X (below). Second flight at Mach 7 in March 2004 marked first known operation of a scramjet in flight. Third flight in November 2004 attained Mach 9.6.

2002 DARPA, Boeing, U.S. Navy Hypersonic Flight Demonstration (HyFly), a dual combustion ramjet-powered strike missile demonstrator program launched (below). Final test attempt failed in 2010.

2009 First experimental test flight of joint U.S.-Australian HiFiRE (Hypersonic International Flight Research Experimentation) fundamental research program.

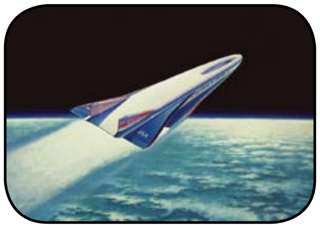
2010 First orbital mission of Boeing-built Air Force X-37B spaceplane, derived from NASA/DARPA X-37A.

2010 First launch of Boeing, Air Force,DARPA, NASA, Pratt & Whitney Rocketdyne scramjet-powered X-51A WaveRider (below). Achieved Mach 5.1 and 210 sec. of hypersonic flight on final flight in 2013.

2010 First unsuccessful flight of DARPA Falcon Hypersonic Test Vehicle 2 (HTV-2) intended to demonstrate prompt global strike capability at Mach 20. Second flight lost in 2011 due to aeroshell degradation.


U.S. AIR FORCE MUSEUM

1966


NASA

1982


NASA

2001


DEFENSE DEPARTMENT

2002


U.S. AIR FORCE

2010

2013 Lockheed Martin unveils Mach 6 SR-72 surveillance/strike concept aircraft to Aviation Week.

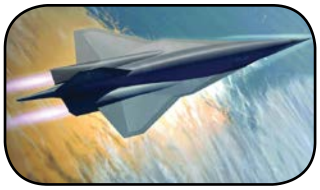
2016 DARPA launches Advanced Full-Range Engine program to demonstrate turbine-based combined cycle-system for hypersonic aircraft, building on previous Mode Transition and Falcon Combined-cycle Engine Technology efforts, the latter completed in 2009.

2016 Lockheed Martin and Raytheon win contracts to compete for DARPA/Air Force Hypersonic Air-breathing Weapon Concept (HAWC) program.

2016 DARPA awards Tactical Boost Glide technology demonstration program to Lockheed Martin.

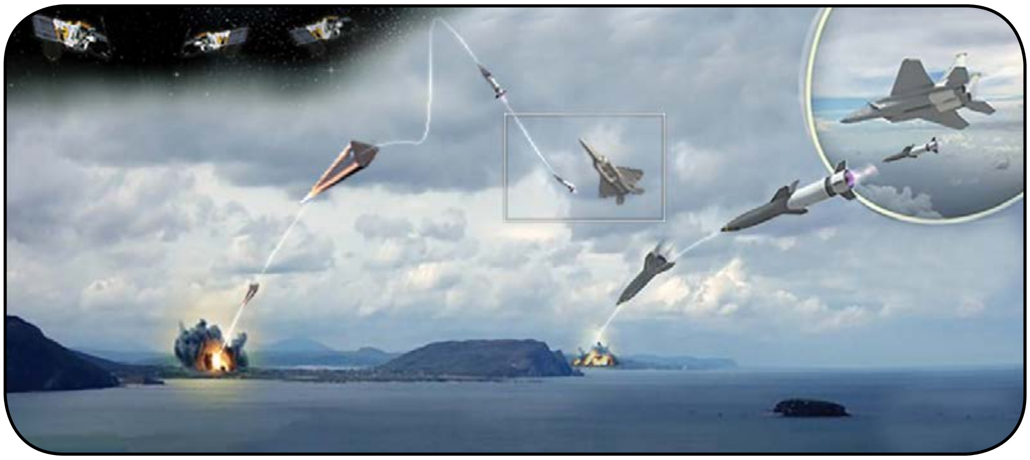
2017 Aerojet Rocketdyne and Orbital ATK awarded contracts under DARPA's AFRE turbine based combined cycle program.

2018 Boeing unveils concept for Mach 6 reusable hypersonic demonstrator.



LOCKHEED MARTIN

2013



DARPA

2016

China Takes Wraps Off National Hypersonic Plan

Guy Norris

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 in Xiamen, China, 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.

NATIONAL NATURAL SCIENCE FOUNDATION OF CHINA

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.

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)

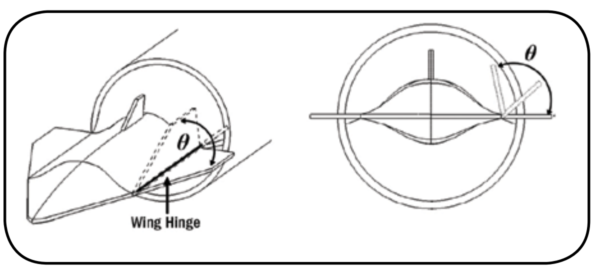
A major revelation early on at the conference was the first formal acknowledgement of a Chinese scramjet flight test in December 2015. It is highly likely, though not yet confirmed, that the milestone achievement is associated with the same program for which the Feng Ru Aviation Science & Technology 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.



CHINA ACADEMY OF LAUNCH VEHICLE TECHNOLOGY

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.

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."

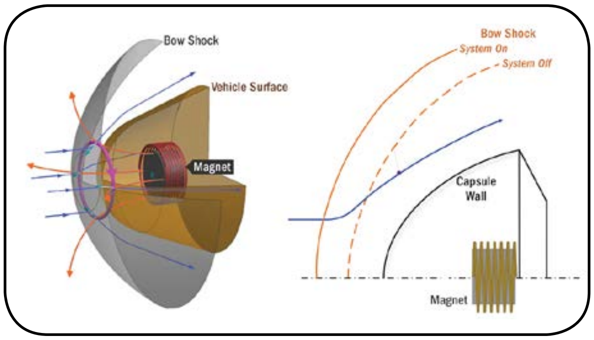
Key accomplishments include development of a theory for hypersonic unsteady flow, as well as understanding of complex flow mechanisms and advances in numerical simulation. "We improved the understanding of coupled-physical effects and found new flow phenomena," says Chen. "We also established optimal 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 scram-

jet. 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."



COLLEGE OF AEROSPACE SCIENCE AND ENGINEERING

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

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 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."

NATIONAL UNIVERSITY OF DEFENSE TECHNOLOGY

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.

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.

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.

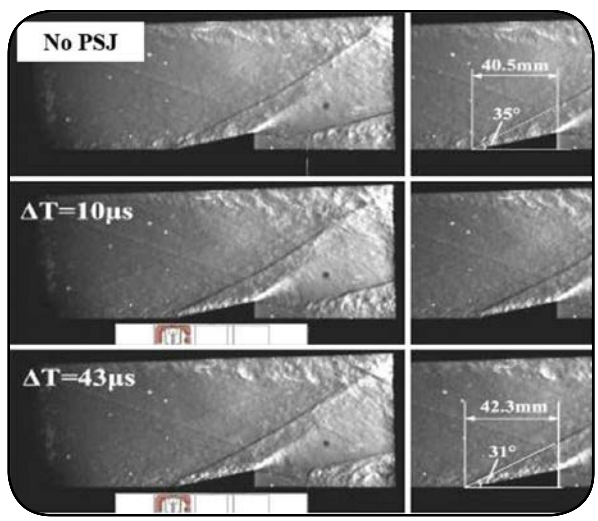
A second highlighted vehicles study, presented by Yuan Yu of the Beijing-based China Academy of Launch Vehicle Technology, evaluated a reconfigurable waverider that would unfold its wings following deployment from beneath the shroud of a launch vehicle. While the details of the application were not discussed, 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.

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.



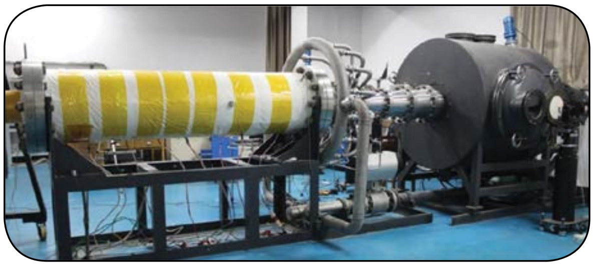
Experiments showed supersonic shockwaves could be controlled with an arc-driven plasma synthetic jet (PSJ) actuator.

AIR FORCE ENGINEERING 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.



NATIONAL UNIVERSITY OF DEFENSE TECHNOLOGY

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

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.

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 internal flow of the turbojet nozzle.

CHINA ACADEMY OF AEROSPACE AERODYNAMICS

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

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.

China Reveals Key Test Progress On Hypersonic Combined-Cycle Engine

Guy Norris

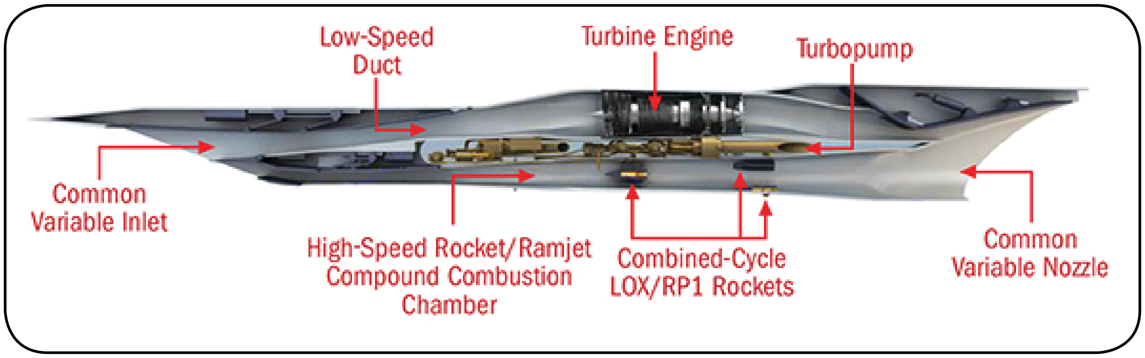
Chinese engineers will test a prototype combined-cycle hypersonic engine later this year that they hope will pave the way for the first demonstration flight of a full-scale propulsion system by 2025. If successful, the engine could be the first of its type in the world to power a hypersonic vehicle or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

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 take-off 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 scram-jet 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."



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.

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.

"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 m2, which basically meets the requirement of the vehicle design," he adds.

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.

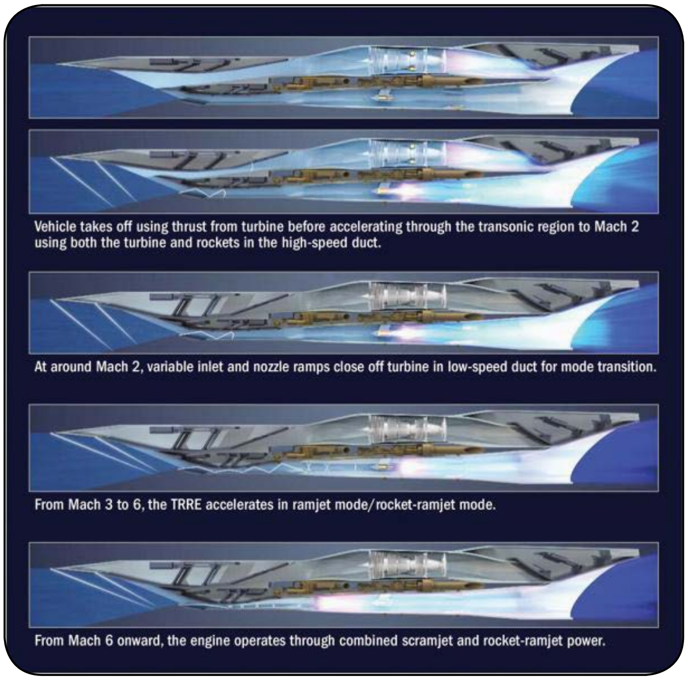
For the follow-on flying demonstrator, Baoxi says the turbine will likely be based on the WS-15, a super-cruising turbofan under development by Xian Aero Engine Corp. for later production versions of the twin-engine Chengdu J-20 stealth fighter. However, even though the initial batch of J-20s entered 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.

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

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."



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

Skunk Works Quietly Marks Progress On Proposed Blackbird Successor

Guy Norris

Four years after revealing plans to develop a Mach 6 strike-and-reconnaissance aircraft, Lockheed Martin says a raft of hypersonic technologies is now sufficiently mature to enable progress toward a flight demonstrator.

The company's secretive Skunk Works unit has been working since at least the early 2000s on the basic building blocks for an operational hypersonic vehicle, and it revealed to Aviation Week it was developing a scaled demonstrator for the SR-72, a proposed successor to the U.S. Air Force's long-retired Mach 3 SR-71 Blackbird spy plane (AW&ST Nov. 4, 2013, p. 18). However, details on any subsequent progress have been scarce since this initial plan was unveiled.

"We have been saying hypersonics is two years away for the last 20 years, but all I can say is that the technology is mature and we, along with DARPA and the services, are working hard to get that capability into the hands of our warfighters as soon as possible," says Rob Weiss, Lockheed Martin Advanced Development Programs executive vice president and general manager.

Tests of a combined-cycle-powered Flight Research Vehicle could pave the way toward a proposed full-scale SR-72 in the late 2020s.

LOCKHEED MARTIN

Speaking to Aviation Week on the sidelines at the American Institute of Aeronautics and Astronautics Aviation 2017 forum June 5-9 here, Weiss cautioned: "I cannot give you any time lines or any specifics on the capabilities. It is all very sensitive. Some of our adversaries are moving along these lines pretty quickly, and it is important we stay quiet about what is going on. We can acknowledge the general capability that is out there, but any program specifics are off limits."

However, Weiss implies that work on a combined-cycle propulsion system and other key advances needed for a viable hypersonic vehicle are reaching readiness levels sufficient for incorporation into some form of demonstrator. Following critical ground demonstrator tests in 2013-17, Lockheed Martin appears to be on track to begin development of an optionally piloted flight research vehicle (FRV) starting as early as next year. The FRV is expected to be about the same size as an F-22 and powered by a full-scale, combined-cycle engine.

While no specific details have been revealed, it is known that Lockheed Martin and Aerojet Rocketdyne have been teamed since 2006 on work to integrate an off-the-shelf turbine with a scramjet to power an aircraft with a combined-cycle propulsion system from standstill to Mach 6+. The development built on work begun earlier under the Air Force/DARPA HTV-3X reusable hypersonic demonstrator that was canceled in 2008 but went a step further to integrate a high-speed turbine engine. The HTV-3X concept was an outgrowth of DARPA's Falcon program, which included development of small launch vehicles, common aero vehicles and a hypersonic cruise vehicle.

"The combined-cycle work is still occurring, and obviously a big breakthrough in the air-breathing side of hypersonics is the propulsion system. So this is not just on combined-cycle but on other elements of the propulsion system," says Weiss. The technology of the "air breather has been matured, and work is continuing on those capabilities to demonstrate that they are ready to go and be fielded," he adds.

Depending on progress with the FRV, which would fly in the early 2020s, Lockheed Martin has said the follow-on step would be development of a full-scale, twin-engine SR-72. Sized to approximately the same proportions as the SR-71, the larger vehicle would enter flight test in the late 2020s.

U.S. Air Force Plans Road Map To Operational Hypersonics

Guy Norris

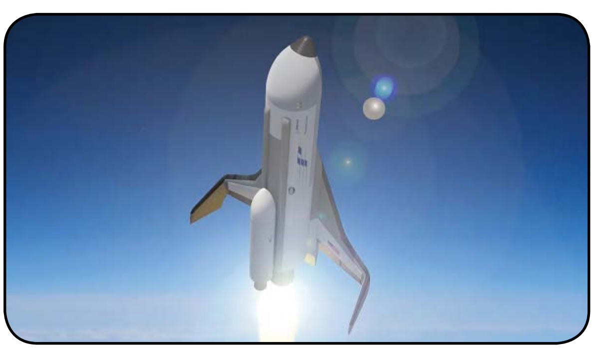
As the U.S. Air Force prepares to solicit industry for development of an air-launched hypersonic conventional strike weapon it is, for the first time, outlining its approach to operationalizing high-speed capability for a wide range of roles.

Despite more than 50 years of U.S. hypersonic development and several false dawns, the Air Force says the technology is only now reaching a point where it can actively plan a workable operational strategy for hypersonic strike, intelligence, surveillance and reconnaissance (ISR) missions. The move has been prompted by advances in homegrown propulsion, materials and controls—as well as the growing threat of Chinese and Russian hypersonic capability.

"We know hypersonic warfighting is here. We know we have got to get there, and we know we have to get some transition strategies to go forward," says Col. Colin Tucker, military deputy for the U.S. Air Force deputy assistant secretary for science, technology and engineering. Building on the initial deployment of expendable weapons, he says, the eventual target is to expand on this capability for robust, repeatable operations using a reusable hypersonic platform.

Speaking at the American Institute of Aeronautics and Astronautics Propulsion and Energy forum in Atlanta, Tucker said the key ingredient to the successful deployment of an operational hypersonic system is early user involvement: "It must have warfighter community buy-in to make sure it is actually something they will use. That means integration with the acquisition, science and technology and warfighter communities. We have to use modeling, simulations and war-gaming to flush out what these weapons will bring to us, not just from a technology standpoint but from a capability perspective.

"At the end of the day, for me to put it on a ramp and give it to a person in a flight suit to go and use, it has got to be more airplane-like. So, logistically, it has got to be supportable, producible, affordable and operational, and not an experiment," he says. To meet the requirements of high-tempo operations, he adds, developers will need to focus on improving the robustness of subsystems and propulsion. "For rocket-powered vehicles like the [Boeing-DARPA] XS-1, we have got to have rocket engines that we can use on a very short time cycle and repeatably. We can't refurbish the engine between each flight; it is just not sustainable."



DARPA

The U.S. Air Force hopes to leverage advances demonstrated by the XS-1 spaceplane in thermal protection, navigation and control and other areas for operational hypersonic missions.

The winged XS-1 spaceplane, dubbed Phantom Express by Boeing, will be powered by the Aerojet Rocketdyne AR-22, a derivative of the rocket company's RS-25 space shuttle main engine. Having beaten competition for the next phase from Northrop Grumman and Masten Space Systems, Boeing is building the XS-1 demonstrator, which will be completed and ground tested by the end of 2019. Over the same period Aerojet will also test the AR-22, ultimately targeting 10 firings over 10 consecutive days. Under the current DARPA plan, the XS-1 is expected to begin initial flight tests in 2020 at speeds up to Mach 5. Subsequent flights will fly at speeds up to Mach 10 as part of multistage missions to deliver payloads to low Earth orbit.

While the XS-1 will operate in the hypersonic regime, the Air Force is also focusing on a "flying wind tunnel," to aid development of a series of air-breathing and rocket-powered expendable and reusable platforms that will operate in the near-space environment. "What do we need to do in an X-15 type of world that will help us take the next

step?" says Tucker. "What types of things are there that we can bring in to push toward something more operational? We are not quite sure what this is yet, but that is something we are taking forward that we think is very important."

Tucker says an aircraft such as the air-breathing Mach 6 SR-72 "Son of Blackbird" ISR platform proposed by Lockheed Martin would be a good first step. He adds, "We are looking at a crawl-walk-run approach, and that requires us to be risk-tolerant. It does not have to be done in one fell swoop."

"So how are we going to get there?" Tucker asks. "We are going to need more ground and flight tests and new infrastructure investments."

He adds, "[We need] sustained commitments from the government and the Air Force that show this is important to us. The start-stop pattern of the past does not help build a robust workforce. I feel genuinely that we are at a point right now where we can honestly say there is going to be some continued work in this area to try and get to an operational system."

Tucker's optimism is based on a dramatic upswing in the Air Force hypersonic research budget. Compared to 2012, when the Air Force spent just under $79 million on hypersonic science and technology programs, the service requested more than $292 million for the same areas in the 2018 presidential budget. Of this, $90 million was requested for prototyping.

While a number of classified hypersonic missile efforts are thought to be underway in the U.S., the only acknowledged committed government research developments are a series of technology demonstrator programs led by DARPA. These include two high-speed strike weapons: the Tactical Boost Glide (TBG) program and the Hypersonic Air-Breathing Weapon (HAWC). The TBG is a follow-on to the unsuccessful HTV-2 hypersonic cruise vehicle demonstrator and is a rocket-launched hypersonic weapon capable of flying more than 1,000 mi. in 10 min. The TBG, in development by Lockheed Martin, is attempting to repackage the high lift-to-drag aerodynamic and aerothermal design concepts of the global-range HTV-2 into a smaller, tactical-range weapon

Raytheon Missile Systems and Lockheed Martin are meanwhile competing for the HAWC, a follow-on to the Air Force Research Laboratory's (AFRL) successful Boeing X-51A WaveRider hypersonic scramjet engine demonstrator.

Leveraging elements of these DARPA/AFRL efforts, the Air Force has meanwhile begun efforts to develop an air-launched Hypersonic Conventional Strike Weapon. Boeing, Lockheed Martin, Northrop Grumman, Raytheon Missile Systems and Orbital ATK have all been listed as potential developers of the precision strike missile, which the service says will be fired at "high-value, time-critical fixed and relocatable surface targets." A contract for development of the weapon—which will be conventionally armed, powered by solid rocket and guided by an integrated GPS/INS (inertial guidance system)—will be awarded in early 2018.

Beyond missiles and XS-1, DARPA's other major hypersonic program is the Advanced Full-Range Engine (AFRE), a ground demonstrator of a turbine-based combined-cycle engine that will enable an aircraft to operate at Mach 5+ from standard runways. Launched 18 months ago, AFRE is a "full-scale engine, and will validate [that] we can have an effective engine," says DARPA Tactical Technology Office Director Brad Tousley. "We need the same sort of thing as the J58 was in the SR-71, and AFRE is the same sort of thing. If that is successful, we think it would open up the trade space for us to work together with the Air Force, the U.S. Navy and others on a really 'no-kidding' reusable hypersonic aircraft.

"It is time for the nation to move forward and develop prototype weapon capability so the Air Force and others can assess through an analysis of alternatives what to do about it," adds Tousley. "The nation needs to do an awful amount of work defending against this capability because the threats are evolving very rapidly."

Captive-Carry Tests Coming For Hypersonic Flying Testbed

Guy Norris

With demand for high-speed test capability on the increase, small launch-vehicle developer Generation Orbit Launch Services is preparing for a critical series of hot-fire and captive-carry flight tests of its hypersonic flying testbed at Edwards AFB, California.

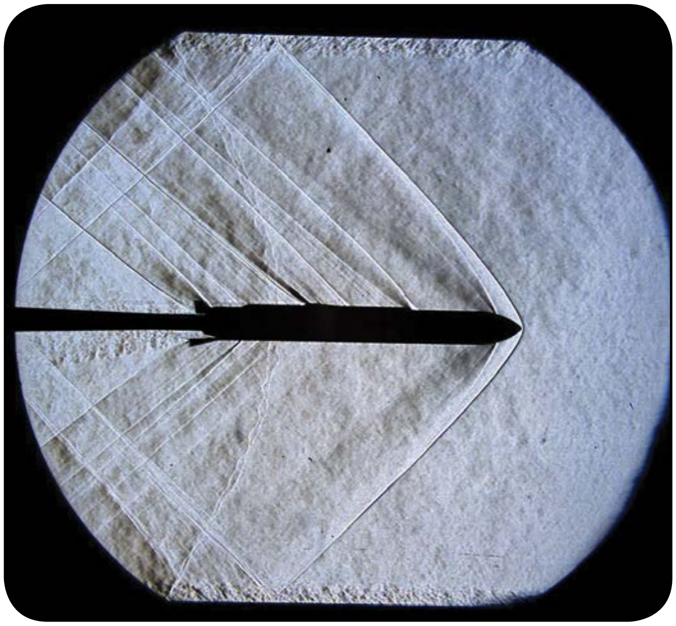
The Atlanta-based company is developing the GOLauncher 1 (GO1) vehicle for suborbital research and hypersonic flight-testing, and aims to fill a gap in high-speed atmospheric test capability which has existed since the retirement of the U.S. Air Force's X-15 in 1968. Upcoming hot-fire evaluations, together with captive-carry work and a series of ongoing wind-tunnel tests, are expected to pave the way for production of the first GO1 flight-test vehicle in 2018 and initial powered flight in early 2019.

Due to be air-launched from a modified Gulfstream III business jet, GO1 is a single-stage liquid rocket designed for a wide range of payloads and trajectories ranging from high-altitude microgravity flights to suppressed trajectories for high-Mach, high dynamic-pressure hypersonic tests. "It is a relatively unique capability that doesn't really exist in the industry right now, specifically on the hypersonic side," says GO CEO Anthony Piplica. "We want to provide affordable and high-tempo access to these high-Mach and high dynamic-pressure conditions on a regular basis."

Weighing almost 2,400 lb. and carrying payloads of 300-1,000 lb., the GO1 is targeted at four main missions, three of which are tailored to hypersonic testing and one for suborbital microgravity research. The hypersonic roles include deployment of free-flyer vehicles with air-breathing propulsion systems, similar to that of the X-51A, as well as delivery of boost-glide vehicles like DARPA's HTV-2.

GO1 also will act as a hypersonic cruise vehicle surrogate, sustaining Mach 6 at 85,000 ft. and a dynamic pressure of 1,000 psf for periods of up to 1 min. "That allows us to test high-speed propulsion systems without having to rely on them for thrust, control or data," says Piplica. Although acknowledging this time period is likely too short to establish structural thermal equilibrium, he adds it is long enough to derive steady-state conditions and is "a really good place to start."

While some users have asked for suborbital capability for a variety of payloads including aero-heating and reentry experiments at up to Mach 25, the company's "bread-and-butter" coverage area will be a flight envelope covering altitudes of 50,000-120,000 ft. and speeds of Mach 4-8. "That's what we are really interested in. That is where propulsion and controls for high-speed systems are, and is the area boundary layer scientists are really interested in," says Piplica.



GENERATION ORBIT

Baseline aerodynamic performance of the GO1 was checked at AFRL's Trisonic Gas-Dynamics facility in Ohio.

Under an Air Force Research Laboratory (AFRL) contract awarded late last year, Generation Orbit is finalizing assembly of a full-scale functional prototype for the hot-fire test campaign at Edwards in November. "The prototype includes propellant tanks, engines, pressurization systems, feed systems, avionics and harnesses. It is everything except the aerodynamic control surfaces and will be used to prove out the vehicle and make sure we learn through the integra-

GENERATION ORBIT

GO1's high wing and body flap will assist with post-launch pull-up maneuver and help maintain cruise test conditions at low angles-of-attack.

tion process early before we get to flight," explains Piplica. Fueled by liquid oxygen and kerosene, the staged-combustion rocket engine is rated at 5,000 lb. thrust at sea level.

Under the same AFRL contract, Generation Orbit also is undertaking wind-tunnel tests of a 5.3% scale GO1 model at Wright-Patterson AFB, Ohio. Initial tests have been conducted in the base's Trisonic Gas-Dynamics Facility, which can operate from Mach 0.23 to Mach 3.

Follow-on testing is due to begin this month in the recently opened AFRL Mach 6 hypersonic Ludwieg-tube wind tunnel and will run through September. The model includes movable control surfaces and modular payload sections to enable testing with different control deflections and payload shapes.

"We also built a 5.3% scale model of a Gulfstream III and will test that in Calspan's [transonic wind tunnel in Buffalo, New York] in October," says Piplica. The work will focus on captive-carry aerodynamics and stores-separation testing. "This is one of the key risks of the program and is something we are paying very close attention to," he adds.

Meanwhile, additional testing of a captive-carry mock-up is underway with NASA. The full-scale inert test unit matches the outer mold lines in terms of mass properties and will be flown in October beneath one of the agency's Gulfstream IIIs. Testing will take place at the Armstrong Flight Research Center in California following completion of ground-vibration testing. According to Piplica, "Captive-carry tests will help us understand the handling qualities of the mated system and validate our structural and loads models. They will then work up to release conditions at 35,000 ft., Mach 0.7 and a flightpath angle of 30 deg." Flights will simulate abort launches and provide data ahead of the stores-separation tests at Calspan.

GENERATION ORBIT

GO3 is a larger follow-on small launch vehicle intended for air-drop from a modified DC-10 carrier aircraft.

Current plans call for the first test-firing of the GO1 in early 2019 in a range 200 nm off the Florida coast. Based from Cecil Spaceport, the mission is targeted at proving basic operability and demonstrating at least 5 sec. of sustained operations at Mach 6 and 1,000 psf. "We are focusing on demonstrating the launch of cryogenic liquid rocket off an aircraft and its insertion capabilities into these conditions," says Piplica.

"No one has done that since the X-15, so we figure we should probably get our feet wet before we invest in building a much larger system," he stresses, referring to a planned follow-on GO3 small-satellite launch vehicle. Taking over from the now-abandoned 40-kg (88-lb) nanosatellite and CubeSat GO2 follow-on to GO1, the GO3 will be a two-stage, liquid-fueled vehicle capable of delivering almost 500-kg payloads to Sun-synchronous orbits. The larger GO3 will be launched from a modified DC-10 carrier aircraft early in the 2020s.

Hypersonic Race Heats With Boeing Reusable Demonstrator Concept

Guy Norris

Boeing is raising the stakes in the accelerating race for U.S. hypersonic leadership by positioning itself to develop a potential future Mach 5-plus strike-and-reconnaissance aircraft.

The move, which was signaled by the unexpected unveiling of a reusable hypersonic demonstrator concept vehicle at an aerospace science and research conference in Florida in early January, directly challenges Lockheed Martin. In 2013, Lockheed revealed plans to develop a Mach 6 successor to the long-retired SR-71 Blackbird.

Boeing's ambitious plan emerges amid continuing signs of a significant upswing in U.S. hypersonic research and development and builds on decades of design experience gained through a variety of high-speed rocket and air-breathing-powered programs. The sharply swept delta-wing vehicle concept notably leverages the X-43 and X-51A hypersonic demonstrator programs but also incorporates several design features from projects produced from companies Boeing later acquired, including the Mach 3 XB-70 Valkyrie experimental bomber project.

"We asked, 'What is the most affordable way to do a reusable hypersonic demonstrator vehicle,' and we did our own independent research looking at this question," says Kevin Bowcutt, Boeing chief scientist for hypersonics. If selected for full-scale development, Boeing is considering a two-step process beginning with flight tests of an F-16-size single-engine proof-of-concept precursor vehicle leading to a twin-engine full-scale operational vehicle with approximately the same dimensions as the 107-ft.-long SR-71.

The concept model was unveiled at the American Institute of Aeronautics and Astronautics SciTech forum in Orlando, Florida. Bowcutt says the twin-tail, waverider configuration continues to evolve but is already representative of a feasible hypersonic design. "It's a really hard problem to develop an aircraft that takes off and accelerates through Mach 1 all the way to Mach 5 and beyond. The specific impulse of an air-breathing engine goes down with increasing velocity, so you have to make the engine larger to get to Mach 5. But doing that means a bigger inlet and nozzle, and trying to get that through Mach 1 is harder."

BOEING

Boeing's proposed reusable hypersonic demonstrator is a waverider concept that builds on X-43/X-51 experience.

However, Bowcutt says careful integration of the airframe and propulsion system through multidisciplinary design optimization (MDO), a process in which designers incorporate all relevant disciplines simultaneously, has enabled Boeing to develop a working configuration. MDO was used to finalize the design of the X-51A waverider, which was the first vehicle to demonstrate sustained air-breathing hypersonic flight.

Although initially independently funded by Boeing, development of the hypersonic vehicle concept is continuing under DARPA's Advanced Full-Range Engine (AFRE) initiative and a closely related turbine-based combined-cycle (TBCC) flight demonstration concept study run by the U.S. Air Force Research Laboratory. Boeing's engine partner for the concept is Orbital ATK, which in September 2017 was awarded a $21.4 million contract for the AFRE program. Boeing began work on the AFRL TBCC flight demonstrator concept study, with Orbital ATK as subcontractor, in 2016.

The vehicle configuration is dominated by the TBCC propulsion system, which combines conventional turbine engines with dual-mode ramjets/scramjets (DMRJ). The turbine engines operate up to a sufficiently high Mach num-

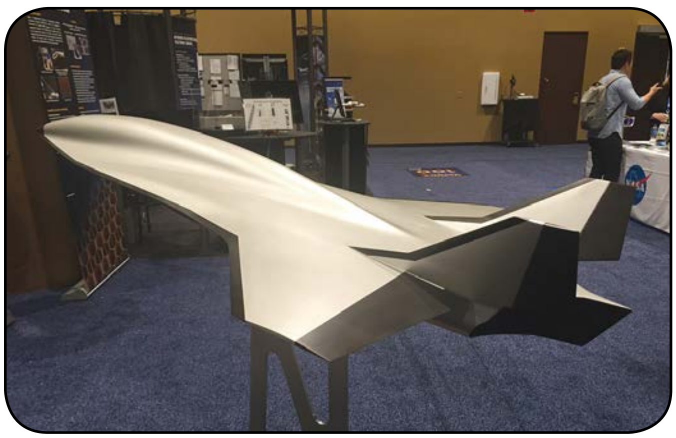
ber to enable transition to the DMRJ. The engines will share a common inlet and nozzle, with the turbine cocooned after transition and then restarted once the hypersonic vehicle slows down for return to a runway landing. The inlets are divided by a prominent septum derived from the XB-70, says Bowcutt, who adds that the TBCC is only one of a number of potential propulsion options. The nozzles are also separated by a prominent boat-tail divider.

"The propulsion system determines the length of the vehicle," says Boeing Research and Technology chief hypersonic aircraft designer Tom Smith. Although Boeing declines to discuss specific aspects of the design, the broad inlets and wide lower fuselage-mounted nacelle suggest the turbine and DMRJ in each TBCC engine are housed side-by-side rather than arranged in an over-under configuration.

The inward-turning inlets are positioned to capture the initial shockwave from the nose of the vehicle, while the sharply swept forebody chines are contoured into the relatively large-span delta wing to provide waveriding capability at hypersonic speed and sufficient lift for landing and takeoff at subsonic speed. The term waverider refers to a design in which the vehicle rides the shockwave attached to the leading edge, thus benefiting from lower induced drag. "As the narrow chine transitions to the wing, that produces a good vortex which you care about at low speed," notes Smith.

Outwardly resembling Lockheed Martin's SR-72 concept, Boeing's design differs in having twin tails and engines grouped in a single large nacelle rather than housed individually. The design, thought to be internally dubbed the Valkyrie II, continues to be refined and, according to sources, is unlikely to feature the distinctive humped forward fuselage shown in the model displayed at SciTech.

Lockheed Martin, which in 2017 indicated that significant progress has been accomplished toward development of a subscale hypersonic flight research vehicle, has been teamed with Aerojet-Rocketdyne on the project since 2006. Lockheed's project builds on earlier work completed under the Air Force/DARPA HTV-3X reusable hypersonic demonstrator program that was canceled in 2008 but goes a step further by integrating a high-speed turbine engine. The HTV-3X concept was an outgrowth of DARPA's Falcon program, which included development of small launch vehicles, common aero vehicles and a hypersonic cruise vehicle.



The Boeing design incorporates twin fins for stability and a cranked delta wing for better low-speed performance.

GUY NORRIS/AW&ST

Although Boeing was heavily involved in the X-51A, which could have paved the way for a high-speed weapon, subsequent work on hypersonic development led by DARPA has largely gone to Lockheed. Under one initiative, Lockheed Martin and Raytheon are working competitively on the air-launched, rocket-boosted Hypersonic Air-breathing Weapon Concept. The second is the Tactical Boost Glide program under which Lockheed Martin is developing an unpowered hypersonic vehicle that will detach from the air-launched rocket stage in the upper stratosphere and glide to its target.