Lawrence Livermore National Laboratory

Science & Technology REVIEW

January/February 2024

HYPERSONIC MATERIALS TESTING

Also in this issue:

- National Security Affairs Program
- Materials Facilities Upgrade
- Academic Collaboration

About the Cover

Before advanced aircraft can travel at several times the speed of sound, scientists need to know that their construction can withstand such unforgiving environments, where air friction can incinerate and vaporize metals. The article beginning on p. 4 introduces Livermore's Energy–Matter Interaction Tunnel (EMIT), a new facility that empowers researchers to mimic the rigors of hypersonic flight. Pictured is Livermore's Ben Goldberg assembling the Small-Scale Pulsed Development Cell to test diagnostics setups on EMIT. The cover conveys the EMIT team's dedication throughout the project's many developmental phases and the necessary adjustments to unveil a powerful experimental apparatus.

Cover design: Mark Gartland; Photography: Garry McLeod

About *S&TR*

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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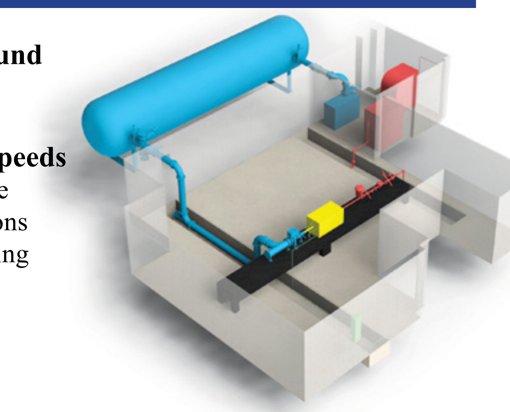
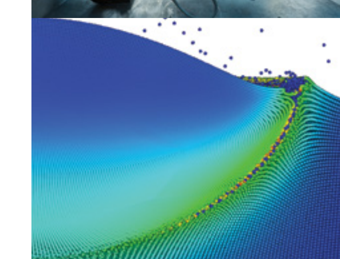


Research Highlights



Departments

Connecting Humidity with Corrosion

Bare aluminum surfaces immediately react with air to form aluminum oxide, which then becomes confined under a nanoscopic film of condensed water vapor. Scientists at Lawrence Livermore performed simulations with Ruby, a Livermore supercomputer, to uncover why atmospheric corrosion of aluminum metal is controlled by the relative humidity in the air. Their research is featured in the June 14, 2023, issue of the *ACS Journal of Applied Materials and Interfaces.*

The team used all-atom molecular dynamics simulations to demonstrate how aluminum ions diffuse through condensed surface water and lead to the formation of corrosion pits. They found that aluminum ions tended to localize near the air-water interface and were completely absent near the oxide. This tendency contributed to height-dependent transport properties within the water film, with atoms diffusing more quickly as the air-water interface was approached. The height of the surface water itself depends on humidity in the air, linking humidity with diffusion rate and, therefore, corrosion rates.

These first-ever findings into the explicit role of humidity on aqueous ion transport will lead to better assessments of corrosion rates used to predict aluminum component lifetimes. "The results highlight that capturing unusual nanoscale effects and their dependence on humidity is essential when modeling atmospheric corrosion at larger length scales," says Livermore scientist Jeremy Scher, the paper's lead author.

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Metasurface Optics Design Breakthrough

Metasurface optics design involves carefully altering the surface of a material to have different properties than the bulk of the material. A team of Laboratory researchers have refined a metasurface process to create taller surface alterations without increasing the space between them, which has important implications for anti-reflective (AR) optics. The team aims to create more durable and stable optics by removing the need for broadband AR coatings, instead achieving anti-reflectivity by creating nanofeatures in the surface of the optic itself. Livermore scientist Nathan Ray is first author on a paper presenting the team's results, which appears in the June 19, 2023, issue of *Advanced Optical Materials*.

To achieve anti-reflectivity over a range of wavelengths, the features need to be spaced closer together than the shortest wavelength, and about as deep as half the longest wavelength. The team created a technique called "seeded dewetting" to build up mask nanoparticle height without compromising the necessary spacing between them. The result is a silica glass AR technology capable of eliminating reflected light over an unprecedented wavelength range and at a large span of incidence angles.

Applications for the new AR technology include uses in lasers at the National Ignition Facility and photovoltaic cells, among others. "We can now cover bandwidth range all the way from ultraviolet to wavelengths larger than 2 microns, which was not possible with existing technology," says Eyal Feigenbaum, the study's principal investigator.

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Observing Confined Water's Behavior

Carbon nanotubes (CNTs) are useful for studying confinement effects on water at scales comparable to the diameter of a single water molecule. Confinement modifies water properties by altering the structure of the hydrogen bond network. However, explaining the experimentally observed differences between the hydrogen bond network of confined water and the bulk liquid has remained a challenge. Livermore scientists revealed the unique hydrogen bonding behavior of water confined in CNTs by combining large-scale molecular dynamics simulations with interatomic potentials constructed using machine-learning methods. Their findings, appearing on the cover of the June 22, 2023, edition of *The Journal of Physical Chemistry Letters,* have the potential to advance energy storage and ion-selective membranes for water desalination.

The team computed the infrared spectrum of confined water then compared it with existing experimental measurements. They found different effects on water structure between CNTs with diameters larger than 1.2 nanometers and smaller-diameter CNTs. The larger-diameter CNTs saw more disruptive effects on hydrogen bonding, leading to a more disordered structure than the bulk liquid. Smaller-diameter CNTs led to the formation of exotic phases of ordered water, such as nanotube ices and single-file structure.

This study improves simulations of confined water for future exploration. "Our work offers a general platform for simulating water in CNTs with quantum accuracy on time and length scales beyond the reach of conventional, first-principles approaches," says lead author Marcos Calegari Andrade.

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Innovation Beyond the Speed of Sound

KEEPING pace with a rapidly changing global security environment requires innovation such as developing weapons systems that withstand harsh environments, defend against adversaries, and serve as a deterrent. For example, weapons systems that deliver warheads using hypersonic glide vehicles are rapidly becoming a significant challenge this century. Unlike conventional ballistic missiles, which follow a predictable path, the in-flight maneuverability of hypersonic glide vehicles allows them to better evade air defenses. These vehicles travel through the atmosphere at speeds over Mach 5 (five times the speed of sound), fast enough to ionize air molecules.

Ionized hypersonic flow is an especially harsh environment for hypersonic vehicles, posing a particular challenge for material development. Key scientific questions related to material survivability, threat interactions, and unexpected environments remain unanswered. The design and development of a unique hypersonic test capability for understanding these material issues including threat environments is the subject of this issue's feature story.

Because in-flight testing is prohibitively expensive, wind tunnels are the tool of choice for vehicle testing. The nation supports many wind tunnel facilities large enough to test vehicle control surfaces, nose cones, and bodies. At the national level, however, multiyear waitlists for testing are not uncommon. Most wind tunnel facilities cannot support enough different types of experimental campaigns needed to develop effective materials, and most lack access for high-fidelity, in situ probes to fully understand and predictively model extreme-condition material evolution and response.

Livermore's Energy–Matter Interaction Tunnel (EMIT) was conceived to address these gaps. EMIT—designed, built, and tested at Lawrence Livermore as part of a Laboratory Directed Research and Development Program Strategic Initiative—is a compact wind tunnel with a test chamber large enough to study material physics under myriad conditions, providing the high experimental throughput necessary for material testing and development. EMIT offers close-up access for high-fidelity diagnostics capable of providing the types of data needed to validate and update hypersonic flow fluid dynamic simulations and a test environment that allows for delicate, in situ probes. The EMIT team achieved their central goals, recently demonstrating Mach 5 flow and successfully developing and deploying novel, non-invasive material diagnostics.

The three highlights in this issue of *Science & Technology Review* showcase how Lawrence Livermore is further expanding its capabilities around national security leadership and policy, revitalizing existing infrastructure, and building upon collaborative relationships within and outside of the Laboratory. The first highlight describes how participation in Texas A&M University's National Security Affairs Program (NSAP) supports the Laboratory's emerging leaders, strengthening their contributions to U.S. national security decision making. NSAP fellows complete an executive-level, graduate studies program that enhances understanding of the security policies and policymaking processes that Livermore's research informs. Past participants, including Laboratory Director Kim Budil, share insights on how engagement in the program shaped their leadership trajectory and changed the course of their careers.

The second highlight demonstrates how revitalizing Livermore's infrastructure with new equipment and improved workspaces can enhance research efforts and expand opportunities for intra-Laboratory collaboration. A concerted effort to refurbish the Materials Science Division's headquarters in Building 235 has already had a positive impact by offering rapid, high-energy laser shots for experimentation outside the National Ignition Facility, enabling improvements for custom additive manufacturing feedstock production, and simulating extreme temperatures and loading for new material development.

This issue's final highlight describes how Lawrence Livermore's Academic Collaboration Team (ACT) partners with diverse universities around the country to attract new talent to the Laboratory. ACT partners doctoral students with Livermore researchers, giving the students applied science experience in a national laboratory setting and our scientists the opportunity to expand research portfolios by exposure to new ideas.

All the articles exemplify Livermore's leadership on key national security initiatives through research, collaboration, and expanded Laboratory capabilities. With these developments, the wind is now at our backs to pursue the bold innovative science and technology that will advance National Nuclear Security Administration and other mission-focused programs.

■ **Jeffrey Bude** is a deputy principal associate director for NIF and Photon Science.

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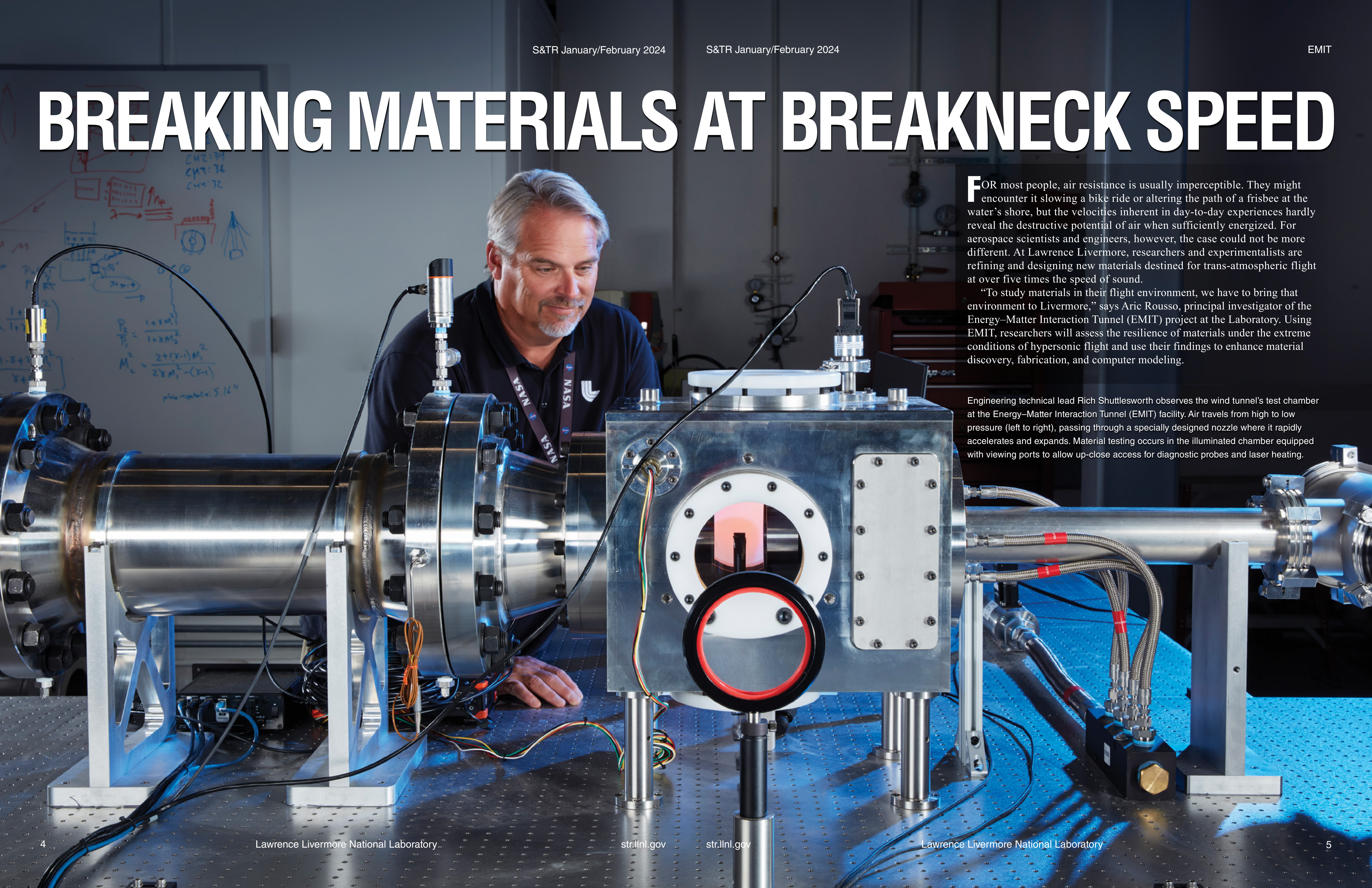
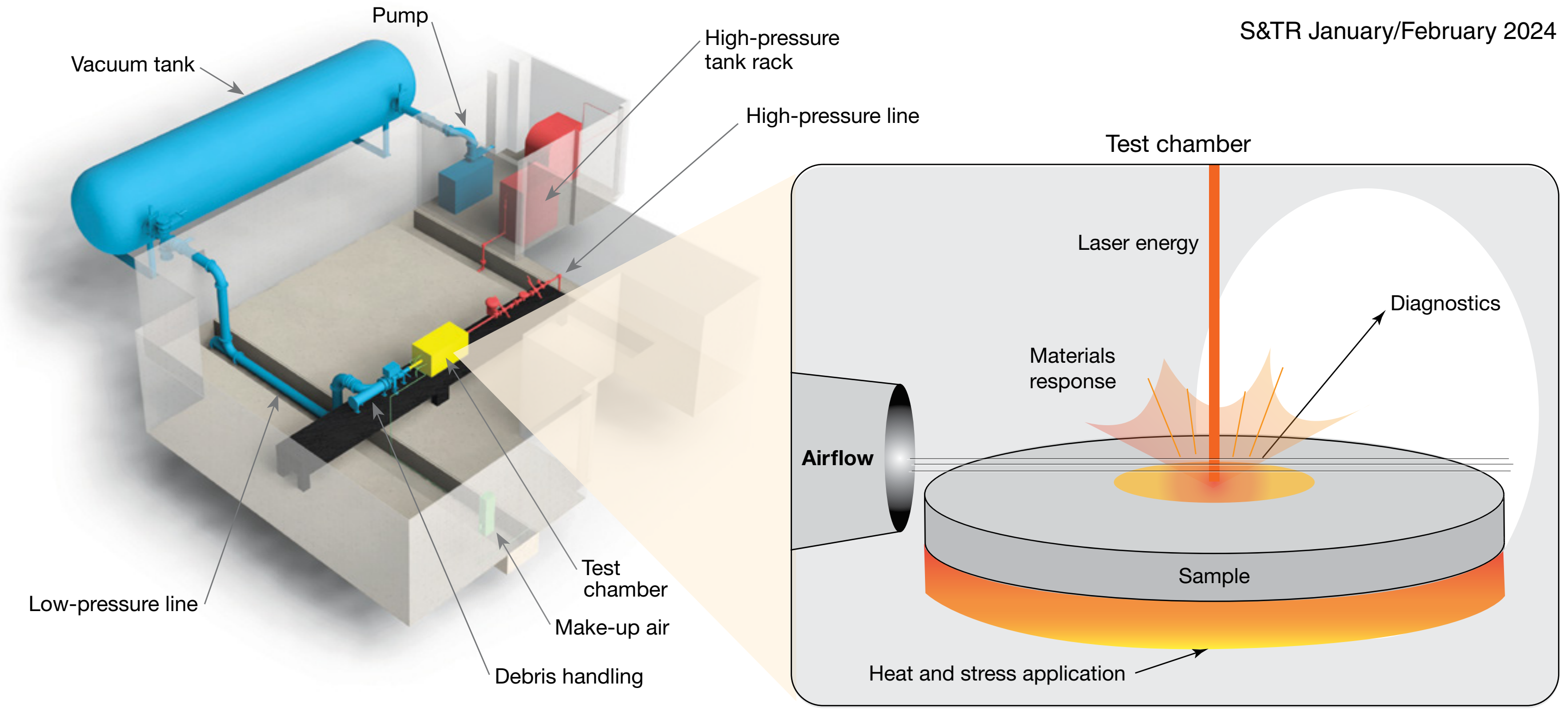
BREAKING MATERIALS AT BREAKNECK SPEED



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.

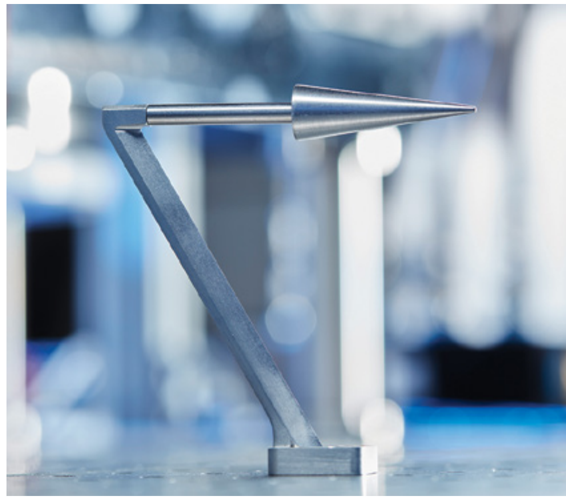
Using EMIT, Livermore will approach irreplicable hypersonic conditions under which high-quality energy–material interaction data are challenging to obtain. "To extend existing material models and predict their behavior, we need experimental data to calibrate those models," says Salari. In earlier work 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.

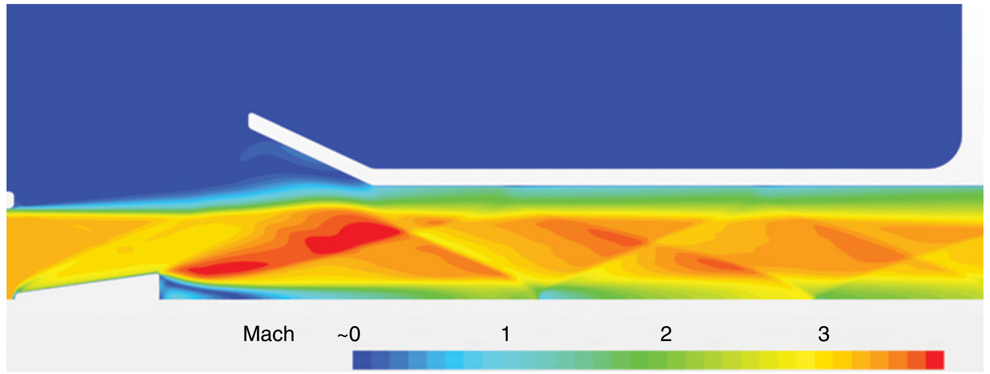
EMIT can investigate similar avenues of damage, but its support of small material samples allows for closer diagnostic access than ever before. By incorporating airflow, EMIT can also closely replicate the shockwaves inherent in flight and those representing kinetic insults. Researchers co-opt the airflow 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.

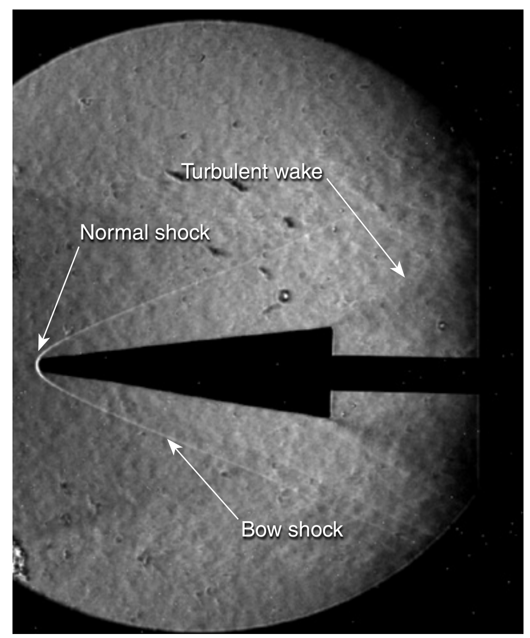
Laser-Precision Measurement

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



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.

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.

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

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) to measure changes within the bulk structure in a way that is non-invasive and resistant to high temperatures.

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).

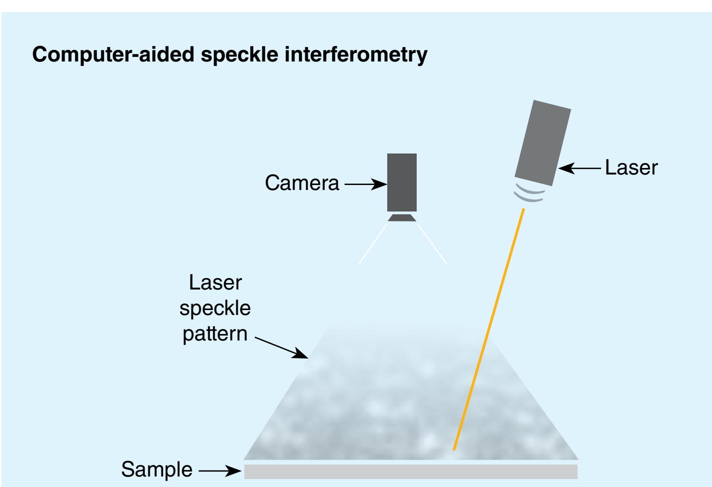
In 2022, the EMIT team validated their implementation of CASI and LBU in a Mach 10 environment housed at NASA Langley Research Center in Virginia, the first in situ demonstration of the techniques in a hypersonic regime. "The publications that came out of the Mach 10 effort are pieces of the larger EMIT 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.

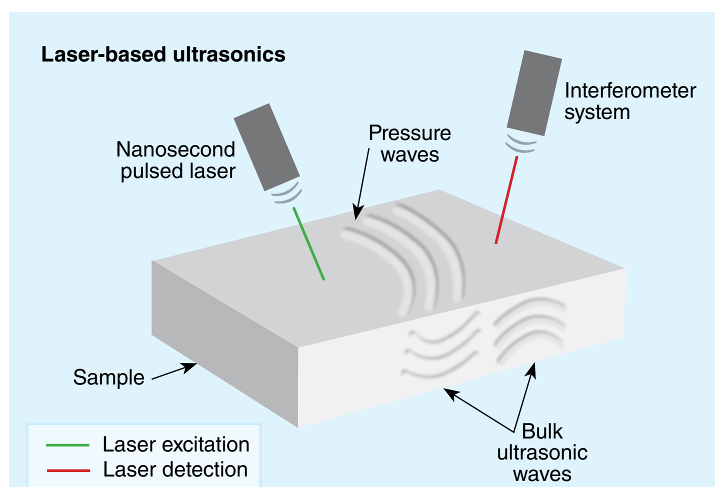
Achieving Liftoff

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.

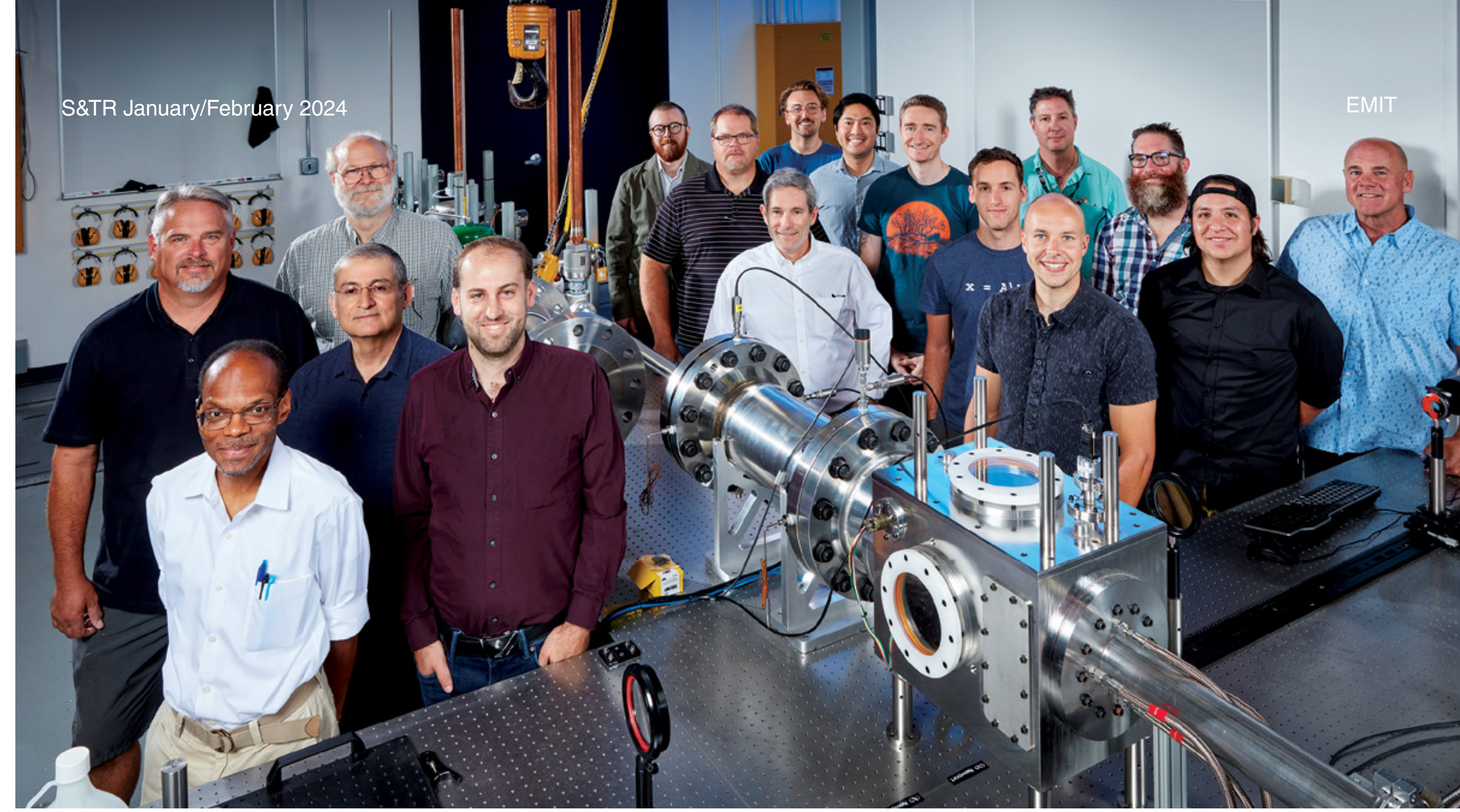
Having passed the brunt of the pandemic, an impressive amount of work has led EMIT to materialize. Although not the only institution investigating hypersonics, Livermore recognizes the need for its own wind tunnel. The Laboratory has already cemented itself at the forefront of developing new, complex 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

For further information contact Aric Rousso (925) 423-3458 (rousso1@llnl.gov).

EXPANDING NATIONAL SECURITY CAPABILITIES

SINCE its inception in 1952, Lawrence Livermore's mission has been national security—ensuring the safety, security, and effectiveness of the nation's nuclear stockpile. In recent years, the mission has broadened as dangers ranging from nuclear proliferation and terrorism to cyberattacks and climate change increasingly threaten national security and global stability. Livermore research is fundamental to national security and defense strategies, and the Laboratory bears a continuing responsibility to provide insights on policy as well. Livermore regularly informs the legislative and executive branches of the United States government and contributes to multiple national security policies, including the Nuclear Posture Review, the National Security Strategy, and National Defense Strategy, among others.

The Laboratory's leadership empowers staff to further enhance skills and approaches to critical thinking and problem solving around national security policymaking. Since 2008, Lawrence Livermore has partnered with the Bush School of Government and Public Service's National Security Affairs Program (NSAP) at Texas A&M University. Led by the program's core instructors, Dr. Jasen Castillo and Colonel Mike Jackson, NSAP provides executive-level education informed by the strategic national security role of Department of Energy (DOE) national laboratories and offers a certificate in National Security Affairs. Livermore helps shape NSAP course curricula and enables personnel to attend through financial support and by creating an environment in which they can solely focus on the coursework.

National Security Affairs Program (NSAP) fellows travel to Texas A&M University's Bush School of Government and Public Service in the early stage of the program to attend courses. (Photo courtesy of Laura McKenzie, Texas A&M University Division of Marketing & Communications.)

Each summer, NSAP participants travel to College Station, Texas, to attend two courses focusing on fundamentals of nuclear deterrence theory, space, cybersecurity, counterterrorism, counterintelligence, and U.S. military power from professors with relevant, real-world experience. Participants then complete the remaining two courses remotely from Livermore during the fall and spring semesters.

Expanded Perspective

According to Eric Schwegler, director of Livermore's Academic Engagement Office (AEO), the Laboratory's motivation in establishing NSAP is an acknowledgment that even with all the Laboratory has to offer to the policymaking

world, the expansion of these contributions enables Livermore to play a more useful role within the broader national security environment. Participants in NSAP have an opportunity to study national security and policy issues beyond the normal course of their work. "NSAP gives participants an expanded perspective on the Laboratory's mission focus areas, the ramifications of what we do, the importance of our work for the country, and how the research we do is connected to the national security decisions leaders in Washington, D.C., make," says Schwegler. "The program puts their research and other responsibilities at the Laboratory in the context of what's happening globally."

Mildred Lambrecht, who administers AEO's education programs, sees NSAP as a unique opportunity for Livermore staff to learn and develop leadership skills. She says, "Throughout the program, Fellows build skills, including communication, that reinforce leadership capabilities. I'm inspired by how a small group of staff from different directorates work together and support each other to complete such an intense and fast-paced program. They rely on each other, motivate one another, share different approaches to learning, and build overall team skills."

Laboratory Director Kim Budil, who participated in the first NSAP cohort from Livermore, has continued to offer strong support for Livermore's engagement. "Because of the nature of our mission, our leaders and future leaders must be aware of the context in which we work. The overlay of national security policy cannot be separated from our work, so when our staff feel more comfortable operating in the policy community, we can all be more effective in our roles," she says.

Nuclear deterrence theory—the study and application of how threats or limited force by one party can convince another party to refrain from certain actions—is foundational to Livermore's mission. Following from this theory, the probability of direct war between nuclear powers decreases,

Lawrence Livermore personnel participate in the NSAP through support from the Laboratory's Academic Engagement Office. Pictured are some of the past participants and staff who help administer the NSAP fellowship at Livermore. From left to right: Mildred Lambrecht, Rebecca Nikolic, Kim Budil, Ashley Bahney, and Trevor Willey.


Kim Budil


Jack Kotovsky


Michael Pivovaroff


Ashley Bahney


Rebecca Nikolic


Trevor Willey


Jennifer Matzel


Vincenzo Lordi

but the probability of minor or indirect conflicts increases. National security strategies and applied scientific research must account for both sets of circumstances. NSAP focuses on nuclear deterrence theory. Other courses on space, cybersecurity, counterterrorism, counterintelligence, and U.S. military power highlight how Livermore's research is critical to keeping the country safe and convey the dangerous consequences of national security information falling into the wrong hands. For example, the counterterrorism class during Budil's cohort enacted the scenario of a potential terrorist-induced chemical spill. Budil recalls, "Because our group had real-world experience of what was truly doable, not just possible, we created a very realistic scenario," she says.

Participants from later cohorts emphasize how NSAP strengthened their connection to Livermore's mission. Rebecca Nikolic, recently promoted to the role of Director of Science and Technology Institutional Assessments at Livermore, says, "NSAP deepened my understanding of the breadth of national security issues our work is connected to, whether economic, technical, or resource related. To lead national security research and development without this knowledge risks missing the big picture." Trevor Willey, a group leader in nanoscale, surface, and interface science, adds that the program helped him shift the focus of his work to real-world scenarios, saying, "When interacting with headquarters and other stakeholders involved in nonproliferation or stockpile stewardship, I now have a better understanding of how the role we play complements other government organizations."

Enhanced Skills

Although formal political science coursework was new to many participants, its relevance to their research at Livermore and how that research could be applied in realistic scenarios was immediately clear. Jack Kotovsky, a mechanical engineer and section lead for micro-technologies, says, "I've always done very technically focused work and had never taken a political science course in my life. This program was new and different, but it made clear early on how political science related to the day-to-day work that I and others at the Laboratory are doing." Even for Livermore staff with a background in political science, such as Ashley Bahney, former acting chief of staff to Budil and current acting deputy chief of staff, the program proved valuable. "Although I had studied international relations, I gained so much from this program because the professors challenged us to think beyond our established ideas of how things work in the real world and to apply the nuclear deterrence and national security theories we were learning," she says. "We got down to the brass tacks of what the actual situations are and how they come together for us in our roles at Livermore."

NSAP also helped Livermore participants more effectively communicate what knowledge, results, and expertise Livermore has to offer to policymakers. Michael Pivovaroff, associate deputy director for Science and Technology, has applied what he learned to evolving geopolitical circumstances. "I'm a 'space guy.' The program helped me think more about the rules of the road for competition in space and the related security needs. I don't think I would have had the confidence to learn from and talk with experts or to provide intelligence-informed assessments if I hadn't done this program," he says.

For Vincenzo Lordi, deputy division leader for Materials Science, the program improved how he presents information to policymakers. "Scientists often want to tell a story and keep the audience on the edge of their seats about the conclusion," says Lordi. "I learned to state my conclusions quickly, up front, and support them afterwards when presenting a white paper to stakeholders." Lordi admits he was not expecting to gain this writing skill from the courses. Now, he uses it all the time. "Political papers are short and to the point. We were trained to use the most precise language and least number of words to get a message across," he says. The NSAP courses also led Lordi to new leadership and research paths at Livermore in which he uses his technical skills to provide assessments to policymakers.

Investment in the Future

Budil was an associate program leader in the Weapons Program at Livermore when she participated in NSAP. After completing the program, she served as senior advisor to the Under Secretary for Science in Washington, D.C., during the Obama Administration. "I put my new knowledge to work thinking about big national security problems and how to bring technical expertise into the discussions." Budil helped convene a panel of eminent national security experts and policymakers including the former Secretary of Defense Bill Perry, the Secretary of Energy, and the Presidential Science Advisor, and provided briefings from the national laboratories on technical considerations of protecting and maintaining the nuclear stockpile. After her Washington, D.C., detail, Budil returned to Lawrence Livermore and later assumed leadership of Strategic Deterrence and then her current role as Laboratory Director.

Like Budil, many Livermore professionals advanced their careers in fulfilling ways following NSAP participation. Because the program encourages a political science-based form of strategic thinking, it sets up participants for leadership roles and increased engagement with decision makers in the U.S. government. After the program, Jennifer Matzel, an associate program leader in nonproliferation research and development and arms control, participated in meetings with National Nuclear Security Administration leadership. She credits the NSAP courses for her ability to engage with national security leaders. "Before I entered NSAP, I had a very strong science and technology background, but I didn't know much about nuclear policy," she says. "After, I was pulled into conversations and meetings on the topic of the New Strategic Arms Reduction Treaty negotiations. I don't think I would have been prepared for that without the NSAP courses."

In a similar vein, Pivovaroff was part of a 2016 cohort to provide background papers on a range of security issues to the DOE administration. Working with Laboratory leadership as well as colleagues from Los Alamos and Sandia national laboratories, Pivovaroff helped present different national security scenarios and their potential outcomes of interest to DOE leaders.

Even with Bahney's background in international relations and political science, the program still presented new opportunities. "I was an analyst in the foreign nuclear weapons program at Livermore, but after NSAP, I took on increased leadership roles at the Laboratory," she says. "Later, I was detailed to Washington, D.C., to work on the Nuclear Posture Review because of my participation in the program."

NSAP registration takes place each autumn, and Livermore staff are encouraged to nominate candidates for the program. Budil emphasizes the program's value to Livermore staff, saying, "NSAP is an investment in our staff, a chance to build their toolkit even if they cannot anticipate upfront how they will take advantage of it. As our staff move up in their career, the skills gained from this program will serve them in good stead."

— Sheridan Hyland

For further information contact Eric Schwegler (925) 424-3098 (schwegler1@llnl.gov).

UPGRADING FACILITIES AND EXPERIENCES

THE rapidly evolving global political climate has changed the trajectory of strategic deterrence for the nation and expedited the timelines of projects and programs across the Laboratory. Lawrence Livermore's Materials Science Division (MSD) provides specialized research that supports multiple mission areas. "Materials enable everything we do at the Laboratory," says Ibo Matthews, division leader. "From targets for the National Ignition Facility (NIF) and clean energy materials to high explosives and actinide materials, you name it."

Recognizing MSD's critical role, the Laboratory has completed a major renovation of Building 235 (B235), MSD's headquarters building. New signs and freshly painted hallways in B235—the hub of Livermore materials science research for 40 years—open to refurbished laboratory areas and reimagined workspaces with functional upgrades supporting staff across Livermore's Strategic Deterrence, Global Security, Engineering, and other organizations as well as academic and industry partners. Matthews started encouraging refurbishment plans in 2021, during the height of the COVID-19 pandemic, citing an increased demand for MSD's unique characterization and diagnostic capabilities. Among improved common areas and upgraded equipment, new facilities of note include the Laser Induced compression for Grain scale with High Throughput (LIGHT) laboratory, a hydride–dehydride (HDH) project, and the ultra-high temperature Gleeble thermomechanical simulator system.

The Laser Induced compression for Grain scale with High Throughput (LIGHT) laboratory enables cost-effective investigations of laser-shocked materials. Researcher Paulius Grivickas and his team train staff to use the LIGHT system.

Heading Toward the LIGHT

The new LIGHT laboratory is home to what materials scientist Paulius Grivickas refers to as Livermore's highest energy, commercially produced laser. A fraction of the size of NIF's lasers, LIGHT can fire one shot every minute, enabling rapid, cost-effective investigations of laser-shocked materials. The LIGHT platform is part of a broader Direct Light Impulse (DLI) testing strategy dedicated to assessing responses of laser-generated mechanical impulses in different materials and material assemblies. At NIF, two of its 192 beams, measuring 35 by 35 centimeters, can be diverted for this purpose into a separate NIF DLI facility for ride-along ablation experiments on large-scale objects. LIGHT can produce the same conditions as NIF DLI on a 1-centimeter scale. Combined with its ability to take multiple shots rapidly and built-in spectroscopy and imaging diagnostics, LIGHT significantly increases testing pace enabling researchers to downselect from a large space of variables to refine experiments.

Current LIGHT developments are tailored to support the W87-1 Modernization Program, (see *S&TR*, December 2022, pp. 4–11) evaluating impulse propagation of materials used in assemblies of complex shapes to assess survivability of weapon systems. LIGHT also works in concert with the W87-1 Survivability Lab, which enables testing and development of advanced diagnostics tools. In the future, Grivickas says LIGHT will be available not only to Livermore researchers but to external collaborators as well, including academic partners.

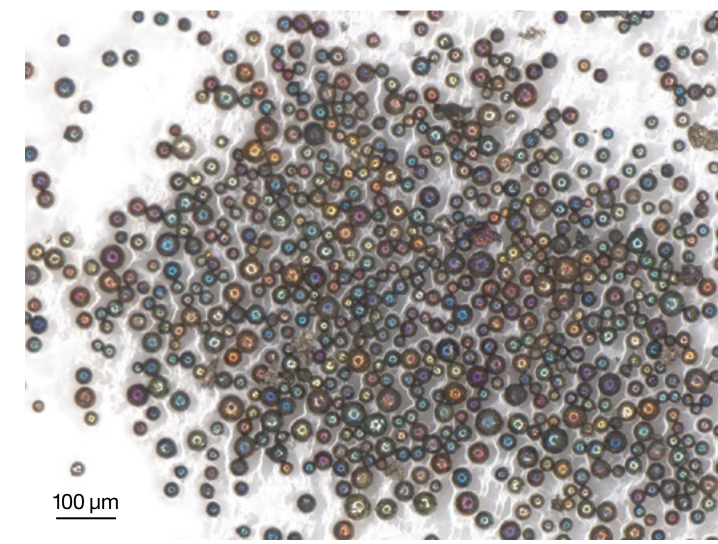
LIGHT is supported by a dedicated technical team familiar with available capabilities such as the ability to study material strength and phase transition, chemical reactions in material synthesis, and impulse dynamics. "LIGHT fills what had been a critical gap," says Grivickas. "Livermore weapon designers who may not have the experience needed to run complex laser ablation experiments hands-on can model system responses under extreme conditions. We will help users leverage what the laser and multiple diagnostics techniques developed to support LIGHT can do."

Accelerating Powder Feedstock Production

Down the hall from LIGHT, the HDH project, led by Kevin Huang, seeks to develop disruptive processes for custom powder feedstock production. Capable of producing metal powders used for additive manufacturing and other applications, the HDH project is MSD's answer to challenges such as the lack of available custom powders or long timelines to procure them. "I think everyone can appreciate the potential for functionalizing and enabling certain applications using 3D printing," says Huang. "Some objects cannot be produced any other way, and having HDH produce powders that are not always readily available is a big deal," says Huang.

HDH can produce powders with exacting requirements but operates at a much smaller, more agile, and more versatile scale than other in-complex facilities. The tools create a consistent and reliable output for established needs, such as powder size distribution, alloy composition, and surface passivation, and those same tools are also used for new, tailored

Staff scientists Logan Winston (left) and Evan Clarke (right) manipulate samples inside the Hydride–Dehydride (HDH) powder machine (above). The HDH project offers the capability to transform a raw slab of uranium alloy into rough flakes before a spheroidization produces a fine sand-like substrate for use in the development of dynamic shapes (below).



Kaila Bertsch adjusts the Gleeble thermomechanical simulator system's sample chamber where she and her fellow materials science researchers can simulate processes relevant to developing materials for ultra-high temperature applications.

powders destined for a variety of testing including powder waste recycling and minimization at the gram-scale. The HDH system's agility and responsiveness enable new materials and new designs for additive manufacturing, making it a unique capability and asset to the Laboratory.

HDH also supports Lawrence Livermore partners including the Y-12 National Security Complex as part of the uranium modernization program under the Laboratory's Strategic Deterrence organization. Jason Jeffries, a former HDH team member and current advisor to the project, notes the versatility of the HDH process as an important corollary to atomization. Whereas the atomizer excels in a highly efficient, large-volume, single-batch mode of operation, the HDH process comprises several independent steps that offer flexibility, individual optimization, and small-scale opportunities. "Dr. Huang's team has built an infrastructure that can quickly collaborate with others across the DOE complex," says Jeffries. "The HDH team has helped to drive spheroidization, passivation, alloying, and even component fabrication for focused studies, and these works have impacted disparate fields from next-generation nuclear fuels to real-world powder specifications for a production agency."

The HDH team has published a manuscript on the ways process conditions affect powder microstructure and presented findings at actinide technology conferences at the Colorado School of Mines and in Lille, France. Huang has hired more staff for the HDH capability and related projects in MSD and looks forward to additional interest from potential new staff, interns, and research partners fostered by B235's upgrades.

Simulating Extremes

Across the hall from the HDH space is the Gleeble thermomechanical simulator system. Using Gleeble, MSD researchers can simulate procedures relevant to advanced processing and novel material development for ultra-high temperature applications, including new, high-melting-point metal alloys such as refractories. This research supports the Laboratory's investments in new metal materials for hypersonics, casting, additive manufacturing, oxidizing or corrosive atmospheres, and other extreme environments.

In the machine's 2-cubic-feet test chamber, MSD researchers simulate the conditions of much larger industrial forges. Gleeble applies resistive heating, running an electrical current through the center of a sample and enabling test temperatures up to 3,000°C—well in excess of typical furnace-based, high-temperature testing equipment—and heating/cooling rate changes of up to 10,000°C per second. By limiting the heat to the sample rather than the entire apparatus, researchers observe in situ the properties and characteristics of materials in extreme conditions and under massive loads in a manner not typically achievable. The monitoring capabilities and simulated environments use one sample to produce the same amount of information typically produced by hundreds of samples in bulk testing at actual scale, enabling rapid process optimization and high-throughput screening of newly developed alloys.

Of particular importance to Livermore is Gleeble's ability to apply loads at strain rates up to 10^2 per second (s^{-1})—greater than that produced by typical lab-scale tensile testers—to simulate dynamic conditions. Anticipated capabilities include operation in toxic or hazardous atmospheres and on radiological materials. While Gleeble's capabilities primarily inform Livermore's Strategic Deterrence programs, MSD scientist Kaila Bertsch notes that Gleeble has been used in several Laboratory Directed Research and Development (LDRD) projects, including work in the study of ceramics, and cited as a component in future LDRD research. "New hires and collaborators would not have expected to see Gleeble outside an industry setting," says Bertsch. "Now, we can train staff on this highly specialized system and hone capabilities relevant to the Laboratory's investments in emerging material technologies."

Fostering Capabilities and Collaboration

In addition to providing a more modern workspace for the critical materials science research performed at Lawrence Livermore, B235's upgrades showcase to guests and new employees how teams can seamlessly go from the research laboratory to spaces that foster cooperation and opportunities to follow up on new ideas. Working with Livermore designer Alii Diaz, Matthews, deputy division leader Harry Radousky, and the project's team reimagined the building's large lobby with an updated color palette, eye-catching wall graphics, and modern furniture. What was already used as an impromptu meeting space was opened up with the removal of bookcases and the addition of what Matthews calls "collaboration stations." Each of the two stations feature large monitors to which collaborators can connect laptops for presentations and large tables with adjustable heights for brainstorming sessions or follow-up conversations.

Radousky says more updates are planned for B235 with the priority being to upgrade the experience of everyone who works there. "Even with all the science and capabilities, we needed the full package, which includes an updated, modern, and comfortable space for existing staff as well as new hires," says Radousky.

Since the initial planning meetings for the renovation of B235, the MSD staff has grown by over 130 people, a phenomenon Matthews attributes to Livermore's recognition of the value added by materials research. He says, "There is nowhere at the Laboratory that isn't touched by what we do. The investment made at B235 shows the real interest in materials."

— *Amy Weldon*

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Renovations to Livermore's Materials Science Division headquarters have expanded research capabilities and enhanced the collaborative work environment for both staff and research partners.

COLLABORATIONS AND CURIOSITY

MATCHING scientist mentors and students on projects to advance the Laboratory's mission has proven to be a reliable first step to promote innovation and build a new employee pipeline. Within Lawrence Livermore's Strategic Deterrence organization, a matching model has been successfully implemented by the Academic Collaboration Team (ACT), enabling students and professors to apply their expertise to projects in high-energy-density science, inertial confinement fusion, nuclear and materials physics, and computation that address evolving program needs. Collaborations are intended to promote innovation and advanced perspectives among partners and yield tangible outcomes, such as publications, patents, and new methods, while encouraging students to consider future employment at Lawrence Livermore.

Counter to the practice of collaborating solely with a set list of tenured faculty members, ACT seeks proposals from early career academics to cultivate new research relationships, provide opportunities to respond to changing program needs with greater agility, and build engagement among students who will soon seek employment. Early- and mid-career Livermore researchers benefit from the chance to explore new areas of science without losing focus on their full-time Laboratory work.

Livermore's Rose McCallen and colleagues in the Strategic Deterrence organization initiated ACT in 2019 based on the understanding that Laboratory capabilities combined with a steady supply of doctoral candidates seeking to establish themselves in their respective research fields could strengthen near-term and long-term success for all parties. With Alison Saunders at the program's helm since 2023, ACT continues to galvanize past university relationships while seeking a more diverse range of institutional partnerships. Saunders, who served as a principal investigator (PI) on a past ACT project, understood the program's value in training the next generation of scientists and guiding strategic university engagement even before she took over the leadership role. "Three years of collaboration with a university professor and doctorate student expanded my knowledge of cutting-edge materials research. The university partners broadened their research scope by modeling their experiments with the Laboratory's advanced simulation codes," says Saunders. "Smaller-scale projects such as those selected for ACT allow the Laboratory to bring in new ideas from our university collaborators while, longer term, building ties to grow hiring pipelines and fostering the continued exchange of academic ideas."

Programmed for Success

ACT publishes a call for proposals each year. Livermore researchers respond with project descriptions, proposed milestones and Laboratory deliverables, estimated costs for student participation, and participant resumes. With the goal of enhancing innovation in target research areas, all proposals are initially reviewed with redacted names of PIs and universities to avoid potential bias. The PIs for down-selected proposals are invited to present their projects to the committee, and five or six projects are selected for funding. ACT establishes subcontracts with university partners and funds the efforts of students and professors for up to three years. Livermore staff continue to be funded by their respective programs.

After projects kick off, students find benefits beyond building and contributing expertise as they receive mentorship from a career researcher and access to one-of-a-kind Laboratory facilities. "An ACT partnership serves as the first professional work setting for many of the selected students," says Saunders. "Working with the same Livermore mentor for several consecutive years enables the partnership to grow and evolve."

Rather than dividing elements of a long-term study among a rotation of students, ACT allows the researcher and student to cultivate a body of work. The ongoing working relationship can also yield quicker turnarounds from research output to return on investment and innovation. Over time, partners become more familiar with the Laboratory's specific methods and sensitive work, preparing them for a potential career at Lawrence Livermore and supporting broader Laboratory goals as well. For example, National Ignition Facility (NIF) physicist Hye-Sook Park mentored a University of California at San Diego student who in turn contributed to research Park pursued, studying material properties at Earth's core. "ACT enabled us to produce important results in this fundamental basic research area and led to the student's advancement in practical knowledge and valuable skills for future Laboratory projects," says Park.

Expanding the Partnership Pool

Completed collaborations have led to a number of publications and to the development of enhanced research tools. (See Sidebars "Expanding Iron's Dynamic Strength," "Refining a Fusion Research Model," and "Studying High-velocity Microparticle Impacts.") Teams have also benefitted from NIF shot time through NIF's Discovery Science program.

While many institutions repeatedly receive ACT awards due to the high caliber of their proposals, students, and expertise, the program set an early goal of encouraging proposals from smaller universities and institutions outside California. Recent university partners have included North Carolina State, Mississippi State, and George Mason universities, and the University of South Florida, building institutional networks beyond earlier ACT collaborators at the University of California at Los Angeles, Stanford University, and University of Notre Dame, among others. "The more students we can recruit and the closer the collaboration, the more data we can collect to refine the program and expand our reach even further," says McCallen, ACT's founder. "Tapping into our university relationships for a workforce with refined skills, knowledge, and abilities will come even more easily as we cultivate a more diverse researcher pool." Saunders is dedicated to continuing McCallen's vision of an ACT program that contributes meaningful research and opens channels to exchange knowledge with other research programs in the Department of Energy and National Nuclear Security Administration.

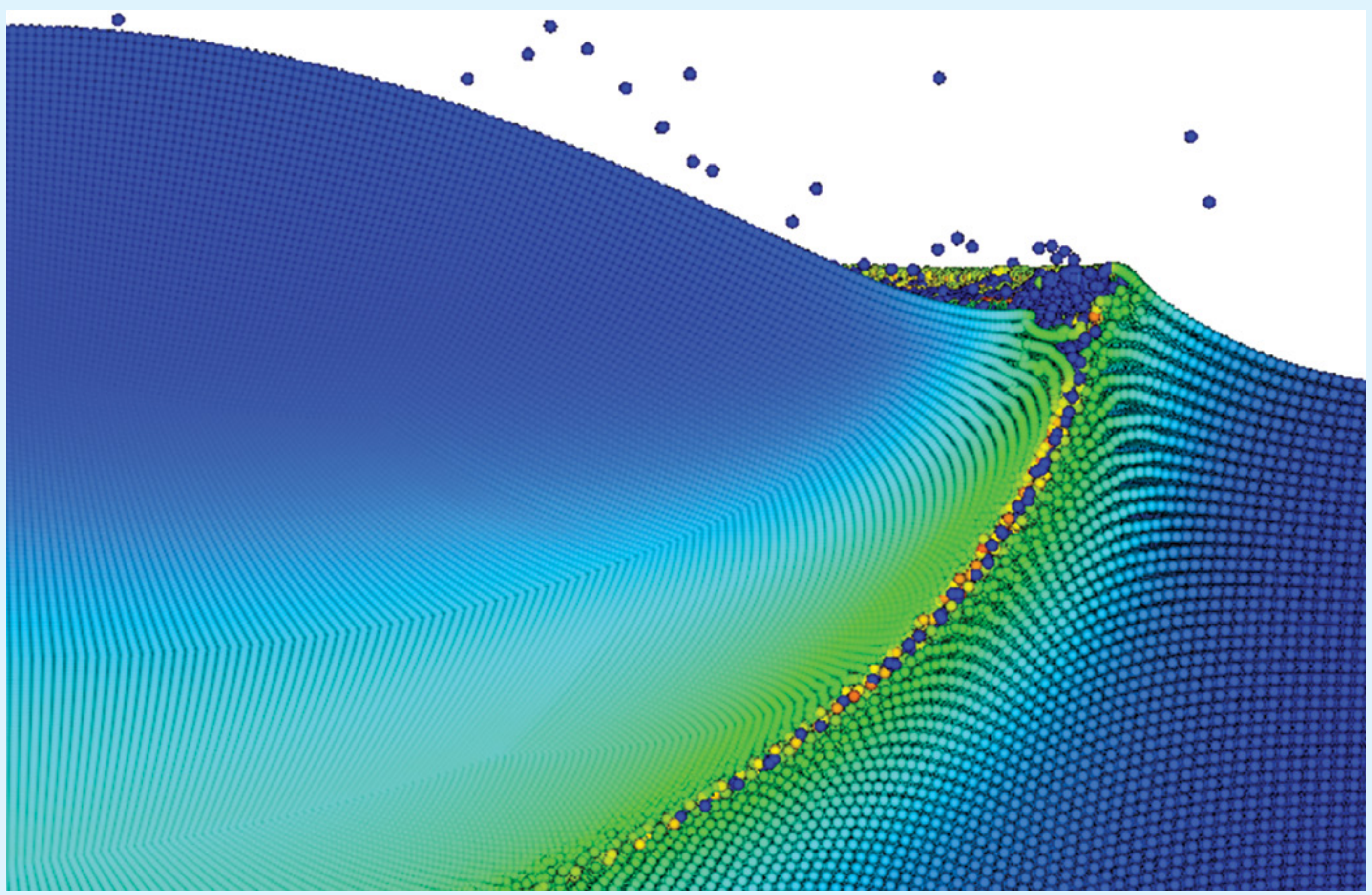
ACT receives more proposals and funds more research projects each year. In 2023, university students submitted 30 proposals leading to six new awards funded by ACT. Saunders is proud to report that at least three recent postdoctoral hires are the direct result of the ACT program. "The connections made definitely draw great talent," says Saunders.

— Gwendelyn Pinkela (additional reporting by Amy Weldon)

For further information contact Alison Saunders (925) 423-0106 (saunders15@llnl.gov).

STUDYING HIGH-VELOCITY MICROPARTICLE IMPACTS

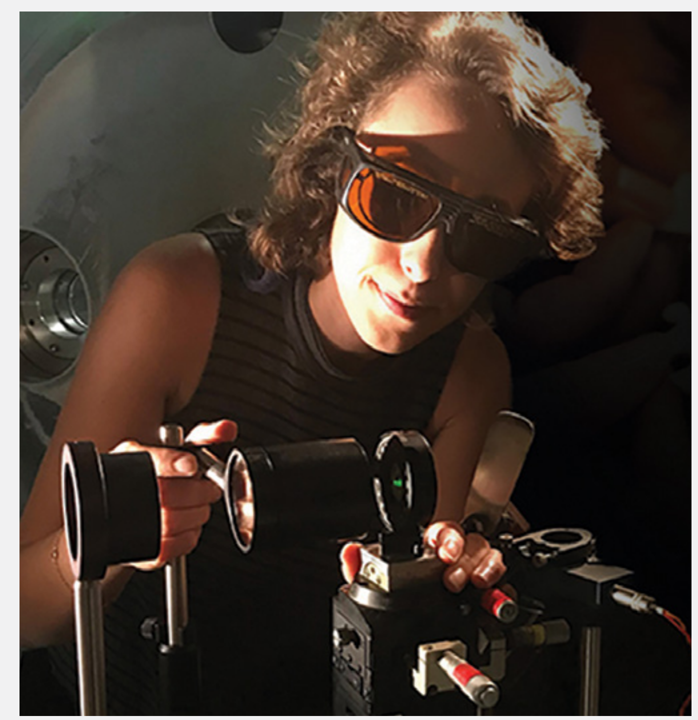
Livermore's hydrocodes, such as ALE3D, predict dynamic material response, providing key particle impact behavior for applications from improving cold spray welding to determining micrometeoroid impacts on spacecraft. Led by Livermore researcher Alison Saunders, a Laboratory team collaborated with Massachusetts Institute of Technology (MIT) student Tyler Lucas and professors Chris Schuh and Keith Nelson to benchmark the constitutive models in such a high strain-rate regime. The MIT group developed the Laser-Induced Particle Impact Test, which uses a table-top laser to accelerate metallic microparticles beyond velocities of 1 kilometer per second. As particles collide with substrates, a high-speed camera with nanosecond temporal resolution captures the impact event. Depending on material and impact velocity, many different phenomena can occur, including rebound, adhesion, hydrodynamic penetration, and melt-driven substrate erosion. Experimental results inform Livermore's ALE3D code to further refine material models. "ACT provided the opportunity to implement Livermore hydrocodes and leverage supercomputers to produce essential data unattainable through other means," says Lucas. "I collaborated with some of the best materials experts and code developers in the field, and they were eager to help me implement my ideas."



Massachusetts Institute of Technology and Livermore teams simulated microparticle impacts with ALE3D hydrocode for insights into physical mechanisms governing experimentally observed particle response. This image captures the simulated impact of a 12-micrometer copper particle (blue dome) striking a copper substrate at 770 meters per second before the particle rebounds. Orange, yellow, and green areas represent regions of elevated strain and, therefore, impact-induced deformation.

EXAMINING IRON'S DYNAMIC STRENGTH

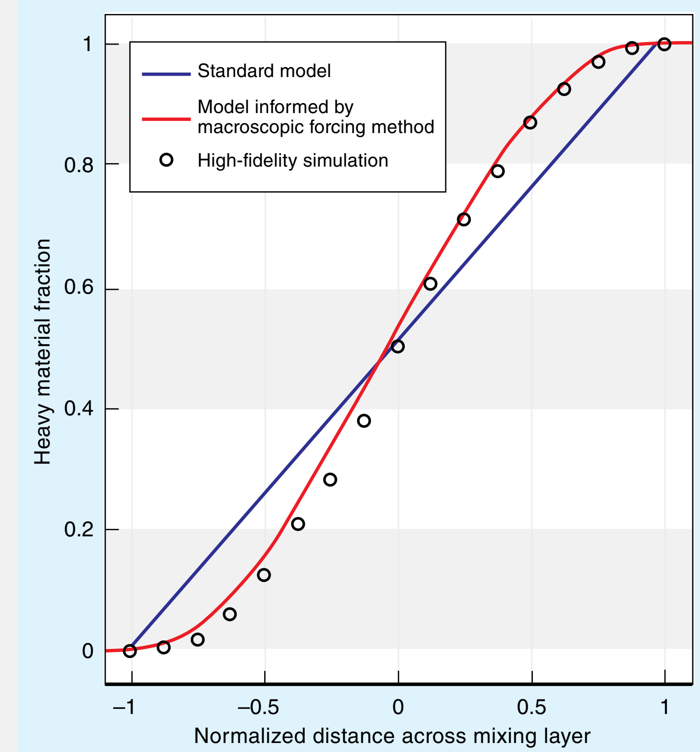
Earth's core is made of iron and nickel, churning deep under 3.5 million atmospheres of pressure. Lawrence Livermore researcher Hye-Sook Park examined the behavior of Earth's high-energy-density iron in collaboration with University of California at San Diego professor Marc Meyers and graduate student Gaia Righi to better understand dynamic failure of iron and iron strength at extreme pressures. Park and Righi implemented laser shock experiments on iron with different initial crystalline lattices and microstructures and then compared results with simulations and models designed to predict the outcomes. Their work, which supports stockpile stewardship, has resulted in three publications and ongoing experimentation. Righi, now the first Harold Brown Postdoctoral Fellow at Lawrence Livermore, says, "ACT gave me the resources to perform laser experiments and simulations and helped me become well connected within the Laboratory. The program contributed to a seamless transition from collaborator to employee."



As a University of California at San Diego student, Gaia Righi worked on an ACT project studying the characteristics of iron at Livermore's Jupiter Laser Facility. Righi is now the Laboratory's Harold Brown Postdoctoral Fellow.

REFINING A FUSION RESEARCH MODEL

In collaboration with Stanford University professor Ali Mani and graduate students Dana Lavacot and Jessie Liu, Livermore's Brandon Morgan addressed the modeling of turbulent mixing, which contributes to degraded target performance in inertial confinement fusion applications. The standard simulation approach, Reynolds-averaged Navier–Stokes (RANS) calculations, can only approximate solutions. Morgan's team sought to develop more predictive RANS models by applying a macroscopic forcing method (MFM) to determine exact differential operators governing the average flow field. "Over the past two years of collaboration, the team has uncovered important factors in modeling flow and developed a new RANS model based on the findings," says Morgan. "ACT helped us develop a promising new modeling technique while also fostering a fruitful hiring pipeline with Stanford University." Future research could be used in National Ignition Facility capsule design simulations.



An ACT-funded collaboration between Livermore and Stanford University yielded a model that better predicts turbulent flow in fusion experiments.

Patents and Awards

In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory. For the full text of a patent, enter the seven- or eight-digit number in the search box at the U.S. Patent and Trademark Office's website (uspto.gov).

Patents

System and Method for Roll-to-Roll Film Tensioning for Reduced Separation Force During Bottom-Up Stereolithography
Eric B. Duoss, James Oakdale, Nicholas Anthony Rodriguez, Hongtao Song, Richard Crawford, Carolyn Seepersad, Morgan Chen
U. S. Patent 11,623,396 B2
April 11, 2023

Fast Image Acquisition System and Method Using Pulsed Light Illumination and Sample Scanning to Capture Optical Micrographs with Sub-Micron Features
Jae Huck Yoo, Eyal Feigenbaum, Manyalibo Joseph Matthews
U.S. Patent 11,624,710 B2
April 11, 2023

Opto-Thermal Laser Detonator
Paul. R. Wilkins
U.S. Patent 11,629,939 B2
April 18, 2023

Radio Frequency Passband Signal Generation Using Photonics
Apurva Shantharaj Gowda, Jacky Chak-Kee Chan, Peter Thomas Setsuda DeVore, David Simon Perlmutter, Jason Thomas Chou
U. S. Patent 11,630,368 B2
April 18, 2023

Porous Ceramics for Additive Manufacturing, Filtration, and Membrane Applications
Patrick Campbell, Sarah Baker, Maira Ceron Hernandez, Jennifer Marie Knipe, Joshuah K. Stolaroff
U.S. Patent 11,638,907 B2
May 2, 2023

Enhanced Material Shock Using Spatiotemporal Laser Pulse Formatting
Manyalibo Joseph Matthews
U.S. Patent 11,638,970 B2
May 2, 2023

Photocurable Resins for Volumetric Additive Manufacturing
Maxim Shusteff, James Oakdale, Robert Matthew Panas, Christopher M. Spadaccini, Hayden K. Taylor, Brett Kelly, Indrasen Bhattacharya, Hossein Heidari
U.S. Patent 11,639,031 B2
May 2, 2023

Optical Authentication of Images
Maxwell R. Murialdo, Brian Giera, Brian M. Howell, Robert M. Panas
U.S. Patent 11,641,282 B2
May 2, 2023

High-Voltage Insulators Having Multiple Materials
Yuri Anatoly Podpaly, Michael Gordon Anderson, Steve Hawkins, Alexander Peter Povilus, Chris Vice
U.S. Patent 11,651,874 B2
May 16, 2023

Discrete Offset Dithered Waveform Averaging for High-Fidelity Digitization of Repetitive Signals
Brandon Walter Buckley, Ryan Douglas Muir, Daniel G. Knierim
U.S. Patent 11,652,494 B2
May 16, 2023

Awards

The **Department of Energy (DOE) Technology Transfer Working Group** honored **Hannah Farquar** and **Roger Werne** of the Laboratory's Innovation and Partnerships Office with two awards for developing the National Lab Accelerator Program: the **DOE Office of Technology Transitions Director's Award** and the **2023 Best in Class for Innovative Technology Transfer.** To date, the National Lab Accelerator Program has provided entrepreneurship training and mentorship to 36 Livermore researchers and hosted 10 pitch events with participants from 15 DOE national laboratories.

Time named Livermore design physicist **Andrea "Annie" Kritcher** to its annual list of the 100 most influential people in the world. **2023 TIME100** honorees were selected for notable achievements, innovation, and impact in 2022. Kritcher was recognized for her role as the principal designer for the National Ignition Facility experiment that produced fusion ignition for the first time in December 2022. On acknowledging the award, Kritcher highlighted the collaborative effort required over many years to achieve ignition.

Global publisher Springer awarded a **2023 Springer Thesis Award** to **Elizabeth Grace**, the Laboratory's High Energy Density Science (HEDS) fellow. Grace's thesis discusses the development of a single-frame laser characterization diagnostic called the Spatially and Temporally Resolved Intensity and Phase Evaluation Device: Full Information from a Single Hologram (STRIPED FISH). STRIPED FISH's capabilities lend a more complete understanding of laser–matter interactions for applications in renewable energy, medicine, and other fields.

Livermore physicist **Tammy Ma** received the **Krell Institute's 2023 James Corones Award in Leadership, Community Building, and Communication**. The award recognizes mid-career scientists and engineers for impacts in their chosen fields and mentorship of young people interested in science. Throughout her career, Ma, who leads the Inertial Fusion Energy Initiative and serves as program element leader for High-Intensity Laser HEDS–Advanced Photon Technologies, has contributed to the advancement of fusion and fostered communication and collaboration in the process.

Abstract

Breaking Materials at Breakneck Speed

Lawrence Livermore scientists have constructed the Energy–Matter Interaction Tunnel (EMIT) for studying material integrity amid the extreme conditions of hypersonic, trans-atmospheric flight. EMIT provides unparalleled optical and diagnostic access to small material samples brought to the point of failure in the test chamber using rapid airflow, laser-added energy, and the onslaught of kinetic or electromagnetic hazards. High-fidelity data collected throughout tests enables scientists to follow a stockpile stewardship approach of refining proprietary multiphysics codes used to predict material performance. EMIT's modular design prioritizes portability; research teams at Livermore will make regular use of the wind tunnel facility, but the instrument's diagnostics can be transported to other national facilities for increased utilization.
Contact: Aric Rousso (925) 423-3458 (rousso1@llnl.gov).

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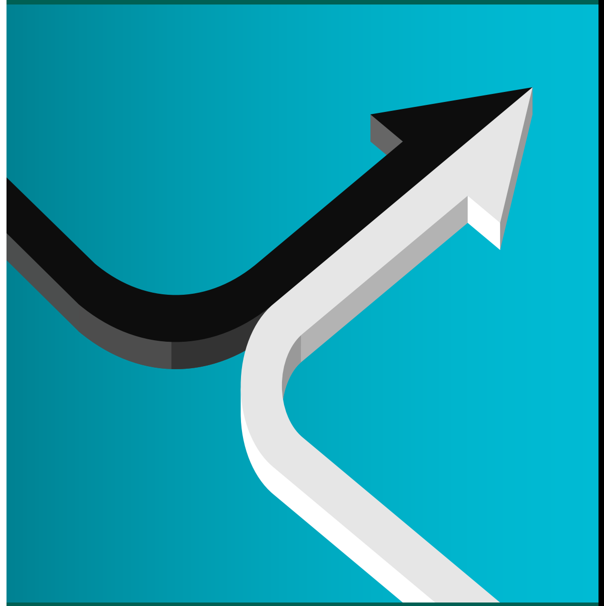
Strategic Laboratory Partnerships



Through long-standing cooperation in research and development, the Departments of Energy and Defense foster a range of advanced scientific and warfighting capabilities.

Also in an upcoming issue:

- *Mutual expertise in renewables, climate, and data science unite Lawrence Livermore and the Korea Institute of Science and Technology.*
- *The Laboratory and its commercial and academic partners usher in an energy future with practical, industrial-scale decarbonization.*

COMING SOON

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