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# MATERIAL MATTERS

*The Quarterly Magazine of NIST's Material Measurement Laboratory*

MEASUREMENT SCIENCE FOR INFRASTRUCTURE RENEWAL

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

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Cover Image: Rust on Iron. Credit: Laitr Keiows, Creative Commons license 3.0

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# A MESSAGE FROM THE MML DIRECTOR

**Michael Fasolka, Ph.D.**
**Director***
**Material Measurement Laboratory**
**NIST**

According to the American Society of Civil Engineers, nearly ten percent America's bridges are structurally deficient or functionally obsolete, one-fifth of our highway pavement is in poor condition, and over two trillion gallons of treated drinking water is wasted each year from an estimated 240,000 water main breaks. In short, our nation's physical infrastructure is in bad shape, and in dire need of attention.

A healthy physical infrastructure is essential for maintaining our physical security, preserving our quality of life, and helping our economy thrive. At NIST's Material Measurement Lab (MML), we are working to make a safe and healthy infrastructure a reality. From providing quality assurance standards that cement and steel manufacturers can rely upon to providing accurate assessment tools for pipeline manufacturers and water treatment, our work enables a better, more reliable infrastructure network.

With so much of our infrastructure in need of attention, MML research also gives decision-makers the intelligence they need to prioritize our nation's many infrastructure projects. Our work helps ensure the accuracy of steel hardness measurements, which are used to check the strength of steel alloys that may be used in infrastructure projects. We measure impact energy, which helps to predict when structures are in need of replacement or repair (before catastrophic failure). We also calibrate the equipment that can measure flaws and weaknesses in existing infrastructure without damaging it or taking it out of service.

To ensure we continue to innovate and lead physical infrastructure measurement, we have renewed our dedication to infrastructure research by making it part of the MML Strategic Plan. Our plan directs our materials and chemical scientists and engineers to develop new materials models that fully account for the ongoing reduction in structural capacity in infrastructure components and systems. Such models promise to guide the development of new infrastructure materials resulting in more effective, lower cost solutions.

In this issue of *Material Matters*, you can read about some of our latest infrastructure research, including advanced corrosion detection (p. 4), an embedded, nanoscale composite damage sensor (p. 5), and our ongoing project to improve pipeline materials (p. 18), in addition to research across the other areas of MML's research portfolio.

Part of NIST's mission is to improve quality of life, and little is more central to the quality of our lives than the infrastructure in which we live. Though much needs to be done, at MML we have the right tools to put words into action.

**During the transition to a new presidential administration, Laurie Locascio, MML director, is serving as NIST's acting associate director for laboratory programs. Michael Fasolka, long-time MML deputy director, is acting director of MML*

# MOVE OVER, SUPERMAN! NIST 'SPECTRAL FINGERPRINTING' SEES THROUGH CONCRETE TO DETECT EARLY CORROSION

An abandoned building on Northern California's McAbee Beach shows the destructive power of corrosion on a steel-reinforced concrete structure. A new NIST evaluation method using terahertz waves can detect the early stages of corrosion on steel rebars directly through their concrete covering. Credit: Per Loll

When you suffer a fall, an on-the-field collision or some other traumatic blow, the first thing the doctor will do is take an X-ray, CT scan or MRI to determine if anything has been damaged internally. Researchers at NIST are using the same principle, but in a more powerful form, to detect corrosion, the primary danger threatening the health of the steel framework within the nation's bridges, roads and other aging physical infrastructure.

What they have developed is a noninvasive "spectral fingerprint" technique that reveals the corrosion of concrete-encased steel before it can cause any significant degradation of the structure it supports. The detection method is described in a new paper in the journal *Applied Magnetic Resonance*.

When water and oxygen corrode iron, different iron oxide products are produced, with the two most common being goethite and hematite. "The brown rust that forms when you leave a hammer out in the rain is mostly goethite, and when a steel reinforcing bar [rebar] corrodes inside a concrete bridge deck, that is mostly hematite," said NIST physical chemist Dave Plusquellic. "We have shown in our new study with goethite, and our previous work with hematite, that terahertz radiation—electromagnetic waves with frequencies 10 to 100 times higher than the microwaves used to cook food—can detect both corrosion products in the early stages of formation."

Current imaging methods for uncovering corrosion use microwaves to record changes in the physical state of the affected steel, such as changes in the thickness of a rebar within the concrete of a bridge or other structure. "Unfortunately, by the time such changes are detectable, the corrosive process is already well on its way toward causing cracks in the concrete," said physicist and NIST Fellow Ed Garboczi.

Additionally, Garboczi said most of the microwave imaging methods rely on comparisons with baseline measurements of the steel taken at the time of construction, a practice that only goes back about 25 years. "That's a real problem since the average age of the 400,000 steel-reinforced concrete bridges in the United States is 50 years and there is no baseline data available for many of them," he explained.

The NIST terahertz wave detection method works because goethite and hematite are antiferromagnetic. In other words, the pairs of electrons sitting side-by-side within the iron atoms in these materials spin in opposite directions, leaving them unaffected by external magnetic fields. In contrast, the electrons in the iron atoms of a household magnet, which is ferromagnetic, spin in the same direction and are either attracted or repelled by external magnetic fields.

"Terahertz waves will flip the spin alignment of one of the electrons in a pair and get absorbed by hematite or goethite," Plusquellic said. "Using a millimeter wave detector, we discovered that this antiferromagnetic absorption only occurs within narrow frequency ranges in the terahertz region of the electromagnetic spectrum—yielding 'spectral fingerprints' unique to goethite and hematite, and in turn, iron corrosion."

With current advances in terahertz sources and detectors, the new NIST nondestructive evaluation technique has the potential to rapidly detect tiny amounts of iron-bearing oxides from early-stage corrosion of steel surrounded by concrete, polymer composites (such as pipe insulation in a factory), paints and other protective materials.

"In the laboratory, we have demonstrated that a 2-milliwatt terahertz source can produce waves that detect hematite through 25 millimeters of concrete," Plusquellic said. "Using terahertz sources with powers in the hundreds of milliwatts and state-of-the-art receivers with unprecedented signal-to-noise ratios, we should be able to penetrate 50 millimeters, the thickness of the concrete covering the first layer of rebar used in most steel-reinforced concrete structures."

Next up for the NIST team will be an attempt to find a spectral fingerprint for akageneite, an iron corrosion product formed in the presence of chloride ions, which come from sources such as seawater and road deicing salt. "Akageneite can cause problems in steel-reinforced concrete similar to those seen with goethite and hematite," Garboczi said.

The antiferromagnetic corrosion detection method was first conceived in 2009 by the late William Egelhoff, a NIST fellow and pioneer in the field of magnetic materials.

S.G. Chou, P.E. Stutzman, V. Provenzano, R.D. McMichael, J. Surek, S. Wang, D.F. Plusquellic and E.J. Garboczi, Using Terahertz Waves to Identify the Presence of Goethite via Antiferromagnetic Resonance, *Applied Magnetic Resonance* (April 2017), http://dx.doi.org/10.1007/s00723-017-0884-y

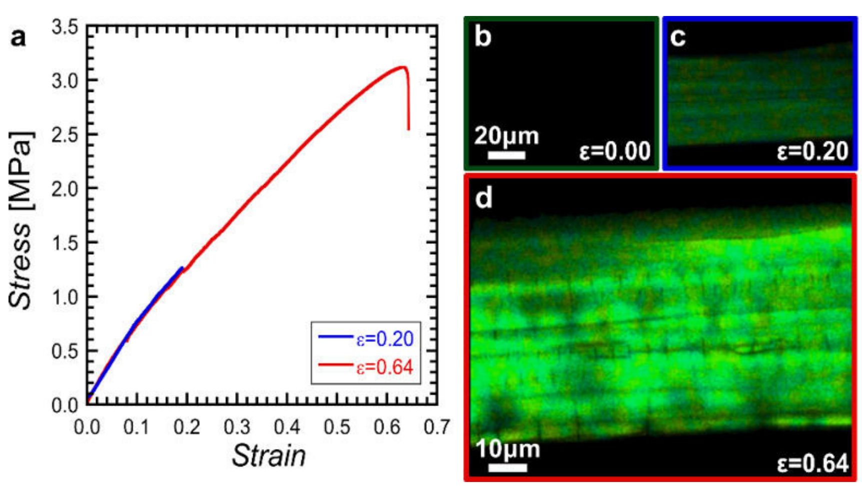
# SILK SENSOR COULD SPEED DEVELOPMENT OF NEW INFRASTRUCTURE, AEROSPACE AND CONSUMER MATERIALS

Consumers want fuel-efficient vehicles and high-performance sporting goods, municipalities want weather-resistant bridges, and manufacturers want more efficient ways to make reliable cars and aircraft. What's needed are new lightweight, energy-saving composites that won't crack or break even after prolonged exposure to environmental or structural stress. To help make that possible, researchers working at NIST have developed a way to embed a nanoscale damage-sensing probe into a lightweight composite made of epoxy and silk.

Examples of the silk used in experiments to detect damage in composites, shown under black light. (Left) Ordinary fibroin of the Bombyx mori silk worm. The observed fluorescence is the result of molecules already present in the protein structure of the fiber. (Middle) Mechanophore-labeled silk fiber fluoresces in response to damage or stress. (Right) Control sample without the mechanophore. Credit: Chelsea Davis and Jeremiah Woodcock/NIST

The probe, known as a mechanophore, could speed up product testing and potentially reduce the amount of time and materials needed for the development of many kinds of new composites.

The NIST team created their probe from a dye known as rhodamine spirolactam (RS), which changes from a dark state to a light state in reaction to an applied force. In this experiment, the molecule was attached to silk fibers contained inside an epoxy-based composite. As more and more force was applied to the composite, the stress and strain activated the RS, causing it to fluoresce when excited with a laser. Although the change was not visible to the naked eye, a red laser and a microscope built and designed by NIST were used to take photos inside the composite, showing even the most minute breaks and fissures to its interior, and revealing points where the fiber had fractured. The results were recently published in the journal *Advanced Materials Interfaces*.




Activation of the mechanophore at the interface of a single fiber bundle silk epoxy by mechanical deformation. Credit: Advanced Materials Interfaces

The materials used in the design of composites are diverse. In nature, composites such as crab shell or elephant tusk (bone) are made of proteins and polysaccharides. In this study, epoxy was combined with silk filaments prepared by Professor Fritz Vollrath's group at Oxford University using *Bombyx mori* silk worms. Fiber-reinforced polymer composites such as the one used in this study combine the most beneficial aspects of the main components—the strength of the fiber and the toughness of the polymer. What all composites have in common, though, is the presence of an interface where the

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# NIST QUEST FOR CLIMATE-FRIENDLY REFRIGERANTS FINDS COMPLICATED CHOICES

Researchers at NIST have just completed a multiyear study to identify the "best" candidates for future use as air conditioning refrigerants that will have the lowest impact on the climate.

Unfortunately, all 27 fluids NIST identified as the best from a performance viewpoint are at least slightly flammable, which is not allowed under U.S. safety codes for most end uses. Several fluids among the list of refrigerants are highly flammable, including propane, the fuel for outdoor grills.

In other words, the NIST study found no ideal refrigerant that combined low "global warming potential" (GWP)—a measure of how much heat a gas will trap if released into the atmosphere— with other desirable performance and safety features such as being both nonflammable and nontoxic. The results appear in *Nature Communications*.

"The takeaway is there is no perfect, easy replacement for current refrigerants," NIST chemical engineer Mark McLinden said. "Going into the study, we thought surely there has to be something else. Turns out, not so much. So it was a bit surprising, a bit disappointing."

To help reduce global warming, nearly 200 nations, including the United States, in October 2016 agreed to amend the Montreal Protocol to phase down by mid-century the refrigerants used in most air conditioning (AC) systems. The partial phase down, rather than a complete phaseout, recognized the complicated choices that will need to be made to select replacements. Fortunately, valuable new data are now available to support those decisions.

"The path forward will involve tradeoffs," McLinden continued. "Safety codes could be revised to allow the use of slightly flammable refrigerants. Blends of two or more fluids could yield a nonflammable refrigerant, but at a higher GWP. Carbon dioxide is nonflammable, but would require a complete redesign of AC equipment."

Copyright: Carolyn Franks/Shutterstock

Current refrigerants are hydrofluorocarbons (HFCs), which are "greenhouse gases" with high GWPs. Although their contribution to climate change is now small, it is expected to rapidly increase along with the use of air conditioning around the world. The Montreal Protocol, the treaty that regulates substances that deplete Earth's protective ozone layer, originally spurred the introduction of HFCs as replacements for ozone-depleting compounds previously used.

U.S. regulators already recognize the difficulty of choosing new refrigerants. The Environmental Protection Agency has not set specific GWP limits, but rather has conducted comparative risk analyses for each refrigerant and end use. The criteria include atmospheric effects and related health and environmental effects, ecosystem risks, consumer risks, flammability, cost and availability.

To help U.S. policymakers and industry understand the limits and tradeoffs involved in a phase-down of the HFCs, NIST undertook a comprehensive, four-year search for the best single-component, low-GWP replacement fluids. GWP is defined as the warming potential of one kilogram of a gas relative to one kilogram of carbon dioxide.

The NIST study focused on possible replacement fluids for small AC systems typical for homes and small businesses. A blend of HFCs called R-410A is now the most popular refrigerant in such systems. These AC units are sealed, meaning they should not release HFCs into the atmosphere. However, the systems can leak, and when they are serviced or discarded, refrigerant may escape and not be recovered and recycled, McLinden said.

The study screened a database of more than 60 million chemicals, estimating the properties based solely on their molecular structure. This built upon a computational method previously developed at NIST.

Because all current refrigerants are small molecules, the NIST search was limited to molecules with 18 or fewer atoms and only eight elements that form compounds volatile enough to serve as refrigerants. This initial screen resulted in 184,000 molecules to be considered further.

Screening for energy properties corresponding to fluids usable in small AC systems and GWP of less than 1,000 (conventionally understood to be the effects over a 100-year timespan) yielded 138 fluids. The researchers then simulated the performance of these 138 compounds in air conditioners. A co-author at The Catholic

University of America in Washington, D.C., helped develop the simulation model and evaluate the results. Further screening to rule out chemically unstable or very toxic compounds or those with low energy efficiency resulted in the final list of 27 low-GWP fluids.

Propane has a GWP of 3, much lower than R-410A's value of 1,924. Potential refrigerants with the lowest GWPs include ammonia, commonly used in large industrial refrigeration systems but toxic and slightly flammable, and dimethylether, a propellant and potential fuel that is only slightly less flammable than propane. Carbon dioxide has a GWP of 1 and is nonflammable, but it would require a different type of refrigeration cycle operating at very high pressures. Other low-GWP compounds include hydrofluoroolefins, a current focus of industry research but slightly flammable.

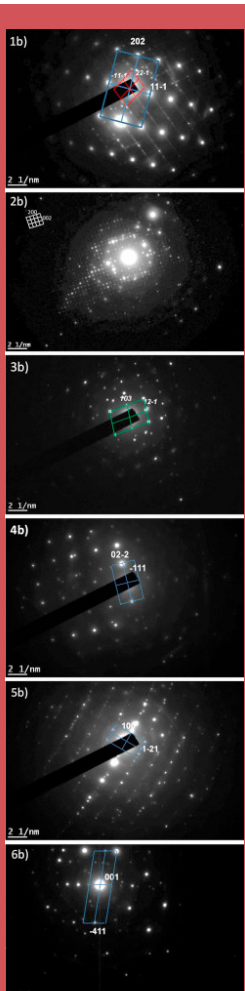
Although there is no specific GWP limit in the United States, phaseout dates have been set for some of the highest-GWP HFCs. (Refrigerants with a GWP of less than 750 are allowed in the European Union for small AC systems.)

NIST's list may offer new ideas because it includes many refrigerants that are not yet on the EPA list of acceptable substitutes. The refrigeration industry has been actively developing new fluids that are slightly flammable, and the results of the present study support this course, McLinden said. Looking forward, the NIST study's conclusions indicate the need to recognize and deal with tradeoffs in planning for the future, he said.

For example, how should safety codes be changed to ensure that flammable refrigerants can be used safely? Blends of different refrigerants may offer a compromise between safety and GWP. For example, a low GWP but flammable fluid blended with a nonflammable but high-GWP fluid could result in a nonflammable fluid with a moderate value of GWP, McLinden noted.

This work was supported by the U.S. Department of Energy.

M.O. McLinden, J.S. Brown, R. Brignoli, A.F. Kazakov and P.A. Domanski, Limited options for low-global warming-potential refrigerants, *Nature Communications*, 2017, http://dx.doi.org/10.1038/ncomms14476

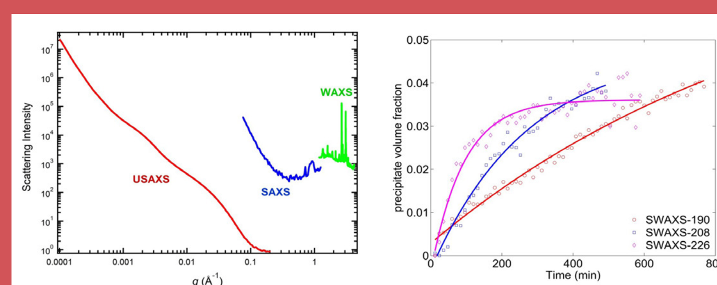



Electron diffraction patterns of phases identified in the AA2024 alloy. Credit: Nataliya Kazantseva

## PRECIPITATION KINETICS AND DEVELOPMENT PATHWAY OF THE MOST WIDELY USED AIRCRAFT ALLOY

The U.S. aluminum industry is estimated to have generated more than $75 billion a year in direct economic impact in 2016. Aluminum alloy 2024 (AA2024), which makes use of copper as the main alloying element and features a good combination of yield strength and toughness, is the most widely used aircraft alloy. Its strengthening mechanism is precipitation hardening, achieved through heat treatment. Despite its obvious commercial importance, a comprehensive understanding of the *in situ* evolution of the precipitate structure and morphology of AA2024 during heat treatment is still lacking, mostly due to the sub-angstrom to micrometer size range that must be characterized.

Under a partner-user agreement between NIST and the Advanced Photon Source at the Argonne National Laboratory, NIST researchers have recently developed a synchrotron-based scattering methodology that enables across-length-scale characterization of structural and microstructural transformation in a wide range of engineering and functional materials. The researchers employed this methodology to examine the nucleation and growth of the hardening precipitates in AA2024, and determine the corresponding kinetic time scales and activation energies. These behaviors are critical to understanding the hardening of the alloy, which is achieved by impeding the movement of dislocations with precipitates.




(Left) Recently developed synchrotron-based scattering methodology enables angstrom-micrometer structural and micro-structural characterization of the same sample volume. (right) *In situ* synchrotron study reveals temperature-dependent growth kinetics of the precipitates in industrially important aluminum alloy 2024.

An improved understanding of the precipitation kinetics, together with their atomic structure and micro-structure, can serve to establish the structure–performance relationships in alloys, and lead to a more rational design of alloys for specific applications.

Zhang, F., Levine, L. E., Allen, A. J., Campbell, C. E., Creuziger, A. A., Kazantseva, N., Ilavsky, J., *In Situ* Structural Characterization of Ageing Kinetics in Aluminum Alloy 2024 across Angstrom-to-Micrometer Length Scales, *ACTA Materialia* 111, 2016, https://doi.org/10.1016/j.actamat.2016.03.058

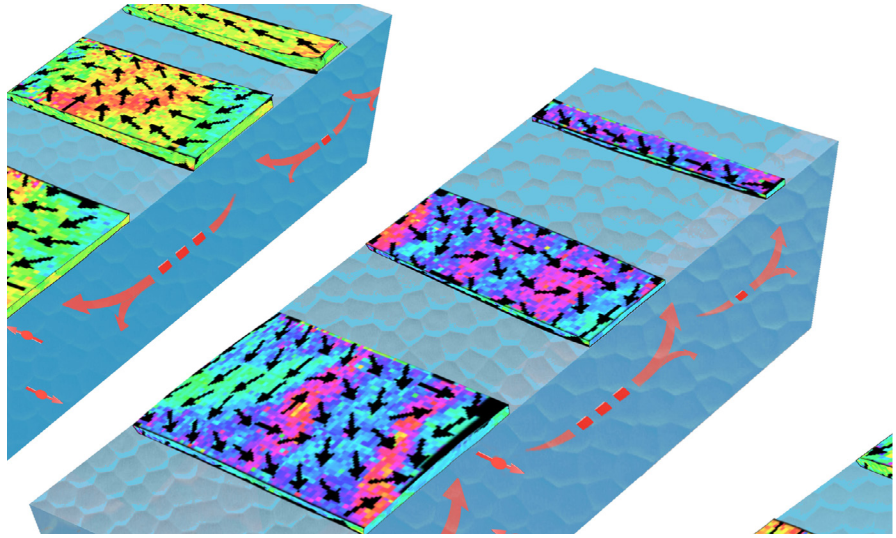
# BETTER NANOIMAGES 'SPIN' THE PATH TO IMPROVED MAGNETIC MEMORY

In work that could help make possible a faster, longer-lasting and lower-energy method of data storage for consumers and businesses, researchers at NIST and their colleagues have developed a technique for imaging and studying a promising class of magnetic devices with 10 times more detail than optical microscopes.

Magnetic materials have attracted a growing number of researchers in the quest to more rapidly store and read bits of digital information. In a magnetic system, data is encoded by the direction of the magnetization: A bar magnet with its north pole pointing up can represent the binary code "0," while the same magnet with its north pole pointing down can represent a "1." Unlike the standard semiconductor computer chip, magnetic memory devices can retain information even if the power is turned off.

By controlling when and how quickly the magnetization can be flipped without expending significant electrical power, scientists hope to improve an existing technology called Magnetic Random Access Memory, or MRAM, into a leading tool for reading, writing and storing information. MRAM is not yet competitive with other existing methods of data storage such as flash RAM, but offers advantages over present-day technologies such as reduced energy consumption.

To realize the promise of MRAM, researchers are probing the nanometer-scale magnetic structure of thin metal films that have the potential to serve as memory devices in MRAM. At NIST, Ian Gilbert and his colleagues have used a high-resolution electron-imaging technique, developed by physicist John Unguris, to examine the nanostructure of magnetic films before and after their magnetization is reversed.



Strips of magnetic material (small colored rectangles) sit atop blocks of a nonmagnetic heavy metal (large blue rectangles). When an electric field is applied to a nonmagnetic block, a flow of spin-polarized electrons enters the magnetic strips and alters the direction of magnetization (black arrows). Credit: Dill/NIST

The technique, scanning electron microscopy with polarization analysis (SEMPA), uses a beam of electrons scattered from a thin film to reveal the nanoscale topography, replete with miniature hills and valleys, of the film's surface. Electrons ejected from the surface by the incoming electron beam are also detected and separated according to the direction of their spin—a quantum property that endows the charged particles with an intrinsic angular momentum and tiny magnetic field. The direction of the ejected electrons' spins reveals variations in the sample's magnetic structure—changes in the direction of magnetization—on a scale about 10 times smaller than seen with an optical microscope.

SEMPA's ability to discern tiny magnetic structures is critical as engineers fabricate smaller and smaller magnetic memory devices, noted Gilbert. With SEMPA, "we can see these really fine textures in the magnetization," he said.

Gilbert and his collaborators, which include scientists from NIST and the University of Maryland, also used electron spin to flip the magnetization in their thin-film sample, an alloy of cobalt, iron and boron. By passing a small electric current through an underlying strip of a nonmagnetic metal film such as platinum, the team created a stream of electrons whose spins all point in the same direction. When this stream of electrons, known as a spin current, passed through the magnetic thin film, their spin exerted a small twisting force, or torque, on the magnetic regions of the film. The torque was large enough to rotate and flip the magnetization.

The SEMPA images taken before a current was applied revealed that the direction of the magnetization varied, on the nanoscale, across the thin-film sample. Each small region of the sample has its own preferred axis along which the magnetization points, said Gilbert. The team recently reported its findings in the journal *Physical Review B*.

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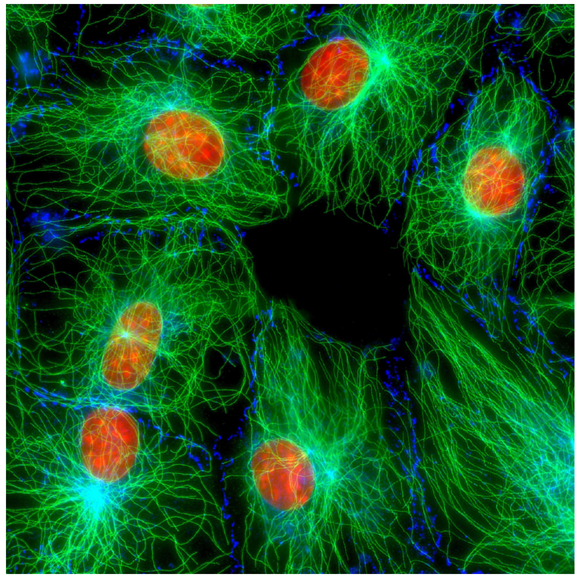
# NIST PATENTS FIRST DNA METHOD TO AUTHENTICATE MOUSE CELL LINES

"A case of mistaken identity" may drive the plot of the latest spy film or crime novel, but it's only a tale of trouble for geneticists, oncologists, drug manufacturers and others working with mouse cell lines, one of the most commonly used laboratory model systems for genetic research. Cell lines that have been contaminated or misidentified due to poor laboratory technique and human error lead to inaccurate research studies, retracted publications and wasted resources. In fact, many scientific funding organizations, such as the National Institutes of Health, now require scientists to verify their cell lines for identity and quality before research grants are awarded.

To help address this challenge, NIST is working with partners to design tools, establish datasets, and further develop and standardize NIST's system to authenticate mouse cell lines. One of the first milestones in this effort is the recently granted U.S. patent (No. 9,556,482) for an authentication method using NIST-identified short tandem repeat (STR) markers—tiny repeating segments of DNA found between genes—for mouse cell lines. The method can be used to verify that a cell line is derived from a particular mouse in the same way forensic experts can confirm the identify of a person using DNA evidence. Once upcoming interlaboratory tests of the STR markers are completed, this will become the world's first validated method for the authentication of mouse cell lines.

The new NIST authentication method uses STR markers that are non-coding (that is, do not provide instructions for protein production the way genes do) DNA segments with a specific sequence of nucleotide bases—the four key components of DNA known as adenine, cytosine, guanine and thymine. Each STR is considered a separate marker for genetic matching because the number of times it is repeated is unique to an individual within a species. For example, a cell line may have one STR sequence—such as G-A-T-A—that repeats five times, another—say G-T-A-T—six times, a third seven times and so on. If another cell line has a high percentage of the same STR sequences in the same numbers, it is considered likely that they share a common ancestry.



A fluorescent microscope image of NIH 3T3 fibroblast cells, a commonly used mouse cell line. Microtubules within the cell appear green while the nuclei show as red. NIST and partners are developing tools, datasets and a standardized authentication method to ensure the identity of mouse cell lines used in research.
Credit: Jan Schmoranzer/Leibniz-Institut für Molekulare Pharmakologie

Misidentified human cell lines and the disruption they cause have been documented for decades. For example, two tainted cell lines were responsible for invalidating approximately $700 million of research studies and some 7,000 publications between the late-1950s and mid-1960s. The International Cell Line Authentication Committee, a volunteer group that monitors and raises awareness of authentication issues, currently lists nearly 500 misidentified human cell lines in its database. Fortunately, there are now standards and public databases that labs can use to confirm the identity of their human cell lines.

In contrast, the extent of misidentification in mouse cell lines is unknown and there are currently no guidelines for authenticating them, said NIST microbiologist Jamie Almeida. "That is why NIST has been working on STR markers that are unique, easy to interpret and capable of distinguishing between different mouse cell lines," Almeida said. "Additionally, we have partnered with the ATCC [formerly the American Type Culture Collection], a global leader in biological materials management and standards, to further develop the STR technology for authentication and establish the Mouse Cell Line Authentication Consortium. The consortium is made up of organizations that have agreed to work with NIST and ATCC to test and validate the patented authentication method using the NIST-identified STR markers."

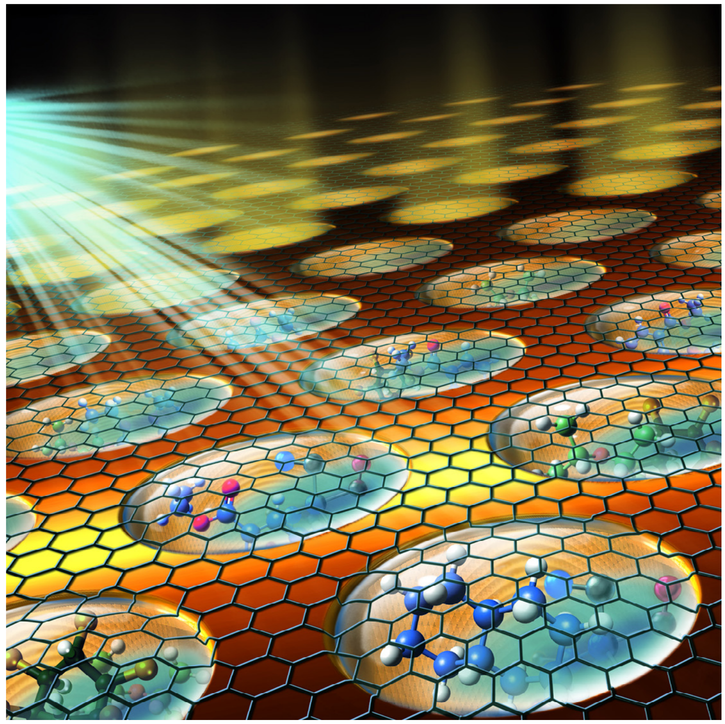
The consortium also will create a consensus standard to unify how authentication is performed across laboratories and will establish a public database that defines which STR profiles identify which mouse cell lines.

"In the future, we hope to see the NIST-identified mouse STR markers and authentication method incorporated into a commercially available assay kit," Almeida said. "The proposed kit, combined with a consensus standard and a cell line database, would provide researchers worldwide with the tools needed to ensure the identity of their mouse cell lines."

The new mouse cell line authentication method using the NIST-identified STR markers is available for licensing for research and non-exclusive commercial purposes through the agency's Technology Partnerships Office.

# GRAPHENE LID REVITALIZES IMAGING TECHNIQUE

By capping liquids with graphene, an ultrathin sheet of pure carbon, researchers at NIST and their colleagues have revitalized and extended a powerful technique to image surfaces. The graphene lids enable researchers for the first time to easily and inexpensively image and analyze liquid interfaces and the surface of nanometer-scale objects immersed in liquids. The new capability has the potential to advance the development of batteries, highly charged capacitors for power-grid technology, and new catalysts such as those used in the chemical industry.



Experimental set-up shows an array of graphene-capped liquids. The caps enable the liquids to be studied using an image technique that previously was restricted to studying solid surfaces. Credit: A. Strelkov/NIST

In the imaging technique, known as photoemission electron microscopy (PEEM), ultraviolet light or X-rays bombard a sample, stimulating the material to release electrons from a region at or just beneath its surface. Electric fields act as lenses, focusing the emitted electrons to create an image.

Researchers have used the method for decades to discern such fine-scale features as the patterns of chemical reactions on the surface of catalysts, as well as the magnetic field structure of memory devices and the molecular architecture of biological compounds. But PEEM has typically been restricted to solid surfaces that are in a high-vacuum environment. The method hasn't had the ability to study liquids and gases at ordinary pressures. A liquid sample, for instance, would evaporate and create sparks if directly exposed to the high vacuum in the PEEM setup.

In the past, scientists have attempted to overcome these challenges by using a technique known as differential pumping, which bridges the gap between the high pressure of the sample and the essentially zero pressure of the microscope. But such instrumentation is not sufficient to reach truly ambient pressure conditions and is too expensive and not widely accessible for routine use, notes NIST physicist Andrei Kolmakov.

Instead, he and his colleagues from NIST, the University of Maryland, the University of Saskatchewan, the Canadian Light Source and Oregon State University developed a cost-effective and easy-to-implement alternative. Sealing a liquid or gaseous sample with a graphene lid just one or two atomic layers in thickness keeps the sample at atmospheric pressure while allowing the system to be placed under vacuum.

In a recent issue of *Nano Letters*, the scientists reported that the graphene lid enabled electrons emitted by the test liquid to pass nearly unimpeded to the detector, yet kept the liquid from escaping into the vacuum of the PEEM. An array of the lids retained the liquid samples for hours under high vacuum, long enough to perform routine electron imaging and spectroscopy experiments.

"This very simple solution, adding a layer of graphene," allows researchers to use PEEM in its standard configuration without the need for extra and expensive equipment, said Kolmakov.

"The concept of extending the use of PEEM to probe liquids is in a way revolutionary," commented physicist Andrea Locatelli of Synchrotron Radiation Laboratory Elettra in Trieste, Italy, who was not part of the research team. "Countless applications can indeed be foreseen," he added.

For instance, noted Kolmakov, the lids allow the liquid to be changed while an experiment is in progress, helping researchers to understand the behavior of the sample under different chemical environments. In addition, because the setup uses an array of identical lids, each can be a different sample, and the technique can be used in conjunction with powerful statistical analysis, data mining and pattern recognition methods.

H. Guo, E. Strelcov, A. Yulaev, J. Wang, N. Appathurai, S. Urquhart, J. Vinson, S. Sahu, M. Zwolak, and A. Kolmakov, Enabling Photoemission Electron Microscopy in Liquids via Graphene-Capped Microchannel Array, *Nano Letters*, 2017, http://dx.doi.org/10.1021/acs.nanolett.6b04460

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components meet. The resilience of that interface is critical to a composite's ability to withstand damage. Interfaces that are thin but flexible are often favored by designers and manufacturers, but it is very challenging to measure the interfacial properties in a composite.

"There have long been ways to measure the macroscopic properties of composites," said researcher Jeffrey Gilman, who led the team doing the work at NIST. "But for decades the challenge has been to determine what was happening inside, at the interface."

One option is optical imaging. However, conventional methods for optical imaging are only able to record images at scales as small as 200-400 nanometers. Some interfaces are only 10 to 100 nanometers in thickness, making such techniques somewhat ineffective for imaging the interphase in composites. By installing the RS probe at the interface, the researchers were able to "see" damage exclusively at the interface using optical microscopy.

The NIST research team is planning to expand their research to explore how such probes could be used in other kinds of composites as well. They also would like to use such sensors to enhance the capability of these composites to withstand extreme cold and heat. There's a tremendous demand for composites that can withstand prolonged exposure to water, too, especially for use in building more resilient infrastructure components such as bridges and giant blades for wind turbines.

The research team plans to continue searching for more ways that damage sensors such as the one in this study could be used to improve standards for existing composites and create new standards for the composites of the future, ensuring that those materials are safe, strong and reliable.

"We now have a damage sensor to help optimize the composite for different applications," Gilman said. "If you attempt a design change, you can figure out if the change you made improved the interface of a composite, or weakened it."

This research was funded through collaborative research agreements with both the Air Force Office of Scientific Research and the Army Research Office.

J.W. Woodcock, R. Beams, C.S. Davis, N. Chen, S.J. Stranick, D.U. Shah, F. Vollrath, and J.W. Gilman, Observation of Interfacial Damage in a Silk-Epoxy Composite, Using a Simple Mechanoresponsive Fluorescent Probe, *Adv. Mater Interfaces* 2017, http://dx.doi.org/10.1002/admi.201601018/abstract

*Continued from page 8*

Such nanoscale variations of the magnetization could become crucial to document, said Gilbert, for engineers trying to optimize the performance of a magnetic memory device. The variation in magnetization direction could also affect the ability of electron spin to flip the magnetization.

"Instead of flipping magnetization up or down, the spin current flips the magnetization along whatever its preferred local [spin] axis happens to be," notes Gilbert. The variation in magnetization direction suggests that materials used for magnetic memory devices may need to be gently heated, a process that aligns nanoscale magnetic domains.

In separate work, NIST scientists Mark Stiles and Vivek Amin, who has a joint appointment with the University of Maryland, focus on the theory describing the torque measured in the SEMPA experiments. There, a stream of polarized electrons generated in a nonmagnetic metal strip interacts with the magnetization of an overlying material. In particular, the team has developed a model that may help determine which group of polarized electrons play the more important role in reversing the direction of magnetization in adjacent material—those originating at the surface of the nonmagnetic material or those from the interior.

The answer could guide the fabrication of more efficient magnetic memory devices. For instance, determining which group of electrons are the dominant actors could suggest ways to minimize the current needed to flip the magnetization, Stiles said.

"Right now, we're in the process of publicizing the model to experimentalists, trying to get them to use it to better understand their data," he noted.

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# ‘START CODONS’ IN DNA AND RNA MAY BE MORE NUMEROUS THAN PREVIOUSLY THOUGHT

For decades, scientists working with genetic material have labored with a few basic rules in mind. To start, DNA is transcribed into messenger RNA (mRNA), and mRNA is translated into proteins, which are essential for almost all biological functions. A central principle regarding translation has long held that only a small number of three-letter sequences in mRNA, known as start codons, could trigger the production of proteins. But researchers might need to revisit and possibly rewrite this rule, after recent measurements from a team including scientists from NIST.

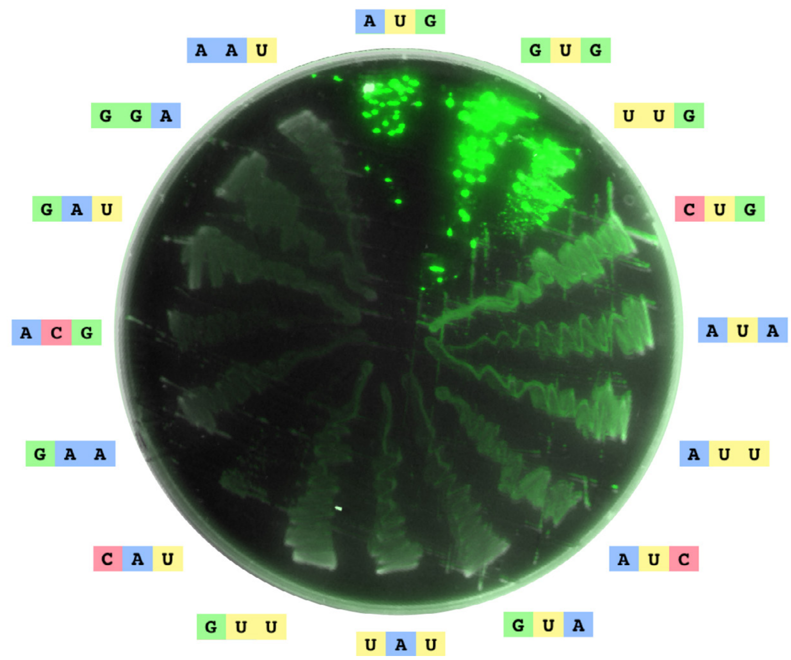


Image of an agar plate streaked with 16 different strains of *Escherichia coli*, each containing a green fluorescent protein with a different start codon (annotated along the edge of the plate). The 16 codons correspond to the 16 strongest expressing codons. Image is a composite of two super-imposed images from a laser scanner.
Credit: Jeff Glasgow/Ariel Hecht/Kelly Irvine/NIST

The findings, published in the journal *Nucleic Acids Research* by scientists in a research collaboration between NIST and Stanford University, demonstrate that there are at least 47 possible start codons, each of which can instruct a cell to begin protein synthesis. It was previously thought that only seven of the 64 possible triplet codons trigger protein synthesis.

“It could be that many potential start codons had remained undiscovered because no one could see them,” said lead author Ariel Hecht, a team member at the Joint Initiative for Metrology in Biology (JIMB), a research collaboration that includes NIST and Stanford.

Scientists made many of their initial discoveries about DNA and RNA, including start codons, in the 1950s and 1960s. Those ideas have since become enshrined in textbooks around the globe as the modern understanding of the rules of molecular biology.

Genetic code is typically represented via sequences of four letters—A, C, G, and T or U—which correspond to the molecular units known as adenine, cytosine, guanine and thymine (for DNA code) or uracil (for RNA code). Fifty years ago, the best available research tools indicated that there were only a few start codons (with sequences of AUG, GUG and UUG) in most living things. Start codons are important to understand because they mark the beginning of a recipe for translating RNA into specific strings of amino acids (i.e., proteins).

The JIMB team’s realization that there might be something amiss in the general understanding of how codons perform began unexpectedly over a round of bagels and coffee. Hecht and his colleagues Jeff Glasgow, Lukmaan Bawazer and Matt Munson were discussing colleague Paul Jaschke’s experiment where he had replaced the start codons of several genes of a virus PhiX174 with codons that should not have started translation (AUA and ACG). However, to Jaschke’s surprise, he was still detecting the expression of those genes that should have been silenced due to removal of their start codons.

Hecht and colleagues, together with Jaschke, pursued what seemed like a rather naive question: What if the results indicated that codons didn’t fit a traditional description of start or not, but instead had varying likelihoods to start translation? To the best of their knowledge, no one had ever systematically explored whether translation could be initiated from all 64 codons. No one had ever proved that you cannot start translation from any codon.

“We kind of all collectively asked ourselves: had anyone ever looked?” said Hecht. A further review of available literature on the topic indicated that the answer was no.

Unlike geneticists working a half-century ago, the JIMB team and others who peer into the inner workings of cells now have far more powerful tools at their disposal, including green fluorescent protein (GFP), a protein adapted from jellyfish, and nanoluciferase, another protein adapted from a deep sea shrimp. Both GFP and nanoluciferase emit light when expressed inside cells and have been optimized within the past decade to produce very strong signals that can be used to probe the cells in depth.

"Ten years ago the tools to make this kind of measurement didn't exist," Hecht said.

NIST specializes in the process of precision measurement, and the start codon challenge proved irresistible to the JIMB team. The collaboration was formed in 2016 with the goal of advancing biomeasurement science and facilitating the process of discovery by bringing together experts from academia, government labs and industry for collective scientific investigations.

With the use of GFP and nanoluciferase, the team measured translation initiation in the bacteria *E. coli* from all 64 codons. They were able to detect initiation of protein synthesis from 47 codons.

The implications of the work could be quite profound for our understanding of biology.

"We want to know everything going on inside cells so that we can fully understand life at a molecular scale and have a better chance of partnering with biology to flourish together," said Stanford professor and JIMB colleague and advisor, Drew Endy. "We thought we knew the rules, but it turns out there's a whole other level we need to learn about. The grammar of DNA might be even more sophisticated than we imagined."

Still, the JIMB team cautions, this paper is really just the first step, and it is unclear what studies of other organisms will reveal.

"We need to be very careful about extrapolating from these findings or applying them to other organisms without further, deeper research," said Hecht. He hopes that this paper will encourage or inspire other researchers to explore the topic to find even more answers.

"It could be that all codons could be start codons," Hecht said. "I think it is just a matter of being able to measure them at the right level."

Ariel Hecht, Jeff Glasgow, Paul Jaschke, Lukmaan Bawazer, et al., Measurements of translation initiation from all 64 codons in *E. coli*., *Nucleic Acids Res*., 2017, http://dx.doi.org/10.1093/nar/gkx070

## NIST TECHNOLOGY USED TO HELP IDENTIFY KEY ENZYMES IN DISEASE

Elephantiasis and river blindness are neglected tropical diseases caused by filarial nematode parasites that are transmitted to humans by insects. Collectively, they afflict 150 million people in over 80 countries and threaten the health of over 1.5 billion. MML scientists recently contributed to a paper in the journal *Nature Communications* that reports the discovery of a series of cyclic peptides and analogues that exhibit potent and isozyme-selective inhibition against enzymes essential for the parasites that cause elephantiasis and river blindness, but that are absent from humans. There are no high-throughput screening methods that can directly measure the activity of these key enzymes (phosphoglycerate mutases). So, the conventional approach uses two additional coupling enzymes to produce a color change in the inhibition screening assay. This can lead to problems if the apparent inhibition is due to a reaction of the drug molecule with the coupling enzymes instead of the targeted mutase enzyme. The NIH National Center for Advancing Translational Science (NCATS) approached NIST about the possibility of applying NIST technology to this problem. To verify the NCATS results, NIST scientists developed a method, based on gradient elution moving boundary electrophoresis, that directly measures the activity of the mutase enzymes.

The cyclic peptides and accompanying crystallographic information described in the paper reveal an important binding mode and inhibition mechanism for an enzyme previously considered 'undruggable' and may be applicable to other difficult drug targets.

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## POPULAR PROTEOMICS TOOL NOW INCORPORATES NIST MASS SPECTRAL SEARCH SOFTWARE

The newest release of Mascot, a popular proteomics software package, incorporates the peptide library search program MSPepSearch developed by the NIST Mass Spectrometry Data Center. Mass spectrometry is the most widely used discovery tool in proteomics and identification of proteins/peptides in a sample is the key first step. Mascot, maintained by Matrix Science Ltd, aims at determination of the precise identities of as many proteins/peptides as possible in each biological sample mass spectral data set. Prior versions of Mascot used simple theoretical fragmentation models of the peptide for identification. In the new release of Mascot, NIST's MSPepSearch is incorporated to allow a faster, more reliable method for identifying peptides by matching them to spectra in a mass spectral library. This method also enables spectra for unusual and unpredictable spectra to be identified in the same way as conventional peptides. NIST has been a leader in developing spectral libraries for many years, including extensive libraries of peptides (http://peptide.nist.gov).

# OUTREACH AND PARTNERING

## LAUNCH OF THE HIGH-THROUGHPUT EXPERIMENTAL MATERIALS VIRTUAL LABORATORY

NIST and the National Renewable Energy Laboratory (NREL) have launched the High-Throughput Experimental Materials Virtual Laboratory (HTE-MVL), with the goal of generating the huge volumes of data needed to validate existing materials models and develop new, more sophisticated ones. The HTE-MVL will consist of a national network of high-throughput synthesis and characterization tools integrated into the Materials Genome Initiative (https://www.mgi.gov) materials data infrastructure. The facility will foster coordination and data integration across high-throughput experimental programs. The result will be a widely accessible, growing resource open to the entire materials research community.

The primary goal of the MGI is the discovery, optimization, and commercial deployment of novel materials twice as fast as today's practice, and at reduced cost. Since its inception in 2011, the MGI has resulted in significant progress in computational simulation and modeling to enable predictions of materials properties. More recently, an experimental component, based on high-throughput experimental materials science, has been added. However, there remain serious challenges that the materials community must overcome to enable widespread deployment of an MGI-type approach to novel materials development. For example, data, both experimental and simulated, must be made discoverable, accessible, and interoperable. Further, even one "brick and mortar" high-throughput experimental facility would be very costly. The HTE-MVL was established in response to both challenges.

To promote the success of this project NIST and NREL are working on several fronts:

- Development of a conceptual model for integration of components within the materials data infrastructure consisting of: registries, repositories, data transfer services, laboratory information management systems, instruments, computing, and more.
- Development of a specialized registry and repository to enable discovery and access of items within the virtual laboratory, such as sample libraries, instruments, data, and more.
- Development of community interchange standards for data and metadata
- Execution of a round-robin experiment where transparent conducting oxide libraries are synthesized and characterized by both institutions and data is managed by the new materials data infrastructure.
- Outreach to critical stakeholders, such as funding agencies, potential new member institutes, potential new users, potential new contributors, and potential new data consumers.

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## FEDERAL MATERIALS SCIENCE LEADERS GATHER AT NIST

"How can federal scientists across agencies most effectively address pressing national needs?" Over 100 federal scientists convened at the Federal Interagency Materials Representatives meeting, held at the NIST Gaithersburg campus on February 1, 2017 to address this question. Participants included federal scientists from the U.S. Depts. of Commerce, Defense, Energy, and Transportation, NASA, the National Science Foundation, and more. Plenary speakers, including Linda Horton from Dept. of Energy, Basic Energy Sciences, Benjamin Leever from the Air Force Research Laboratory, and Heather Evans from NIST shared best practices and lessons learned for planning and managing government agency investments in science, engineering, and technology to enhance the impact of materials research in the U.S. Scientists discussed successes and challenges in strategic planning, coordination, research overlap, the connection between basic and applied research, and leveraging center- and institute-based research structures during breakout sessions. The annual meeting is open to federal scientists.

## COLLABORATION TO UNDERSTAND ARMOR BACKING MATERIAL RHEOLOGY

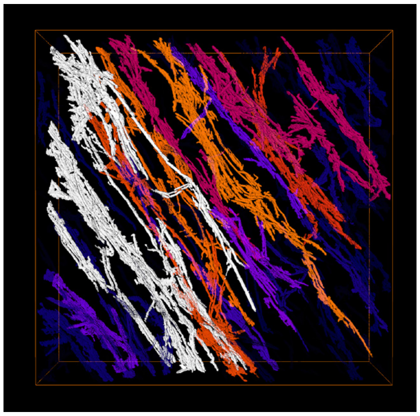
Behind-armor blunt trauma is a deformation in the ballistic witness material caused when armor stops a projectile from perforating armor. Understanding the rheological behavior of this material is critical for the future of both Department of Defense and civilian documentary standards that rely on ballistic witness materials for determination of compliance with requirements for behind-armor blunt trauma protection. Recently, members of MML's Security Technologies Group hosted representatives from the Army Research Laboratory (ARL) in Aberdeen, Maryland and Aberdeen Test Center (ATC) to discuss rheological characterization of a potential new ballistic witness material being formulated by ARL and ATC designated as ARTIC. NIST will use new specialized technology to characterize the rheological properties of several candidate formulations of ARTIC.

## REGENERATIVE MEDICINE STANDARDS COORDINATING BODY

More and larger companies are entering the regenerative medicine field through the development of cell therapies such as CAR-T. Standards play an important role in helping to assure the quality of regenerative medicine products and processes, and speed regulatory approval. The Standards Coordinating Body (SCB) is an industry-led public-private partnership with NIST to help coordinate standards development for regenerative medicine. Coordination is key considering the passage of the 21st Century Cures Act, which directs the U.S. Secretary of Health and Human Services to confer with NIST and other stakeholders to facilitate the coordination and prioritization of the development of standards for regenerative medicine. MML representatives recently met with representatives of the SCB to discuss priorities for carrying out the intentions of the agreement. The partnership with the SCB will be important as NIST determines how best to prioritize activities in this rapidly evolving field.

## NIST/IBM COLLABORATIVE STUDY ON SELF-ASSEMBLED STRUCTURE PUBLISHED

The journal *Macromolecules* recently published a paper by MML researcher Vivek Prabhu, with a colleague from the IBM Almaden Research Center, on block co-polymer self-assembled structure. The paper shows, through very detailed experiments, that the chemical nature of the end-group of a block co-polymer can strongly affect the microstructure of a self-assembled structure. Block copolymers are like surfactants in that one part of the molecule is different than the other (i.e. 'likes' oil or 'likes' water). These copolymers self-assemble into a variety of structures that are used in drug delivery, food products, or as microgels. The structure determines the properties such as the rate of a drug delivery. Here, the chemical nature of just the end group, a small part by mass, is strong enough to lead to many structural changes that are probed in detail. Link: https://dx.doi.org/10.1021/acs.macromol.6b02524



## NATARAJAN WINS FEI IMAGE AWARD

Bharath Natarajan, a NIST associate from Georgetown University working on the 3-D imaging of carbon and cellulose nanofibers in the Nanomanufacturing Program, submitted an image of a 3-D volume reconstruction of a forest of carbon nanotubes (CNT) embedded in epoxy, titled "A (CNT) bundle is strong." The transmission electron microscopy (TEM) sample was prepared by focusing ion beam (FIB) milling in a FEI Helios FIB and imaged in an FEI Titan TEM using electron tomography. The tilt series was reconstructed and then processed using in-house software to identify CNT bundles and color them based on their size. This bundling information is key to understanding the network properties as well the axial mechanical properties of these composites.

## GLOVER RECEIVES ASTM AWARD

Jack Glover, of MML's Security Technologies Group, has received an ASTM F12 Award of Excellence in recognition of his efforts and accomplishments in developing the recent significant revision of the ASTM F792 "Standard Practice for Evaluating the Imaging Performance of X-ray Systems." This revision included the design, development, and performance verification of the image quality artifact standards and of the algorithms used to compute the image quality parameter values. ASTM F792 is the major technical performance standard for testing cabinet X-ray systems, such as those used to screen carry-on baggage at airports. The standard was first published in 1982 and is used throughout the world for testing cabinet X-ray systems. For the first time in 15 years, the standard recently underwent a major revision. The working group, led by NIST researchers Jack Glover, Ron Tosh, Larry Hudson, and Nick Paulter, also included representatives from the governments of Germany, UK, Brazil, and Australia as well as U.S. agencies such as the Department of Homeland Security, Transportation Security Administration, and Federal Bureau of Prisons and numerous equipment manufacturers. This revision of the standard was a major improvement and was necessary to keep pace with the evolving technology at the checkpoint. The F12 Award of Excellence was established in 1997 and is conferred, as warranted, by Committee F12 on Security Systems and Equipment in recognition of meritorious contributions to the cause of voluntary standardization, specifically with respect to security systems and equipment standards. The award has been established to recognize outstanding service to Committee F12.

## BEST PAPER AWARD FROM THE MICROSCOPY SOCIETY OF AMERICA

The Microscopy Society of America recently recognized a NIST/University of Arizona authored paper (led by MML's Vladimir Oleshko) as the best paper in the Materials Applications category. The paper is entitled, "Analytical Multimode Scanning and Transmission Electron Imaging and Tomography of Multiscale Structural Architectures of Sulfur Copolymer-Based Composite Cathodes for Next Generation High-Energy Density Li-S Batteries" (*Microsc. Microanal.* 22, 1198-1221). *Microscopy and Microanalysis* is an international microscopy journal published for the Microscopy Society of America (MSA) by Cambridge University Press. It is the official journal of the Microscopy Society of America, Microanalysis Society, and several other societies. Each year the journal selects the best paper in three different categories: Materials Applications, Biological Applications, and Techniques and Equipment Development. The award will be presented to Oleshko at the Microscopy and Microanalysis 2017 Meeting by Ian Anderson, President of MSA.

## NIST GUEST RESEARCHER HONORED WITH LITHUANIA NATIONAL SCIENCE PRIZE

On March 7, 2017, Gintaras Valinčius, division chief at the Biochemical Institute of Vilnius University and NIST guest researcher, was awarded the Lithuania National Science Prize. Valinčius was recognized for his indefatigable commitment to research/science development in Lithuania and the European Union, teaching at Vilnius University, and his seminal contributions to electrochemistry and electrochemical impedance to spectroscopy (EIS) in particular. The National Science Prize is one of the top prizes awarded to scientists in Lithuania and has been called 'Lithuania's Nobel Prize.' Valinčius has a long history of collaborative research with NIST and the Institute of Bioscience and Biotechnology Research. Valinčius first came to NIST as a visiting scientist in 1998 and has returned nearly every year to conduct research focused on hybrid bilayer membrane and tethered bilayer lipid membranes. Using tether compounds synthetically prepared by retired NIST employee, Dave Vanderah, Valinčius carried out careful EIS measurements demonstrating the preparation of highly insulating lipid bilayers, essential for the study of integral membrane proteins, which comprise 60% of all drug targets by the pharmaceutical industry. Together they have co-authored 14 papers since 2003. Over the last three years, Valinčius has developed the first theoretical framework that allows EIS spectral data to be interpreted in more realistic structural models rather than the less informative resistance-capacitance circuit models.

## TARLOV DELIVERS MEMORIAL LECTURE AT UMD SCHOOL OF PHARMACY ANNUAL RESEARCH DAY

On April 12, 2017, MML Division Chief Michael Tarlov gave the Andrew G. DuMez Memorial Lecture at the University of Maryland School of Pharmacy in Baltimore, held during their annual research day. Tarlov's talk was entitled "The Role of Measurements and Standards in the Development and Manufacturing of Biopharmaceuticals." After the talk, Natalie Eddington, Dean of the UMD School of Pharmacy, presented Tarlov with an honorary award.

## COBLE ELECTED FELLOW OF THE AMERICAN ACADEMY OF FORENSIC SCIENCE

Mike Coble of MML's Applied Genetics Group was recently elected Fellow of the American Academy of Forensic Science (AAFS) at their 2017 annual meeting. AAFS is a multi-disciplinary professional organization that provides leadership to advance science and its application to the legal system. The objectives of the Academy are to promote professionalism, integrity, competency, and education, and foster research, improve practice, and encourage collaboration in the forensic sciences. Over the past 16 years, Coble has been an active member in AAFS, presenting his work on DNA mixture analysis, and acting as moderator, student presentation judge, and workshop leader. The leadership of AAFS recognized these contributions and Coble's substantial contributions to the forensic science literature and training regarding DNA mixture analysis with the honor of Fellow.

*A sample of high-strength X70 steel pulled apart by NIST testing.*

## MEASUREMENT SCIENCE FOR INFRASTRUCTURE RENEWAL

*NIST helps pipeline operators realize the safety benefits and cost-savings of new high-strength steel alloys.*

NIST's Material Measurement Laboratory provides new test methods and data to inform improved design methods, material choices, and industry standards for fossil fuel pipelines. We have unique facilities for measuring steel properties as specimens are pulled, bent, or otherwise stressed, like they might be in actual service. Our data informs computer models that predict how new, stronger steels behave under various conditions, contributing to the safe use of thinner walled pipes that are more cost-effective. We're also leading an effort to reduce the need for expensive, full-scale pipe bursting tests with laboratory-scale test methods that significantly reduce costs, and our research on pipeline welds is being used to revise American Pipeline Institute standards.

We have a history of success in contributing to new standards and codes that benefit industry while maintaining safety: NIST's tests on the pipeline steel used to transport hydrogen, a plentiful and clean burning fuel that can help the U.S. become less dependent on foreign petroleum, led to a code change that allowed hydrogen pipeline owners to switch to stronger, thin-walled pipes without increased cost. The stronger steel means that pipelines can be larger in diameter and move hydrogen at higher pressures, so more hydrogen can be transported faster and safer.

- **2.5 million** miles of pipelines cross all 50 U.S. states to transport natural gas, liquid petroleum products, and other chemicals critical to our energy infrastructure and economy
- **$5.3 billion** in total costs and 885 deaths and injuries from significant pipeline incidents since 2005
- **$100 million** saved by energy companies by avoiding unnecessary shutdowns thanks to data from NIST research that confirms assessment methods for vintage pipelines. More than 50% of the pipelines in the U.S. are made of older grades of steel

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## MATERIAL MEASUREMENT LABORATORY

The Material Measurement Laboratory supports the NIST mission by serving as the national reference laboratory for measurements of matter, providing broad support for chemical, biological, and materials sciences. Our fundamental and applied measurement science research expands possibilities for determining the composition, structure, and properties of manufactured, biological, and environmental materials, and the processes that create them. In addition, MML drives the development and dissemination of tools—including measurement protocols, certified reference materials, critically evaluated data, and best practice guides—that help assure quality measurements of matter. Our research and measurement services support progress in areas of national importance including advanced materials, energy, environment, food safety and nutrition, forensic science, health care, manufacturing, physical infrastructure, and safety and security. MML also coordinates the NIST-wide Standard Reference Materials® (SRM) and Standard Reference Data programs.

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