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Advanced manufacturing extends operational boundaries of hybrids

BY TIMOTHY MARQUARDT AND JOSEPH MAJDALANI

The **Hybrid Rockets Technical Committee** studies techniques applied to the design and testing of rocket motors using hybrid rocket systems.

▲ **Virgin Space Ship Unity** in space with three crew members aboard.
Virgin Galactic

Virgin Galactic in February launched **Virgin Space Ship Unity** into space with a crew of three aboard, 10 weeks after its first trip beyond the 80-kilometer space boundary. Powered by a hybrid motor that provided 320 kilonewtons of thrust for nearly 60 seconds, this spaceship reached **Mach 3.04** and an apogee of nearly 90 km before returning to the Mojave Spaceport in California.

Researchers at Stanford University demonstrated **laser ignition of a hybrid fuel grain** in a lab-scale slab burner. They presented high-speed imaging results in July that identified the underlying ignition mechanism as the entrainment and laser heating of small soot particles formed during fuel pyrolysis or chemical decomposition. A small and lightweight laser diode, combined with a few simple optical elements, provided energy to a specific point on the fuel surface and heated soot particles well beyond the temperature required for fuel pyrolysis. These particles then transferred energy to the vaporized propellant mixture, igniting the motor. Experiments have confirmed that only those fuels that produced soot were compatible with this technique, but the method holds promise for broader applicability. Tests in a single-port motor that aimed the laser at a small target area of a compatible fuel embedded in a larger, non-soot-producing fuel grain demonstrated ignition of the motor at both atmospheric and vacuum exit conditions.

NASA's Jet Propulsion Laboratory in California and Marshall Space Flight Center in Alabama continued to lead technology development for a **Mars Ascent Vehicle** intended to deliver samples from the surface of Mars into orbit. To this end, Whittinghill Aerospace of California carried out **full-scale motor testing of a wax-based fuel with MON-25**, a mixed oxide of nitrogen, in April and July at the Mojave Spaceport. Test motors and oxidizer were conditioned to an assumed Mars operational temperature of minus 20 degrees Celsius. In this study, researchers achieved high-performance, stable burns with durations of 60 seconds. The Space Propulsion Group of California and Montana performed similar but smaller, separate tests in Butte, Montana, in January and April and had the same results. In addition, researchers at Purdue University in August presented findings that they demonstrated the hypergolic ignition and multiple relights of a paraffin-based hybrid motor with various hypergolic solids added to the headend of the **fuel grain containing MON-25**. Tests showed good agreement with previously completed MON-3 testing, with some tests experiencing ignition delays.

The **additive manufacture of advanced hybrid rocket motors** to enhance burn rates and efficiencies continued to grow. This year, the Aerospace Corp. of California produced hollow liquid fuel grains that used 3D-printed features to meter the delivery of liquid fuels such as kerosene. This arrangement combined the capabilities of liquid-engine performance with the safety and simplicity of hybrids. In the first half of the year, Aerospace Corp. flight-tested an advanced hybrid rocket with these new liquid grains and a 54-millimeter rocket motor.

In a separate program, Aerospace Corp. and Penn State continued development of a **hybrid propulsion unit for cubesats**. Collaborators at Penn State demonstrated start, stop and restart capabilities of the unit early in the year before returning it to the Aerospace Corp. for further development. The propulsion unit consists of a 3D-printed solid fuel grain in a combustion chamber integrated into and surrounded by a toroidal oxidizer tank. The chamber/tank component was created with direct metal laser sintering, a form of 3D printing that melts metal powder together with lasers. This technique eases the production of intricate parts that possess the necessary thermal and mechanical properties for use in propulsion systems.★

Contributors: *David Dyrda, Andrew Cortopassi and George Story*

2 supersonic aircraft programs reach testing milestones

BY JONATHAN S. LITT, TIM CONNERS AND JEFFREY D. FLAMM

The **Inlets, Nozzles and Propulsion Systems Integration Technical Committee** focuses on the application of mechanical design, fluid mechanics and thermodynamics to the science and technology of air vehicle propulsion and power systems integration.

Boom Supersonic made substantial progress in the design, assembly and testing of its **XB-1 supersonic demonstrator** aircraft. This work culminated in engine ground testing, which concluded in February at the U.S. Air Force Academy in Colorado. The test demonstrated that measured inlet distortion levels were acceptable for XB-1's three **GE J85-CAN-15** engines. This achievement followed wind tunnel testing of the inlet at the Boeing Polysonic Wind Tunnel in St. Louis in late 2018.

The XB-1's 2D hybrid compression inlet model was designed for sustained Mach 2.2 operation and uses modular fore and aft ramps, spill door geometry and a wide-throat bleed slot that was based on Concorde's. An **aft-mounted auxiliary intake** effectively reduces low-speed distortion, although it is not required to meet flow demand. Analysis of test data proved that high throat bleed gives the inlet a modest amount of efficient internal compression and produced test-based pressure recoveries across the operating range that met or exceeded Concorde's published performance. The functional design and analysis of the inlet was completed in nine months, with the model fabrication taking an additional three months. A shortened development phase was made possible by baselining the design from a known successful example, **Concorde's wide-throat slot inlet**; by judicious use of well-understood computational tools and methods along with the ability to upsurge CPU demand as needed using cloud computing; and by restrained parametric surveys that allowed rapid convergence toward a high-performance, though not necessarily optimized, design.

Another noteworthy XB-1 development at Boom this year is the design of the vehicle's **aerodynamically complex secondary flow path** through the extensive use of computational tools. This involved modeling the throat bleed management, engine bay cooling flow, pressure relief systems, integrated ejector nozzle and J85 variable nozzle geometry. Ejector nozzle performance was characterized using **high-fidelity computational fluid dynamic models** of the fully coupled secondary flow path. This effort improved aero-model fidelity and reduced uncertainty of the overall vehicle mission performance. Along with axisymmetric inlet concepts, the test-verified 2D inlet geometry and architecture are supporting conceptual design studies for Overture, Boom's commercial supersonic airliner.

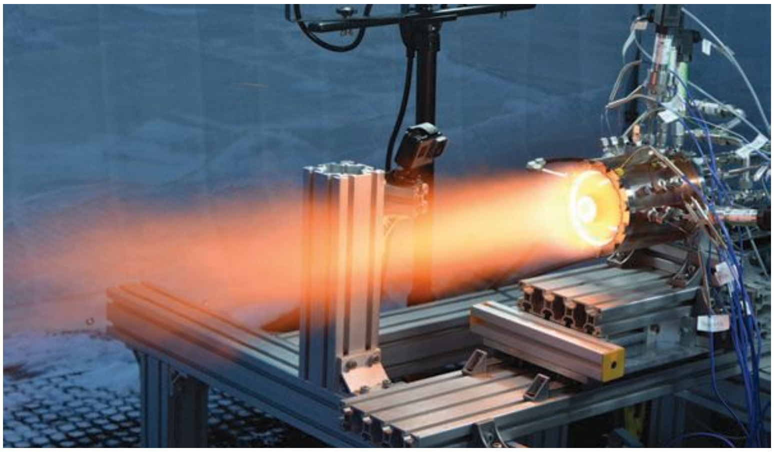
In preparation for the **X-59 Quiet Supersonic Technology** critical design review, which occurred in September, engineers from Lockheed Martin, General Electric and NASA completed NASA's low-boom flight demonstrator inlet dynamic distortion test entry at the **8-by-6-foot Supersonic Wind Tunnel** at NASA's Glenn Research Center in Cleveland in May. The test verified the acceptability of the unsteady inlet distortion characteristics. The 9.5% scale model was tested at Mach numbers from 0.3 to 1.55. A mass flow plug was used to vary inlet mass flow. Instrumentation included an 80-probe rake at the aerodynamic interface plane: 40 pitot pressure probes and 40 high-response Kulite probes in side-by-side arrangement. ★

▼ **The X-59 Quiet Supersonic Technology** 9.5% scale model was tested at Mach numbers from 0.3 to 1.55 in the 8-by-6-foot Supersonic Wind Tunnel at NASA's Glenn Research Center. NASA

Advances in science and technology of pressure gain combustion

BY AJAY AGRAWAL AND DON FERGUSON

The **Pressure Gain Combustion Technical Committee** advances the investigation, development and application of pressure-gain technologies for improving propulsion and power-generation systems and achieving new mission capabilities.



▲ **A rotating detonation engine** was tested at Nagoya University in Japan in preparation for a sounding rocket experiment planned for 2020.
Nagoya University

For propulsion and power-generation systems, **detonation-based pressure-gain combustion** has the potential to deliver higher fuel efficiency at reduced weight and footprint. This makes PGC attractive for terrestrial systems, as well as aerospace applications such as rockets and hypersonics. Recent investments have enabled quantitative flow and combustion diagnostics and improved the technology readiness level by transitioning laboratory concepts toward practice. Government, industry and academic institutions around the globe this year continued to advance PGC to a new and higher technical level.

The U.S. Air Force, Navy, Department of Energy and NASA continued to support several PGC research efforts. In June, the Air Force Research Laboratory and Innovative Scientific Solutions Inc. conducted a ground demonstration of **a rotating detonation engine, or RDE, capable of propelling a Long-EZ aircraft**. This effort demonstrated adequate thrust for takeoff and cruise operation, and acoustic measurements confirmed a safe noise level for ground operations.

The Department of Energy's National Energy Technology Laboratory funded RDE development efforts by Aerojet Rocketdyne with teammates from Purdue University, University of Michigan, University of Alabama, University of Central Florida and Southwest Research Institute. In May, the campaign conducted **hot-fire testing of a 30-centimeter diameter natural gas and air RDE** at Purdue's Zucrow Labs. Using multiple hardware configurations, the team demonstrated detonation combustion with a low loss injector and an exhaust diffuser designed to condition the exit flow for a downstream turbine.

NASA researchers continued in-house numerical investigation and optimization efforts in resonant pulse combustion and RDE systems for application to gas turbine engines. Additionally, under an internal Center Innovation Fund, a rotating detonation rocket engine nozzle optimization study and high-level rocket system benefits model development were initiated. In May, NASA solicited development proposals under Phase I Rocket Engine and Research, Development, Demonstration, and Infusion Early-Stage Innovations grants programs.

In August, researchers at Purdue University reported development of **an axial and outflow radial turbines suitable for small core RDEs**. In an effort to assess the performance of the turbine-combustor interactions, an optically accessible test rig was developed in cooperation with Spectral Energies.

In February, University of Michigan researchers **identified and quantified regions of parasitic and commensal secondary combustion** that affect the detonation wave in an RDE and identified the presence of secondary waves. Secondary combustion and secondary waves couple together, ultimately changing the stability and structure of the primary detonation wave.

In March, a team of researchers at the University of Alabama used time-resolved particle image velocimetry to measure the exhaust flow of an RDE operated on methane and oxygen-enriched air mixtures and demonstrated that the circumferential flow oscillations decreased by operating the RDE at high pressures, and a downstream diffuser further homogenized the flow for turbine applications. Activities at the Naval Postgraduate School from April through June focused on RDE parametric studies of combustor inlet area ratios, channel width and back-pressurization conditions to determine pressure-gain performance. This was done through the application of **equivalent available pressure** which is an important parameter in evaluating the performance of a PGC device.

In Japan, Nagoya University, Keio University, Institute of Space and Astronautical Science of Japan Aerospace Exploration Agency, and Muroran Institute of Technology **fabricated the preflight model of a detonation engine system** toward a sounding-rocket spaceflight test scheduled for August 2020.

At Tsinghua University in Beijing, the **effects of a perforated wall on the hydrogen/air rotating detonation** were studied emphasizing analysis of acoustics and propagation stabilities. Experiments were also performed on kerosene/oxygen-enriched air rotating detonation. Using an Eulerian-Lagrangian two-way coupling model, a 2D simulation of two-phase kerosene-air rotating detonation was conducted using high-order numerical methods. ★