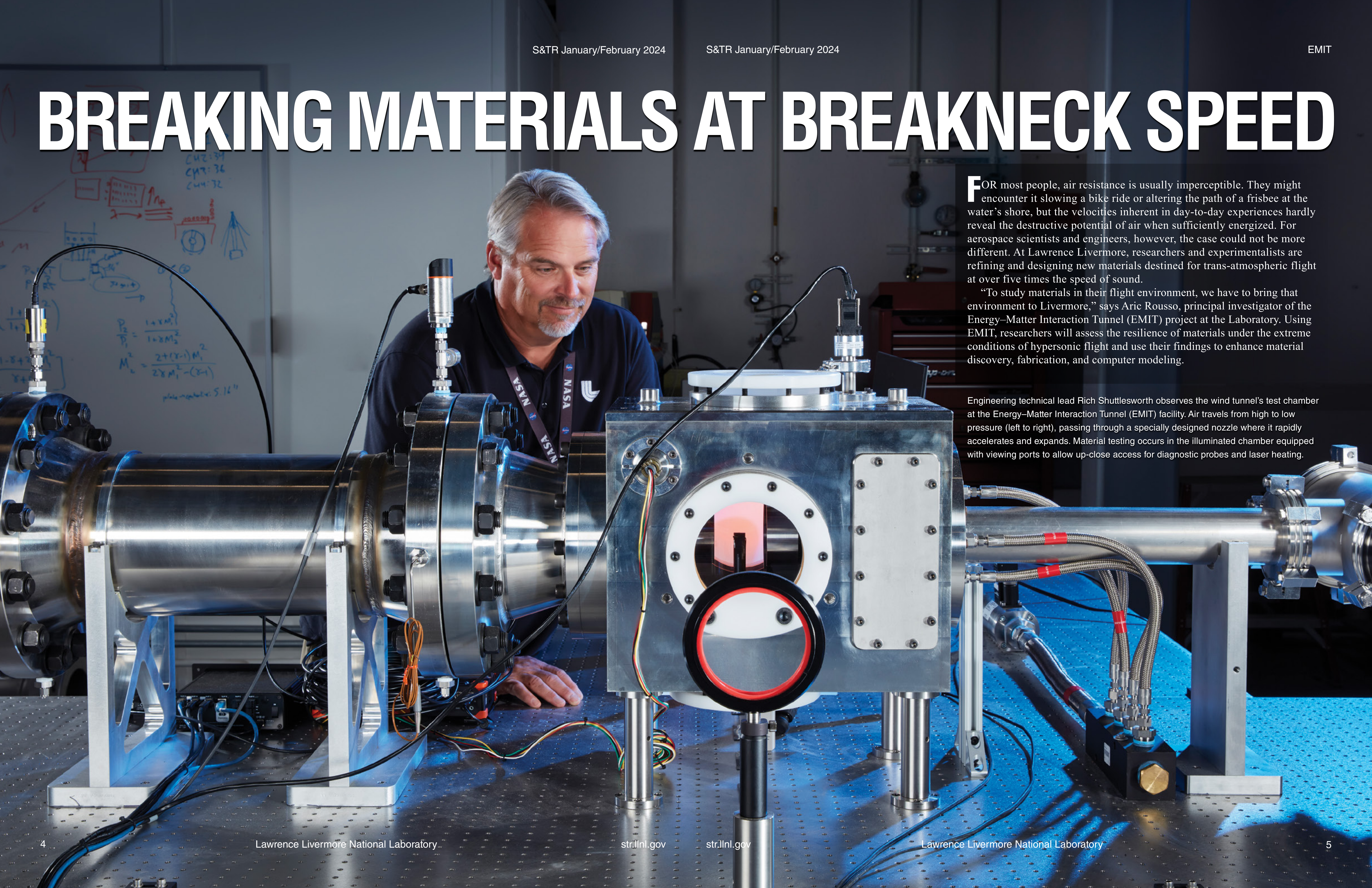
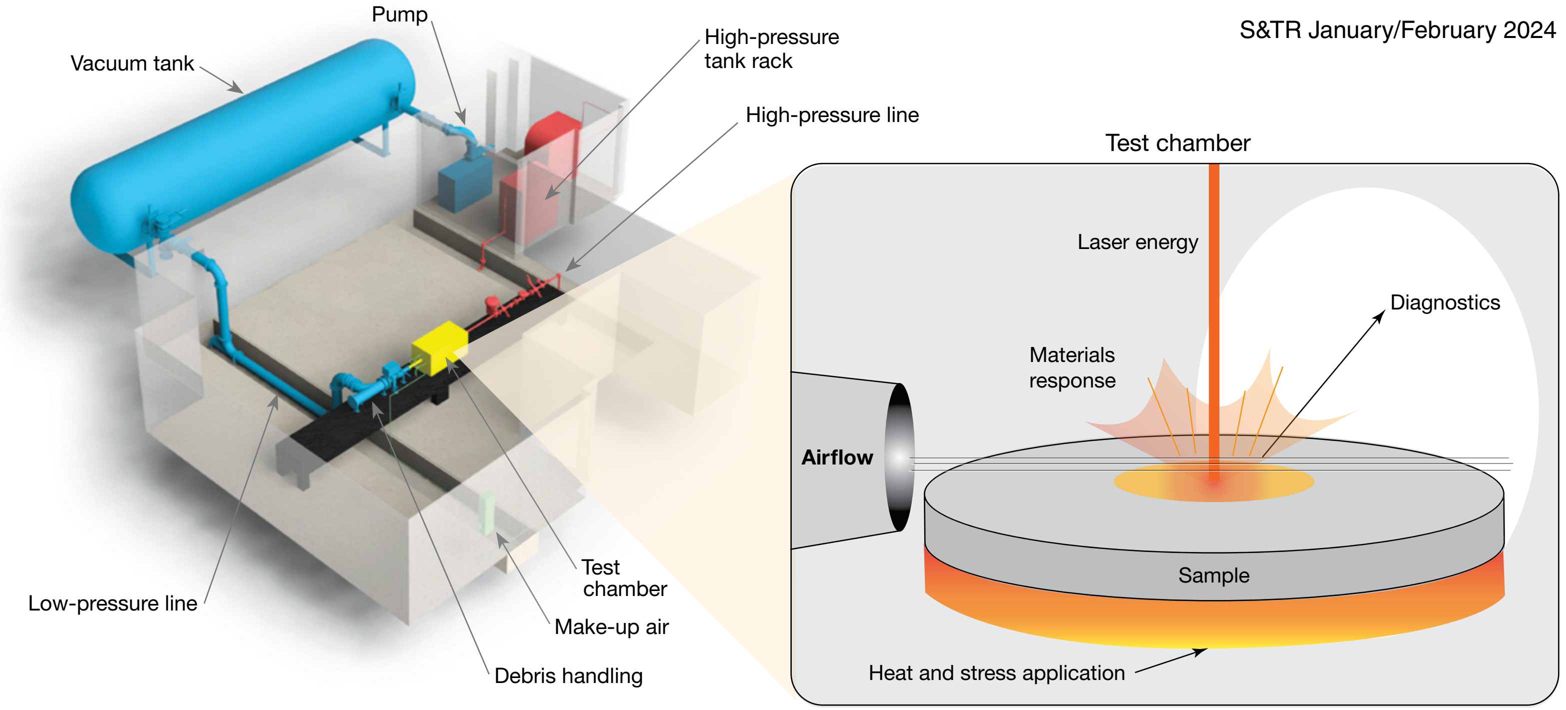
# BREAKING MATERIALS AT BREAKNECK SPEED

FOR most people, air resistance is usually imperceptible. They might encounter it slowing a bike ride or altering the path of a frisbee at the water's shore, but the velocities inherent in day-to-day experiences hardly reveal the destructive potential of air when sufficiently energized. For aerospace scientists and engineers, however, the case could not be more different. At Lawrence Livermore, researchers and experimentalists are refining and designing new materials destined for trans-atmospheric flight at over five times the speed of sound.

"To study materials in their flight environment, we have to bring that environment to Livermore," says Aric Rousso, principal investigator of the Energy–Matter Interaction Tunnel (EMIT) project at the Laboratory. Using EMIT, researchers will assess the resilience of materials under the extreme conditions of hypersonic flight and use their findings to enhance material discovery, fabrication, and computer modeling.



Engineering technical lead Rich Shuttlesworth observes the wind tunnel's test chamber at the Energy–Matter Interaction Tunnel (EMIT) facility. Air travels from high to low pressure (left to right), passing through a specially designed nozzle where it rapidly accelerates and expands. Material testing occurs in the illuminated chamber equipped with viewing ports to allow up-close access for diagnostic probes and laser heating.



As indicated in this schematic showing different sections of the EMIT facility, air is stored in high-pressure tanks (red) and injected into the test chamber (yellow) where material samples less than 5 centimeters thick are exposed to hypersonic flow, heated, and assessed by diagnostics as indicated in the inset image. Passing through the test chamber, air finally vents into the vacuum tank (blue). As needed, make-up air (green) is added to the test chamber to control pressure and simulate environments at different altitudes.

## Preparing for Takeoff

Propelling the project is the need to understand how different materials withstand the nominal rigors of hypersonic flight and, more important, how they survive off-nominal hazards. Supported through the Laboratory Directed Research and Development (LDRD) Program, the ambitious undertaking first began as an Exploratory Research project but soon grew into a Strategic Initiative project to broaden its scope and capabilities. “This project is hardware intensive. We’re developing the facility for conducting experiments as well as researching and orchestrating new diagnostic equipment needed to make precision measurements,” says Rousso.

Unsurprisingly, hypersonic environments are difficult to replicate at ground level. Hypersonic flight is not merely a faster version of supersonic flight, which already tops the speed of sound. Rousso explains that the term “hypersonic” refers to the velocity regime where gas chemistry begins to take effect. At approximately Mach 5 and above, the boundary layer of air enveloping an object is energized so violently that bonds within the air molecules can be ripped apart, leaving behind excited gas species that can chemically react with the material surface. “Now, instead of simply treating air as a fluid, we have a flying chemistry experiment,” he says.

Simulating the unique airflow dynamics, temperature, and chemical reactivity of hypersonics “is a game of give-and-take,” says Kambiz Salari, who co-launched the EMIT effort and designed the facility from the ground up. “No one facility can perfectly mimic all flight conditions simultaneously.” In flight, friction from air traversing a surface generates temperatures easily in excess of 2,000 K (1,727°C)—past the operating threshold of many metals. Such temperatures can be reproduced by arc-jet facilities to measure materials’ heat response, but at the expense of “dirty,” contaminant-ridden airflow meant to maximize material ablation. “Quiet” wind tunnels, on the other hand, minimize surface reactivity, enabling fine probing of aerodynamics by producing clean flow at sub-freezing temperatures around 100 K (-173°C) due to the rapid expansion of air from the expansion nozzle. In fact, heating is required to prevent air from liquefying.

“Researchers either get the aerodynamics highly accurate, or else the heat conditions, but never both,” says Rousso. EMIT takes a middle-ground approach, providing clean airflow and material heating. The tunnel does not house scale models of aircraft; rather, it is designed to test small, planar material samples referred to as “coupons” at half-hour turnaround times.

The unidirectional blowdown tunnel first compresses air to extreme pressure—for EMIT, up to 340 times atmospheric pressure. The compressed air is stepped down to operating pressure, passed through a series of metal screens to enhance uniformity, and released through a specially designed nozzle, at which point the air rapidly expands and cools. Unlike true atmospheric flight, this cold, turbulent-rich airflow delivers little heat flux, so the material coupons are heated by a laser source outside the chamber—substituting photons for friction. Although the entire setup straddles multiple rooms, the main experiment chamber fits on a meters-long benchtop. In fall 2023, EMIT successfully held Mach 5 tests up to one minute in duration, allowing the team to advance to materials characterization experiments.

## With the Flow, Against the Grain

At hypersonic speeds, slight irregularities can have major consequences. EMIT will study how different materials respond to kinetic and electromagnetic encounters, termed “insults,” that could arise in the flight environment, for instance hail, shockwaves, or lightning strikes. The consequences of these interactions are incredibly challenging to predict. Rousso explains, “In the event of even an extremely minor kinetic insult, we want to know if the surface of a material will erode or fracture irreparably. Or might it smooth out in flight and prove benign? Making that prediction is incredibly challenging.”

Their methodology is a familiar one at the Laboratory: “This project provides experimental data to enhance physics-based modeling and simulation, much like Livermore’s approach to stockpile stewardship” says Rousso. Whether—or to what extent—material degradation occurs implicates myriad factors. To test a slew of interaction scenarios, research teams using EMIT will vary parameters related to airflow, laser-added heating, and the character of insults while close-watching diagnostics gauge material responses in each case.

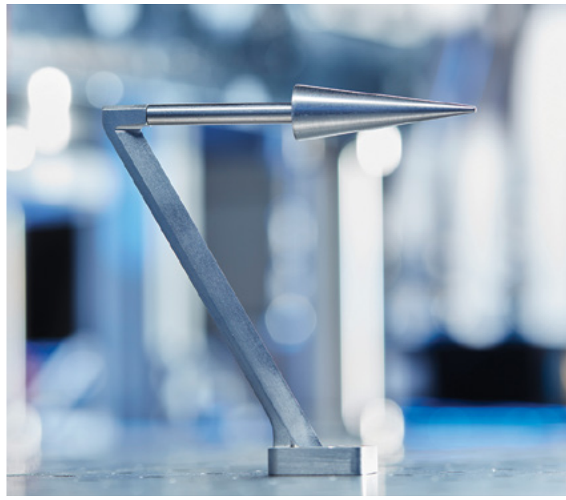
Using EMIT, Livermore will approach irreplicable hypersonic conditions under which high-quality energy–material interaction data are challenging to obtain. “To extend existing material models and predict their behavior, we need experimental data to calibrate those models,” says Salari. In earlier work studying laser impact on material surfaces at the National Ignition Facility, Salari and colleagues recognized then-current experimental resources only supported a static environment and not the airflow conditions that would realistically accompany materials in motion. According to Salari, replicating airflow is necessary to impart the surface shear and flow pressure whose interplay affects surface gas chemistry, he explains. “These factors are all coupled. If you test materials in the absence of flow, you get an entirely different response than with proper flow and pressure,” he says.

Although the facility could support computational fluid dynamics tests to observe how airflow responds to surface features—the popular depiction of wind tunnels—much of that data has already been collected and incorporated into physics codes. Instead, EMIT is devoted to testing materials. Salari stresses, “Our focus is more akin to studying how the surface of the Apollo re-entry capsule would have fared as it entered Earth’s atmosphere, encountering shocks, heat flux, and gas dissociation upon hitting increasingly dense air.

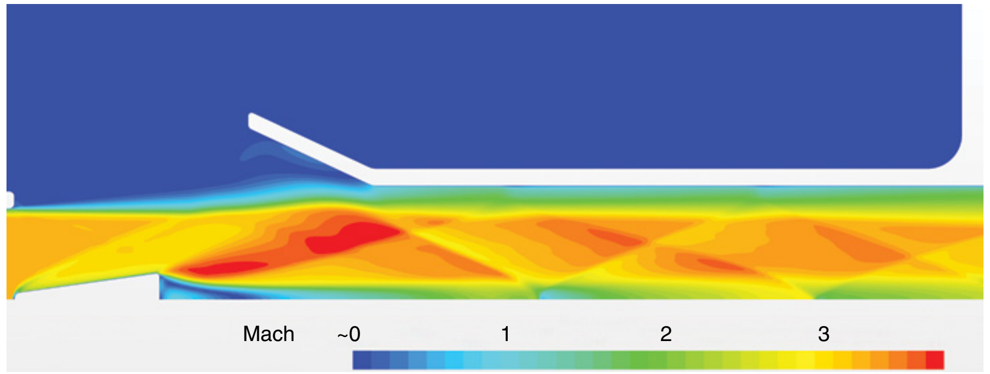
EMIT can investigate similar avenues of damage, but its support of small material samples allows for closer diagnostic access than ever before. By incorporating airflow, EMIT can also closely replicate the shockwaves inherent in flight and those representing kinetic insults. Researchers co-opt the airflow itself, deflecting it off a rigid object known as a “sting” inserted into the chamber. The sting’s carefully designed geometry forces oncoming air to rebound, falling into contact with the bow shock of the test platform to produce a modifiable shockwave that slams into the coupon.

Ultimately, EMIT will ensure material responses predicted by numerical models keep up with real-life material development elsewhere at the Laboratory. “Livermore has a wealth of material codes, but as materials become increasingly complex, we have fewer observations with which to refine computational models of their properties,” says Salari. Composite materials, he adds, are particularly challenging to model. “Even after conducting experiments, their behavior is difficult to understand, especially because micro- and macro-scale effects differ.” New composites often consist of fiber plies held in place by a matrix structure, and the collective response of multiple materials with stratified construction is much harder to predict than in that of simpler metal solids.

Aided by increasingly powerful computational capabilities such as Livermore’s mainstay multiphysics code, ALE3D, researchers can address materials’ complexity and inevitable manufacturing irreproducibility through a highly methodical approach. “Tackling entire system response at once is not feasible, so we isolate specific physics,” says Salari. For instance, because



A specially manufactured device called a “sting” is placed inside the wind tunnel. Fast-moving air rebounds off the sting’s surface to generate shockwaves, which then impinge on material samples to test their durability.



A fluid dynamics simulation shows left-to-right airflow encountering a miniature cone model used to study shocks generated by the sting. The 2D simulations, colored to visualize Mach number, are axisymmetric, revealing the full wind tunnel when mirrored over the lower horizontal.

behavior varies with heat, serial tests can increase operating temperature, perhaps revealing a trend in material response linked to heat. Then, researchers test another factor in tandem, for instance applying mechanical stress. Afterwards, damage propagation is compared to model predictions, and functional properties of the model are updated to align its results with observation.

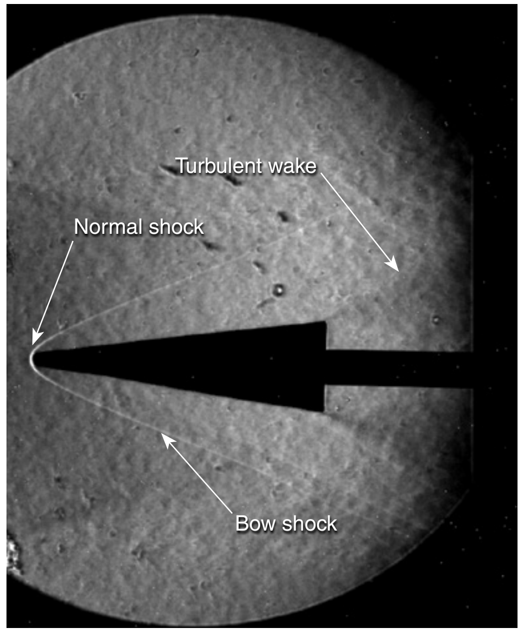
## Laser-Precision Measurement

Refining material models demands highly accurate data—and lots of it. EMIT's design guarantees up-close experiment access for dozens of diagnostic tools rarely afforded by full-scale tunnel facilities. To get the most out of each test, EMIT's vast array of telemetry "is not just concerned with the before and after. The instruments gather time-dependent data using high-fidelity, high-repetition diagnostics from multiple viewpoints," says Rousso.

Inside the temperature- and pressure-controlled test chamber, researchers use multiple instruments in concert to determine qualities of the rapidly moving air: high-speed pitot tubes face into the flow to measure the pressure of the incoming air, and a hot-wire anemometer measures air velocity by monitoring changes in conductivity of an electrified wire cooled by the airflow. All other diagnostics reside outside the chamber. "No one would stick a thermometer into a Mach 5 test chamber on a whim. Imagine the impact to the carefully controlled environment! Instead, we rely on non-invasive means of measurement," explains diagnostic team lead Ben Goldberg, who runs the Diagnostic Development Laboratory adjoining the main EMIT facility. There, the team has constructed a Small-Scale Pulsed Development Cell to serve as a testbed for carrying out dozens of preliminary experiments at high-repetition rates and significantly reduced operating cost before an experimental setup graduates to a full-blown run on EMIT.

Throughout a test, optical and laser diagnostics will closely monitor three main categories of phenomena, the first being conformation of induced airflow. EMIT uses multiple methods to measure fast-moving, invisible air. Disturbances in a fluid, whether turbulence or shockwaves, produce localized density changes that in turn alter refractive index of the medium, an effect taken advantage of by a technique called schlieren imaging. "With schlieren, quiescent air remains invisible but variations are prominent, making it a useful tool for qualitative airflow assessment. For example, 'Does this pattern look correct to the eye, or not?,'" says Goldberg. The schlieren setup nominally operates at 5 kHz but can achieve frame rates up to 20 kHz as needed to identify the most fleeting fluid phenomena.

For precise, quantitative results, flow velocity is determined by using the air itself as a measuring tool. Femtosecond Laser Electronic Excitation Tagging is a cutting-edge technique that relies on a recently acquired femtosecond laser to effectively paint the airflow with a brief strip of light so that other tools can track distortion as it continues downstream. Upon striking the fast-moving air, the laser light splits diatomic nitrogen. The relatively slow recombination of nitrogen atoms (up to 10 microseconds) produces a fluorescence detectable by cameras to perform high spatial-resolution velocimetry. Measurements closer to the boundary layer are achievable with krypton tagging velocimetry that seeds the flow with inert krypton gas. The process is complicated by substance availability and a delicate seeding process, but the benefits of each technique permit flexibility to meet the growing demands of EMIT collaborators.



Schlieren imaging detects changes in the refractive index of a moving fluid to reveal fluid dynamics. In this image taken at EMIT, supersonic airflow (left to right) interacts with a nose cone model yeilding an abrupt air pressure change that forms a normal shock perpendicular to the airflow at the front of model, a bow shock detached from its body, and turbulence in its wake.

## Material Responses Inside and Out

With airflow measured, the team can turn to EMIT's main charge: characterizing material responses, which in a hypersonic environment are mechanical and chemical. Observing slight changes to a small, flat, mostly rigid object is no straightforward task. Loaded flush into a wedge-shaped sample holder, the coupon is studied by laser light trained at or near its surface. Mechanical deformations such as stress, strain, and bending cause subtle changes to the coupon's surface geometry, altering the deflection angle of incident laser light. As a result, the microscopic pattern of light reflected by a small surface section experiences spatial and temporal shifts. Once a rapid series of images is collected during a test, the Computer-Aided Speckle Interferometry (CASI) process algorithmically deduces the material response that must have occurred to produce the changes in light reflected from a region.

While CASI can amplify surface effects, energy–matter interaction is not confined to a material's outermost layer; responses can propagate through its interior, or "bulk," possibly with deleterious effects invisible from the outside. "Speckle interferometry shows changes to the surface, but we need another technique to probe below the surface," says Goldberg. The team turned to laser-based ultrasonics (LBU) to measure changes within the bulk structure in a way that is non-invasive and resistant to high temperatures.

Diagnostic team lead Ben Goldberg inspects a series of mirrors under the hood of EMIT's newly acquired femtosecond laser system used to measure airflow and chemical effects.

LBU transforms light into sound and reads the effects once again with light. During a test, rapid laser pulses on the order of nanoseconds irradiate the coupon's surface, briefly energizing and locally expanding the material to produce periodic pressure waves—in essence, sound waves—that travel throughout the bulk material. If the waves encounter underlying irregularities, acoustic distortions or echoes will be detected by another laser light surveilling the surface for these tiny undulations. With LBU, the researchers can detect and characterize structures such as sub-surface cracks or cavities indicating loss of material from solid to gas phase (outgassing).

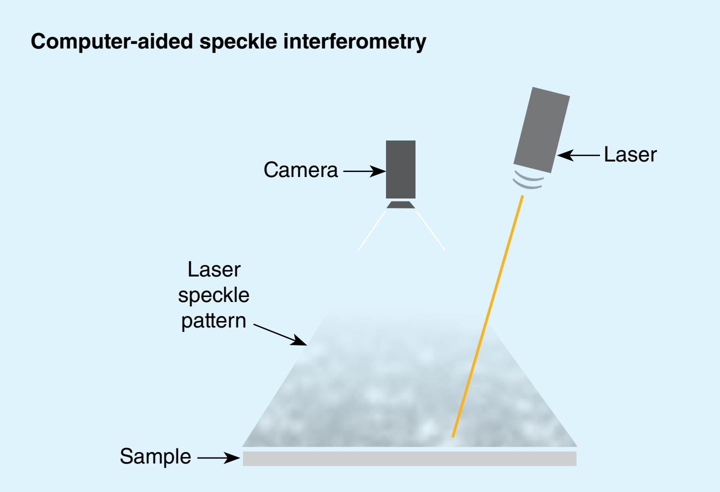
In 2022, the EMIT team validated their implementation of CASI and LBU in a Mach 10 environment housed at NASA Langley Research Center in Virginia, the first in situ demonstration of the techniques in a hypersonic regime. "The publications that came out of the Mach 10 effort are pieces of the larger EMIT story. They confirm that we can obtain quality measurements using these methods in hypersonic flow," says Goldberg. The team has since completed a follow-up experimental campaign at the University of Arizona's in-draft wind tunnel facility where, using the high-throughput setup, LBU measured flow-induced temperature changes of materials. Once heated to 120°C in still air, the rapid onset of high-speed airflow cooled the bulk material by 40°C within 15 seconds as measured by an interferometer, verifying LBU could be used similarly on EMIT.

The story continues with the team's plans to equip EMIT with more diagnostics targeting the final class of phenomena: gas chemistry. In hypersonic environments, ionized air rushing near a surface heightens the likelihood of chemical reactivity, especially in instances of damage, and the substances outgassed by the material travel outward into the flow leaving behind the voids detected using LBU. Knowing the behavior of different gas species—their temperature, dispersal, and reactivity—is vital for avoiding unwanted chemistry and damage propagation. EMIT will employ a range of in situ fluorescent and spectroscopic techniques to assess the location of species of interest and the temperature of gases ejected from the material surface—a surprisingly confounding task, according to Goldberg. He explains, “If I say the air temperature in my office is 22°C, that single measurement makes sense because, although air molecules continue to move about, the static air is near equilibrium. Hypersonic conditions are far from equilibrium. Temperatures there cannot be described by one value; instead, several measurable degrees of freedom exist at the molecular level, including translation, rotation, vibration, and electronic energies of molecules.” The immense effort of equipping EMIT has paved the way for another LDRD project to develop state-of-the-art gas phase diagnostics.

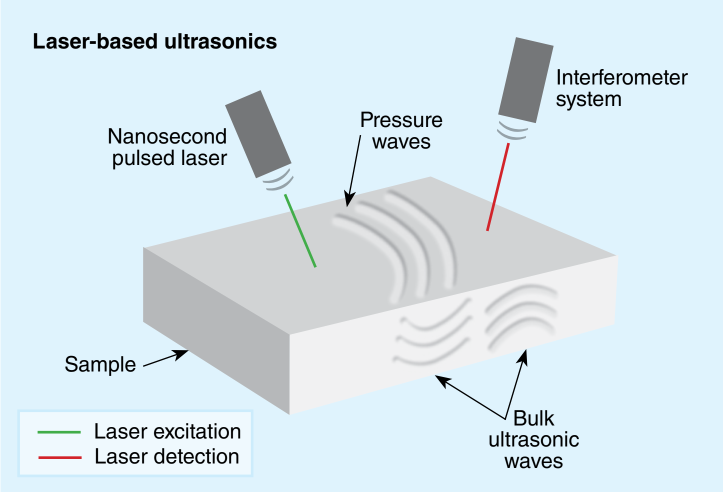
## Achieving Liftoff

For now, team priorities are testing the acquired equipment and porting diagnostics from the Development Laboratory to EMIT as they strive to overcome the effects of material and labor complications introduced by the COVID-19 pandemic. State-wide shelter-in-place requirements had made on-site construction work difficult to coordinate, and supply chain backups jeopardized project timelines. “Components that once had six- to eight-week lead times were suddenly out 40 weeks,” recalls Rousso. “We did the best we could, working remotely to hit the ground running once possible, but we were still incredibly limited.” The project timeline was not the only instance of turbulence. “People’s lives were changing,” he adds. “As they re-evaluated their career and their involvements amid COVID, personnel challenges were a natural consequence.” The experience has been somewhat of a whirlwind introduction to executing such major projects for Rousso, who came to Livermore in 2019 after completing a Ph.D. in aerospace engineering. Following turnover of earlier principal investigators during the pandemic, Rousso stepped in as project lead to manage EMIT’s trajectory.

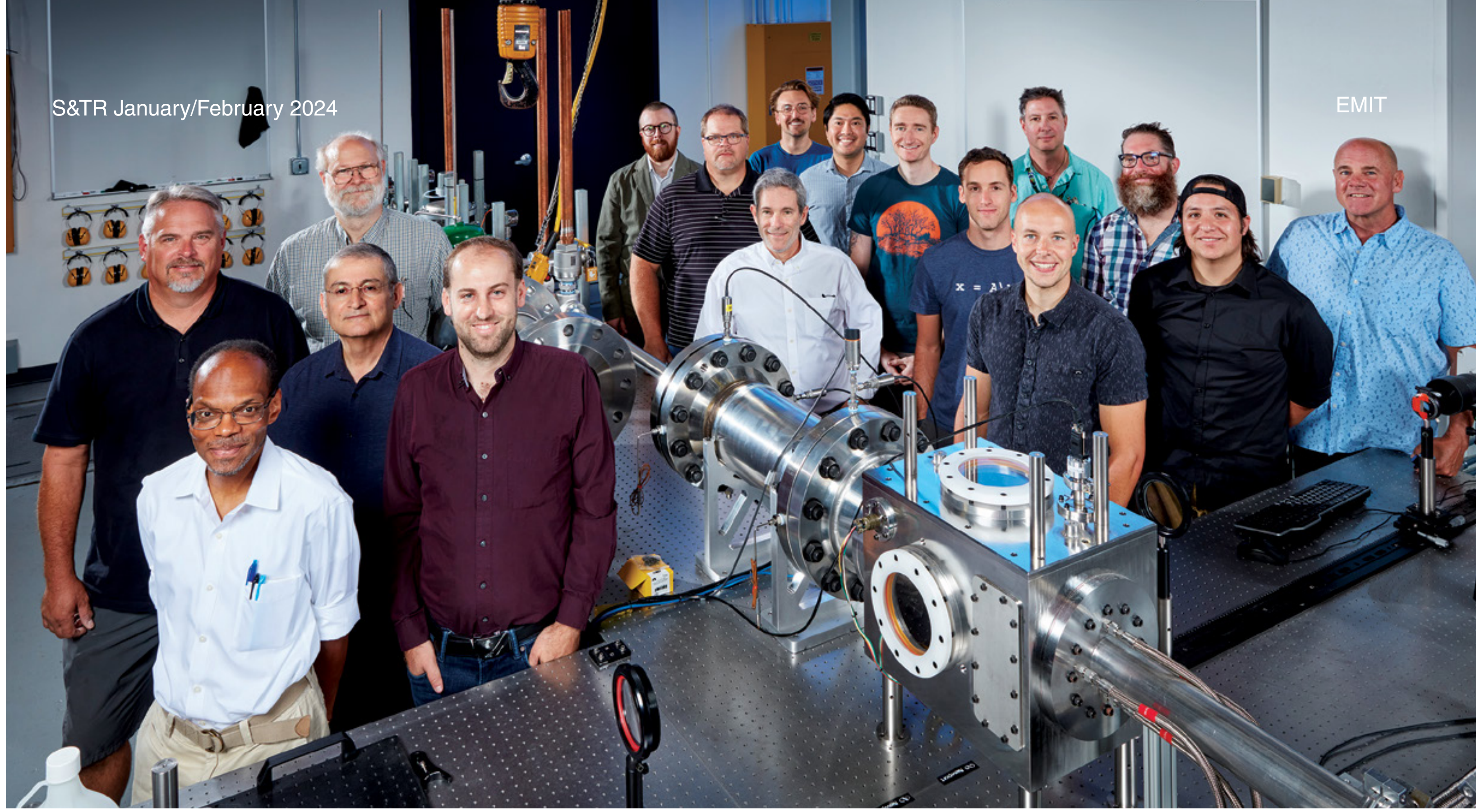
Having passed the brunt of the pandemic, an impressive amount of work has led EMIT to materialize. Although not the only institution investigating hypersonics, Livermore recognizes the need for its own wind tunnel. The Laboratory has already cemented itself at the forefront of developing new, complex materials and refining their associated fabrication processes. As EMIT powers up for regular use, Laboratory research centers now have a convenient location to test innovations such as additively manufactured metal alloys and composite materials. The team is currently in talks with material development groups at the Laboratory looking to take advantage of the new capability. The fact that the tunnel does not work with whole plates or components but rather batches of small, mostly flat samples makes EMIT an ideal space for materials testing. In early stages, material development yields samples on the scale of inches—exactly the size EMIT is built to handle with quick turn-around.



Computer-aided speckle interferometry amplifies microscopic changes to the material sample’s surface. The material’s microstructure reflects a distinct speckle pattern when struck by laser light, and snapshots of the pattern’s evolution over the course of an experiment can reveal superficial mechanical deformation.



In laser-based ultrasonics, laser energy causes periodic material expansion, producing pressure waves that propagate across and below the material’s surface. Interior cracks or voids formed during the test are revealed by delays in the expected time of arrival between a wave crossing the surface versus through the interior (bulk).



The EMIT team consists of scientific researchers, engineers, technicians, and graduate students. Pictured left to right: Rich Shuttlesworth, Gregory Markham, Kambiz Salari, G. Fred Ellsworth, Aric Rousso, Erik Busby, David Payne, Joe Zaug, Brandon Replogle, Jordan Lum, Scott Steinmetz, Evan Garrison, Spencer Jeppson, Lionel Keene, Ben Goldberg, Allen Palacio Montanez, and David Ethridge. Not pictured: Jason Glover, Hansel Neurath.

Expanding on EMIT’s utility, Goldberg says, “Many major, national-level facilities often have two- to three-year waitlists to perform testing. Once there, strict scheduling can demand binary priorities—‘Did this particular test work, or not?’—rather than allow extensive testing to definitively explain the physics behind an experimental outcome.”

Complex mechanical and chemical interactions are not exclusive to materials in the hypersonic domain. As such, the wind tunnel apparatus and its diagnostic tools are separate, allowing the diagnostics to go on the road. “For example,” Rousso explains, “research at Livermore’s High Explosives Applications Facility (HEAF) often deals with similar effects to those seen in wind tunnels. We developed our diagnostics with portability in mind so that they’re easily wheeled over to HEAF for their work.” The suite of high-fidelity laser diagnostics can be delivered to facilities across the Laboratory or across the country.

Extensive collaboration is necessary to develop and validate performance of the numerous instruments involved. As noted by Livermore’s Erik Busby, who manages laser acquisition and external collaborations, the EMIT team drew upon specialized expertise from researchers at NASA and several universities such as the University of Colorado at Boulder through the Laboratory’s Stewardship Sciences Academic Alliance program. They undertook five experimental campaigns at facilities nationwide, including the University of Arizona, the Arnold Engineering Development Complex in Tennessee, and CUBRC, a non-profit defense research center in New York. With maturation of the project, the EMIT group itself has grown, bringing in new technical hires and graduate researchers.

In addition to future on-site users, collaborators will be eager to make use of EMIT’s unique capabilities. “EMIT is already building a base of users across academia and the national lab system,” says Busby. “Wind tunnels are often delicate facilities not intended to withstand material disintegration. EMIT, however, is designed to take materials to the point of failure, which is necessary to understand off-nominal conditions.” Conversely, EMIT’s diagnostics will be integrable with other wind tunnels, broadening data collection potential. “In many ways, we’re a stepping stone,” says Rousso, “and we’re excited to open for business.”

*— Elliot Jaffe*

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