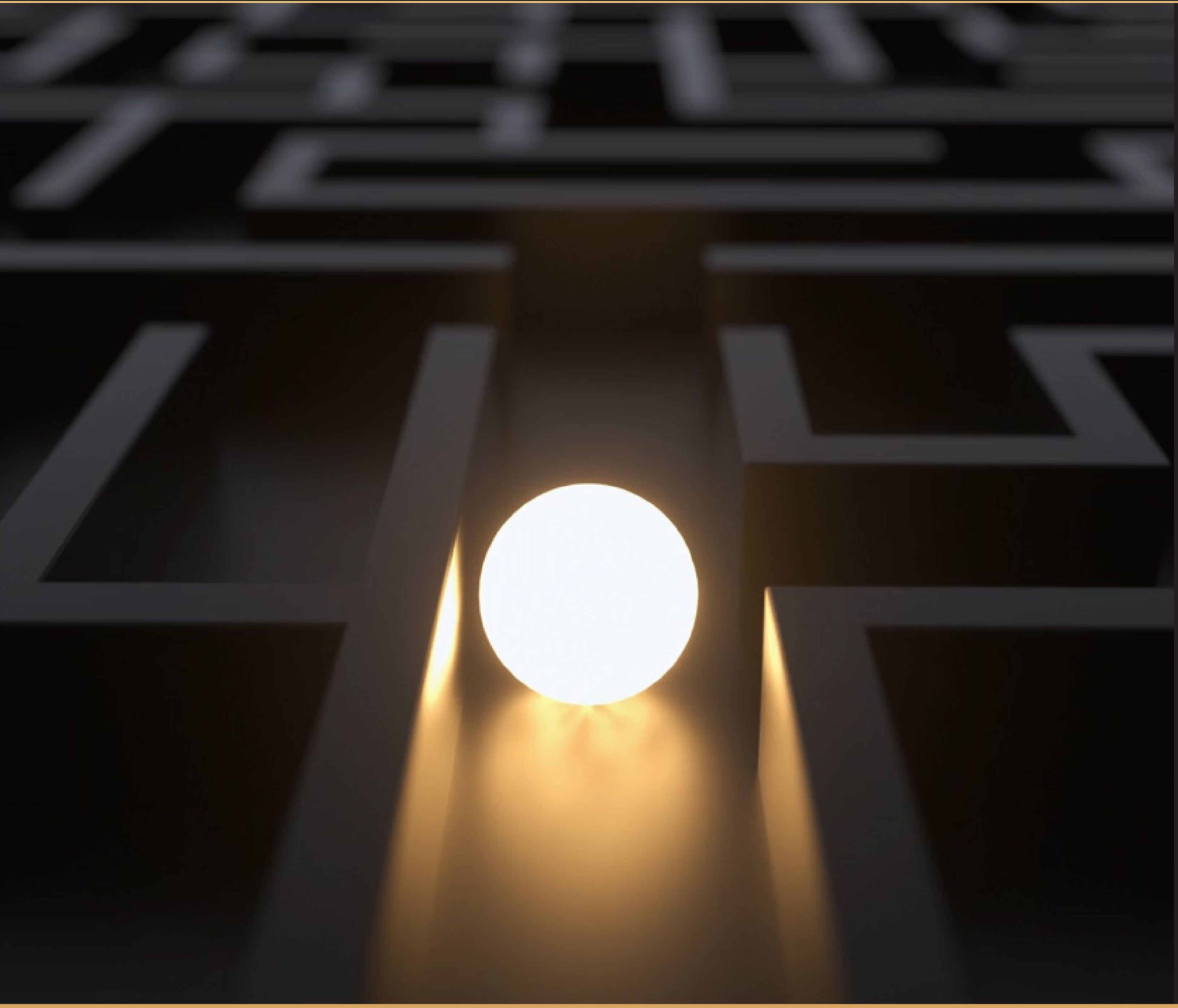
RESEARCH

Laboratory Directed Research & Development

Leading to ***amazing*** results.



2025 ANNUAL REPORT

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Sandia National Laboratories

U.S. DEPARTMENT of ENERGY

NNSA National Nuclear Security Administration

LDRD

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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LABORATORY DIRECTED RESEARCH AND DEVELOPMENT
2025 ANNUAL REPORT

From the Chief Research Officer

As we reflect on the accomplishments of the Laboratory Directed Research and Development (LDRD) program in FY25, it's clear that Sandia's commitment to advancing national security and technological innovation remains as vital and vibrant as ever.

Our strategic approach to LDRD is anchored in the three program objectives: Mission Agility, Technical Vitality, and Workforce Development. Together, these guide our efforts to respond swiftly to emerging national security needs while fostering an environment of innovation and collaboration.

LDRD helps us stay agile, allowing Sandia to effectively anticipate new threats and opportunities before specific mission needs arise. By investing in research that pushes the boundaries of science and engineering, we are developing technical capabilities that will help our nation tackle future problems with advanced solutions. And by nurturing and developing the skills of the workforce through the LDRD program, we are equipping employees who can drive innovation within the Labs and across the Department of Energy (DOE) Complex.

Throughout this report, you will discover the advanced technological areas or research fields that are critical to national security, defense, and scientific innovation. They each are complex, require interdisciplinary talent and cooperation, and possess the potential to significantly impact various sectors, including defense, aerospace, energy, and information technology.

The following list of "Hot Topics" is not comprehensive, but it effectively highlights some key "can't miss" sectors where Sandia and the National Nuclear Security Administration (NNSA) are actively contributing to national efforts.

- **Space applications**
- **Digital assurance for high consequence systems**
- **Hypersonic technologies**
- **Radiation-hardened electronics**
- **Pulsed power technologies**
- **Quantum computing technologies**
- **Advanced materials**
- **Artificial Intelligence**

We view Sandia's discretionary R&D funds, via our LDRD program, as one of the most consequential investments we make on behalf of our country. The continued success and impact of our LDRD program is an imperative. We believe the LDRD program is on a great trajectory to impart much-needed technology step changes for our Nation.

Douglas B. Kothe
Associate Laboratories Director & Chief Research Officer
Advanced Science and Technology

Contents

HOT TOPICS

Space applications

- *Strengthening national security through GPS-denied megasonics navigation system*
- *Bolstering national defense by monitoring and characterizing natural and artificial hypersonic objects*
- *Revolutionizing defense and communications with self-amplified resonators*
- *Science and Technology Advancing Resilience for Contested Space (STARCS) Mission Campaign: Designing effective experiments to increase space system resilience*
- *STARCS Mission Campaign: Increasing satellite resilience against laser dazzle with event-based imaging*
- *STARCS Mission Campaign: Developing advanced models for protecting solar cells*
- *STARCS Mission Campaign: Boosting satellite operations to combat cyberattacks effectively*
- *STARCS Mission Campaign: Securing space infrastructure through data-driven digital twin modeling*
- *See also Digital Assurance for High Consequence Systems (DAHCS) Mission Campaign*

Digital assurance for high consequence systems

- *Digital Assurance for High Consequence Systems (DAHCS) Mission Campaign: Jabberwocky: Developing a common language for digital assurance*
- *DAHCS Mission Campaign: Theorems in Service of Sound Composition, Rapid Modeling, and Scalable Analysis*
- *DAHCS Mission Campaign: Attack Graphs for Digital Assurance*
- *DAHCS Mission Campaign: Semi-Automated Vulnerability Exploration*
- *DAHCS Mission Campaign: System Theoretic Reasoning Across Tiers of Abstraction*
- *DAHCS Mission Campaign: Templates for Risk-informed Assurance with Curvature Embeddings*
- *See also Science and Technology Advancing Resilience for Contested Space (STARCS) Mission Campaign*

Hypersonic technologies

- *Advancing optical emission predictions for next-generation hypersonic vehicles*
- *Thermal Protection Systems (TPS) Grand Challenge: Transforming thermal protection systems analysis for next-generation hypersonic vehicles*
- *Strengthening national security through GPS-denied megasonics navigation system*
- *Improving hypersonic airflow analysis for modern defense applications*
- *Bolstering national defense by monitoring and characterizing natural and artificial hypersonic objects*
- *Fortifying fire control algorithms for cooperative hypersonic target prediction and interception*

Radiation-hardened electronics

- *Enhancing national defense with custom radiation-hardened RF circuits*
- *Radiation-Hardened Edge Processing (RAD-EDGE) Grand Challenge: Accelerating real-time artificial intelligence with advanced analog in-memory computing*
- *Advancing understanding of combined radiation effects on critical microelectronics*
- *Evolving semiconductor technology for national security applications*

Pulsed power technologies

- *Designing Z platforms for transformative opacity research*
- *Assured Survivability and Agility with Pulsed Power (ASAP) Mission Campaign: Developing a better way to manage debris on the Z machine*
- *ASAP: Improving energy efficiency in pulsed power systems with new materials*
- *ASAP: Optimizing energy efficiency in the Z Accelerator for national security*
- *ASAP: Enhancing current delivery using innovative vacuum cassette technology*
- *ASAP: Innovative transmission line designs for future pulsed power systems*
- *ASAP: Evaluating next-gen pulsed power architectures for dynamic materials properties experiments*
- *Advancing magnetized liner inertial fusion performance by understanding electothermal instability*
- *Improving the predictive capability for modeling metallic liners used in fusion research*

Quantum computing technologies

- *Advancing portable optical clocks for enhanced navigation and security*
- *Upgrading quantum systems through innovative ion trap integration*
- *Improving navigation accuracy through advanced semiconductor laser technology*
- *Assessing localized states impact on next-gen materials for moving energy and information*
- *Revolutionizing x-ray detection by advancing quantum sensors using atomic precision advanced manufacturing*
- *Creating secure quantum communication channels with silicon defects*
- *Discovering quantum computing errors using interpretable neural networks*

Advanced materials

- *Investigating nanoscale processes that underlie the ignition of reactive materials*
- *Understanding how material composition affects radiation resistance in fusion materials*
- *Enhancing energy storage and flexible electronics by understanding deformation in layered materials*
- *Unlocking molecular insights to support material development and energy efficiency*
- *Optimizing thermal expansion in polymers for diverse industrial applications*
- *Revolutionizing construction materials utilizing zeolite minerals*
- *Strengthening energy security by developing novel high-entropy metal-organic frameworks*
- *Fortifying safety in confined spaces through tailored metal-organic frameworks materials*
- *Accelerating defect materials discovery using machine learning*

Artificial Intelligence (AI)

The LDRD program continues to leverage current AI tools to enhance our research productivity and make substantial and growing investments to advance the state-of-the art of AI tools pertinent to our broad mission space. A differentiating thrust for Sandia's AI research investments is the development of trusted AI tools. Read about one LDRD project in FY25 (**Evolving qualitative data into trustworthy insights using generative AI**) that is poised to make a significant impact.

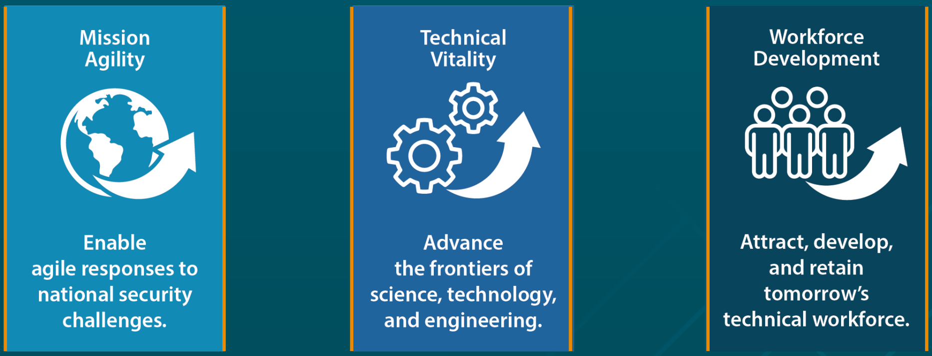
LDRD Program Overview

Sandia operates as a federally funded research and development center (FFRDC) dedicated to the advancement and application of cutting-edge science and engineering to address national security challenges. This mission is driven by the experts conducting research at the Labs and supported through collaborations with universities and industry partners.

The LDRD program at Sandia is designed to sustain the scientific and technical excellence of the Labs while enhancing the capacity to meet future national security requirements. This program uses discretionary funds for innovative, foundational research projects that develop and leverage essential science, technology, and engineering (ST&E) capabilities. In accordance with Congressional intent (P.L. 101-510) and guidance from the Department of Energy (DOE Order 413.2C, Chg 1), Sandia's LDRD program plays a vital role in preserving the nation's scientific and technical vitality.

LDRD PROGRAM OBJECTIVES

The objectives of Sandia's LDRD program provide overall direction and are in alignment with DOE Order 413.2C and guidance from the National Nuclear Security Administration (NNSA). The Mission Agility and Technical Vitality Objectives are reinforced by the Workforce Development Objective, which is essential for cultivating, expanding, and utilizing the technical expertise required to carry out R&D projects.

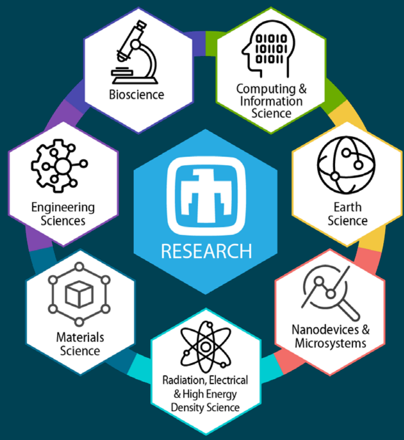


SANDIA'S LDRD PROGRAM STRUCTURE

Sandia's LDRD investments are organized around three Program Areas, which are subdivided into Investment Areas (IA). Each IA concentrates on research priorities that are discipline- or mission-based, as determined by Sandia's leadership. The structure of the LDRD program and the distribution of funds to the relevant IA are intended to ensure that LDRD investments are aligned with Sandia's strategic goals and the future needs of national security missions.

LDRD INVESTMENT AREA ROLES

RESEARCH FOUNDATIONS



The Research Foundations manage discipline-based science, technology, and engineering competencies that tackle the significant national security challenges within Sandia's mission scope. Each Research Foundation is dedicated to nurturing distinctive or unique capabilities across seven specific areas.

MISSION FOUNDATIONS

Sandia manages five primary portfolios that address challenges related to national security missions. The LDRD Mission Foundations are aligned with these portfolios and carry out the applied research necessary to develop capabilities and demonstrate effective solutions.

STRATEGIC INITIATIVES

Strategic Initiatives (SI) foster strategic partnerships and initiatives directed by the CRO/Labs. These initiatives encompass:

- Grand Challenge projects aimed at addressing significant research obstacles that necessitate large, multidisciplinary teams
- Mission Campaign IAs designed to intentionally transition ST&E from concept to mission impact
- Exploratory Express for executing short-term projects of strategic significance
- New Ideas to explore fundamental R&D for discovering transformative breakthroughs
- Strategic academic collaborations (138 in FY2025) and the Harry S. Truman and Jill Hruby Postdoctoral Distinguished Fellowships

LDRD Program Value – Performance Indicators

PERFORMANCE INDICATORS

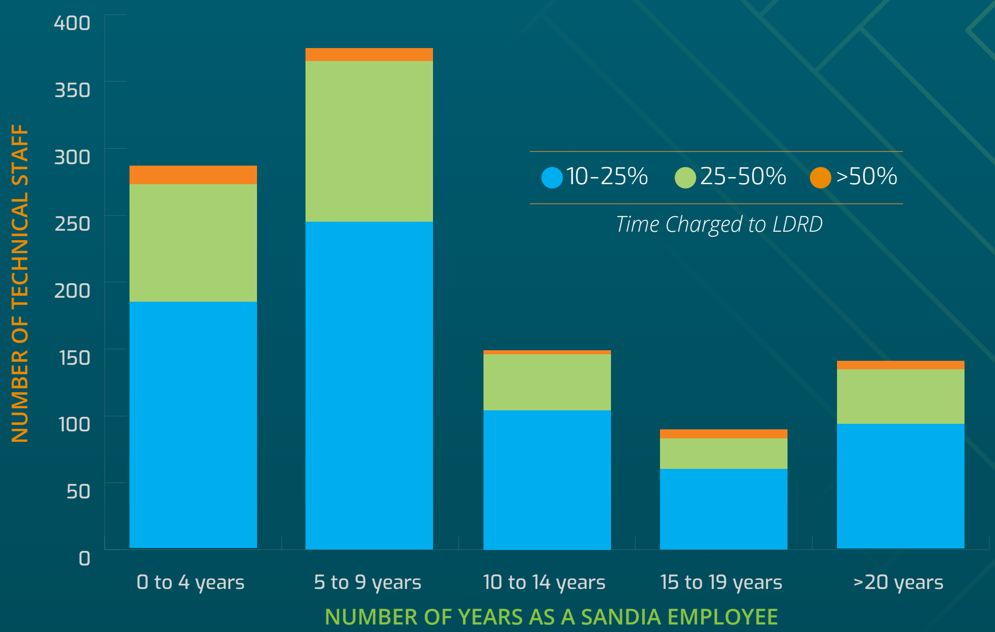
Although the FY2025 LDRD program accounted for only approximately 5.1% of Sandia's overall costs, the metrics presented below demonstrate that LDRD has a significantly greater relative impact on key performance indicators (KPI) and metrics for the Labs. The bar graph depicts the contributions of earlier career staff, underscoring LDRD's crucial role in attracting, developing, and retaining a top-tier workforce to address our most pressing national security challenges.

$260.6M
Total
Program Cost
(not including PM costs)

$445K
Median
Project Size

536
Total
LDRD Projects

260
New Projects
in 2025



57%
OF SANDIA TOTAL
278
LDRD-Supported Postdocs

58%
OF SANDIA TOTAL
19
LDRD-Supported Postdoc to Staff Conversions

33%
OF SANDIA TOTAL
416
Refereed Publications

51%
OF SANDIA TOTAL
138
Technical Advances

38%
OF SANDIA TOTAL
33
Patents Issued

29%
OF SANDIA TOTAL
53
Copyrights

85%
OF SANDIA TOTAL
6
R&D 100 Awards

Long-term Metrics

THE LONG-TERM IMPACTS OF LDRD INVESTMENTS

The LDRD program represents an investment in the nation's future, providing mission support that is frequently realized over an extended period. This section emphasizes the long-term (>5 year) impact of LDRD as a national asset. The performance indicators are updated on an annual basis. As anticipated, the data may fluctuate from year to year, so cumulative totals will be included and refreshed every five years.

ROOTED IN LDRD

Background

Through continuous improvement efforts, representatives from each LDRD program at the NNSA laboratories (Sandia, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory) regularly engage in a working group to exchange best practices and discuss methods for tracking the long-term impact of LDRD investments. The working group has established a set of common quantitative and qualitative long-term indicators, promoting a systematic approach for use by each NNSA LDRD laboratory. Additionally, it recognized that individual laboratories may opt to report other long-term indicators that align with their specific missions and capabilities.

Alignment with LDRD Objectives

The KPIs for LDRD, which encompass numerical KPIs represented by metrics and qualitative KPIs reflected in project highlights, demonstrate the long-term benefits and successes of the program in achieving its three objectives: Mission Agility, Technical Vitality, and Workforce Development. Since the KPIs intersect across these three objectives, this report will not offer a direct 1:1 mapping.

Importance of Qualitative Data

Creating numerical indicators to measure the success of R&D programs is generally acknowledged as a challenging task. The NNSA LDRD metrics working group established numerical success indicators for both Technical Vitality and Workforce Development. Project highlights, or "success stories," reflect achievements in Mission Agility and certain elements of the other two LDRD objectives that are not adequately represented by numerical metrics.

Tracing impact back to LDRD

In this section, you will encounter references to "LDRD roots." LDRD mentors and principal investigators (PI) frequently discuss the significance of an achievement having LDRD roots. A straightforward example might involve an invention idea that emerges during an LDRD project, with the development of the invention completed within the timeframe of LDRD funding. However, R&D progress is often slow. Generally, an achievement (such as an invention, publication, or capability) is considered to have LDRD roots if it is linked to one or more LDRD projects that were essential for its realization. In other words, if a current LDRD project builds upon a prior LDRD achievement, it is regarded as having "roots" in that earlier project. Additional relevant definitions for metrics will be provided in the following sections.

The Indicators

TOP 2%

A significant indicator of career progression in the ST&E fields is the acknowledgment of individuals as distinguished members of the technical staff, referred to as Senior Scientists/Engineers and Fellows at Sandia, Fellows at Los Alamos National Laboratory, and Distinguished Members of the Technical Staff at Lawrence Livermore National Laboratory. The term "Top 2%" is used here to reflect the intention at each laboratory to restrict membership to the top 1% or 2% of scientific and technical personnel. Typically nominated and vetted by a committee, the Top 2% are honored for achievements akin to a lifetime achievement award, specifically for their contributions to the mission of each laboratory.

Each year, Sandia appoints a select number of staff to the rank of Senior Scientist/Engineer, an honor awarded for exceptional leadership and consistently outstanding contributions to Sandia's national security missions. In FY25, 7 out of the 9 staff members promoted to Senior Scientist/Engineer had participated in the LDRD program as principal investigators or team members during their careers. Since FY11, 76% of Sandia's Senior Scientists/Engineers have careers with LDRD roots.

Sandia also offers special recognition to an elite group of individuals known as Sandia Fellows, who are acknowledged for their significant accomplishments for the Labs and the nation. Throughout Sandia's history, only 22 individuals have held this title (20 with R&D careers and 2 in non-technical roles). In FY25, ten of the R&D Fellows were on staff, all of whom have been involved with LDRD during their careers. The Strategic Initiatives pillar of the LDRD Program funds a series of projects selected and managed by Sandia Fellows. These Fellow projects allow the Labs' most exceptional R&D staff to mentor promising employees as they engage in cutting-edge, potentially high-impact research and development. In FY25, there were 33 active Fellow projects across eight Investment Areas (IA). Learn more about three Fellow projects:

- *Amplifying understanding of semiconductor reliability under neutron damage*
- *Unlocking molecular insights to support material development and energy efficiency*
- *Revolutionizing construction materials utilizing zeolite minerals*

LDRD AND TOP 2% TECHNICAL STAFF AT SANDIA

	SINGLE YEARS			FIVE YEARS		TO DATE*
	FY23	FY24	FY25	FY16-20	FY21-25	FY11-25
TOTAL AWARDS	26	14	10	53	75	157
AWARDS WITH LDRD ROOTS	21	10	8	44	57	118
PERCENTAGE WITH LDRD ROOTS	80%	71%	80%	83%	76%	75%
AVERAGE YEARS FROM FIRST LDRD EXPERIENCE	19	17.4	19.0	17.8	18.0	16.9

**Initial year to date: Each laboratory has chosen the appropriate lookback period that will ensure data integrity.*

SELECTED NEWLY PROMOTED SENIOR SCIENTIST HIGHLIGHTS

- George Bachand
- Cathy Branda
- Peter Marleau

Another important indicator of advancement and leadership in the ST&E field is the R&D 100 Award. Known as the prestigious "Oscars of Invention," these awards recognize the latest and most outstanding innovations, highlighting the top technology products from the previous year. The LDRD Program Offices at national labs/sites frequently collaborate with sister organizations, such as the Intellectual Property Office and Public Affairs, to determine whether R&D 100 winners in either the standard category or special awards have "LDRD roots." Due to the lengthy development process from an LDRD concept to practical application, the staff involved in an award-winning technology product may differ from the researchers who originally initiated the R&D. Each site's LDRD Program Office conducts a thorough interview process to uncover the specifics of how the LDRD efforts contributed to the acclaimed invention.

Since 1963, Sandia has received 165 awards, showcasing the Labs' contributions to developing products and technologies that have the potential to transform industries and improve the world. In the past three years, 73% of Sandia's R&D 100 winning contributions have been rooted in LDRD, while over the last 20 years, 70% have originated from LDRD.

LDRD AND R&D 100 AWARDS AWARDED TO SANDIA NATIONAL LABORATORIES

Counts include standard R&D 100 awards and special recognition awards, as well as awards led by other organizations where Sandia was a key partner.

*Initial year to date: Each NNSA laboratory has chosen the appropriate lookback period that will ensure data integrity.	SINGLE YEARS			FIVE YEARS		TO DATE*
	FY23	FY24	FY24	FY16-20	FY21-25	FY06-25
TOTAL AWARDS	6	2	7	32	28	101
AWARDS WITH LDRD ROOTS	4	1	6	22	19	71
PERCENTAGE WITH LDRD ROOTS	67%	50%	75%	69%	68%	70%
AVERAGE YEARS FROM FIRST LDRD EXPERIENCE	12.5	2	9.5	5.6	6.6	5.7

R&D 100 AWARD WINNERS

Electro-Optical Sensor (EOS) for High-Energy Environments and Applications

Israel Owens (PI). Team members: Andy Biller.

Israel Owens was the principal investigator for the award-winning Electro-Optical Sensor.

The Electro-Optical Sensor (EOS) offers a new solution to a long-standing challenge in measuring high voltages. It uses a tiny crystal, about the size of a dime, and a laser smaller than a shoebox to measure voltages up to 20 million volts without touching the electrical source. This non-contact method makes it safer to operate in situations where traditional methods may pose risks.

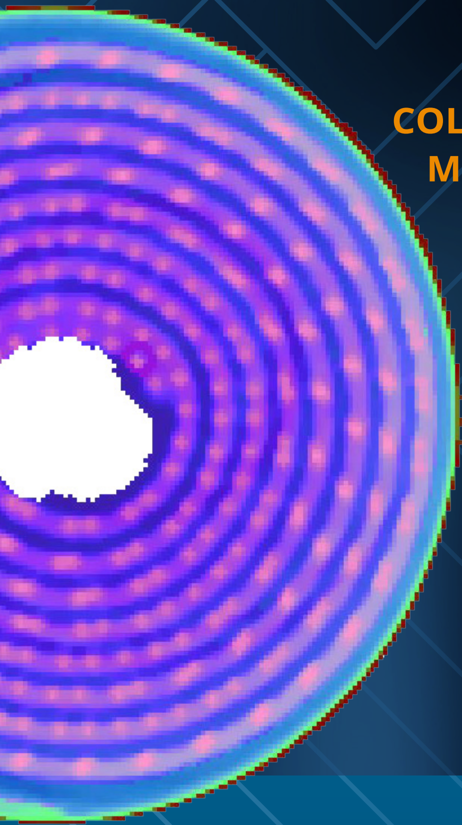
The EOS provides a clear and direct relationship between the measurement it takes and the actual voltage, which makes the process easier and more reliable. Additionally, its potential uses extend beyond just high-energy physics; it can also be applied in areas like lightning research and monitoring electrical utilities, showcasing its versatility and wide-ranging impact.

The remarkable EOS has connections to LDRD projects.

Watch the video.

COLORIZED HYPERSPECTRAL X-RAY IMAGING WITH MULTI-METAL TARGETS (CHXI–MMT)

Ed Jimenez (PI). Team members: Noelle Collins, Courtney Sovinec.



The CHXI-MMT technology is a major breakthrough in X-ray imaging, especially since there have been minimal advancements in the way x-ray images are acquired for over the past 50 years. By combining a special nano-patterned X-ray source with advanced detection methods, this technology provides incredibly detailed images that enhance diagnostic accuracy and analysis depth. In addition to imaging, it also identifies materials by examining how they absorb different wavelengths of x-rays. This dual capability of high-resolution imaging and precise material characterization marks a significant

CHXI-MMT scan of a CR123A Lithium Duracell Battery (the kind of battery used for a smoke detector). The colorization delineates between the different materials within the battery.

LOW COEFFICIENT OF THERMAL EXPANSION (CTE) MOLECULES TO RESOLVE THERMAL EXPANSION PROBLEMS IN POLYMERS

Erica Redline (PI). Team members: Chad Staiger, Eric Nagel, Jason Dugger, Kenneth Lyons, Alex Commisso, Meghan Kiker, Jeff Foster (Oak Ridge), Zachariah Page (UT Austin).

Materials scientist and principal investigator Erica Redline (center) led the R&D 100 Award winning research team helping make materials more durable. (Photo by Craig Fritz)

Harsh, dynamic environments can wreak havoc on applications, especially when multiple types of materials are bonded together, and they expand and contract at different rates due to temperature changes. This mismatch in thermal expansion can lead to failures in products before their expected end-of-life. Currently, manufacturers often add fillers to help reduce this mismatch, but this approach only partially solves the problem and can create other issues, such as processing.

Sandia partnered with the University of Texas at Austin and scale-up partner Tetramer Technologies, Inc. to develop a new solution. They created a special molecule that can adjust thermal expansion properties of polymers/plastics because of its chemical structure. Polymers are like beaded necklaces in that they are made up of several different beads (monomers) strung together. By replacing some of those beads with the special molecule, the polymer can better match the expansion rates of different materials without needing fillers.

This innovation, which is rooted in two LDRD projects, is a significant advancement in addressing the thermal expansion mismatch between polymers and metals or ceramics, a common issue in the industry. Traditionally, addressing this mismatch requires a lot of time and effort, often involving expensive or specialized materials. By using this new molecule, which is targeted for use in more affordable polymers, manufacturers can reduce costs and potentially eliminate the need for harmful materials, making their products safer and more efficient.

Watch the video.

advancement, particularly valuable in medicine, materials science, and forensics.

Because it enables high-precision measurements with traditional X-ray sources, it reduces the need for costly accelerator facilities and makes advanced imaging techniques more accessible to various industries and research institutions.

The technology addresses traditional X-ray imaging's limitations while enhancing reliability and accuracy, which is crucial for applications like surgical planning and structural integrity assessments. Overall, its capabilities open new possibilities in biomedical imaging, Transportation Security Administration applications, non-destructive testing, and advanced manufacturing, driving innovation and breakthroughs in science and technology. This breakthrough has roots in four LDRD projects beginning with one in 2012.

Watch the video.

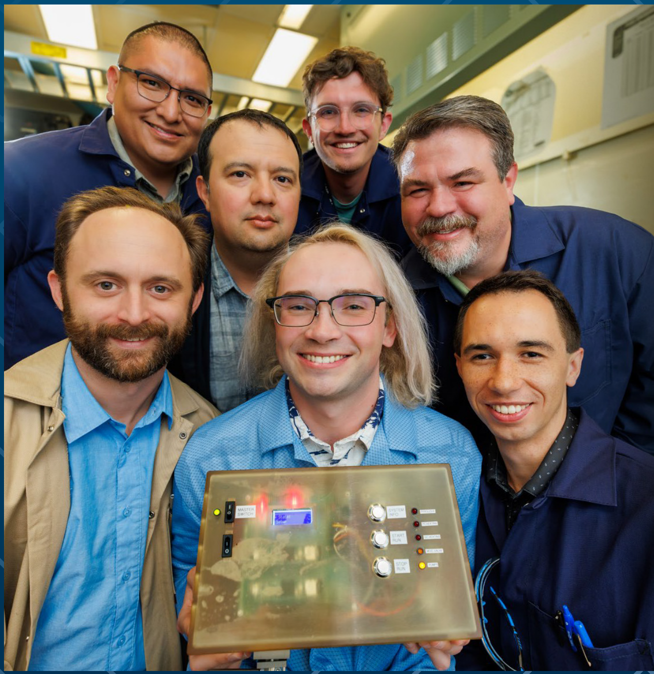
FENTANYL ANALOG INDEPENDENT DETECTOR (FAID)

Joshua Whiting (PI). Team members: Phil Mille, Ken Pfeifer, Matthew Moorman, Jason Sammon, Bryan Weaver, Alex Hare, Haley Bennett, Stephanei Eilts, Ashur Rael.

The FAID is a groundbreaking, hand-portable technology that revolutionizes public safety by delivering critical detection capabilities anytime, anywhere. Unlike older detection tools, FAID can recognize the basic chemical patterns found in fentanyl, which allows it to identify current and new versions of the drug.

With fentanyl being the leading cause of death among Americans aged 18 to 45 and over 4,000 potential analogs identified by the Department of Homeland Security, existing detection systems struggle to keep pace with this evolving threat. They rely on extensive libraries of synthesized analogs, leaving gaps in detection capabilities. In contrast, FAID can find fentanyl and its variations in very small amounts, even when mixed with other substances. This technology is a significant step forward in chemical detection, helping to protect our military personnel, emergency responders, and police officers. This technology has roots in two recent LDRD projects.

Watch the video.



A team of researchers from Sandia won an R&D 100 award for their hand-portable Fentanyl Analog Independent Detector.

TIME-RESOLVED DIFFRACTION FOR NIF (NATIONAL IGNITION FACILITY)

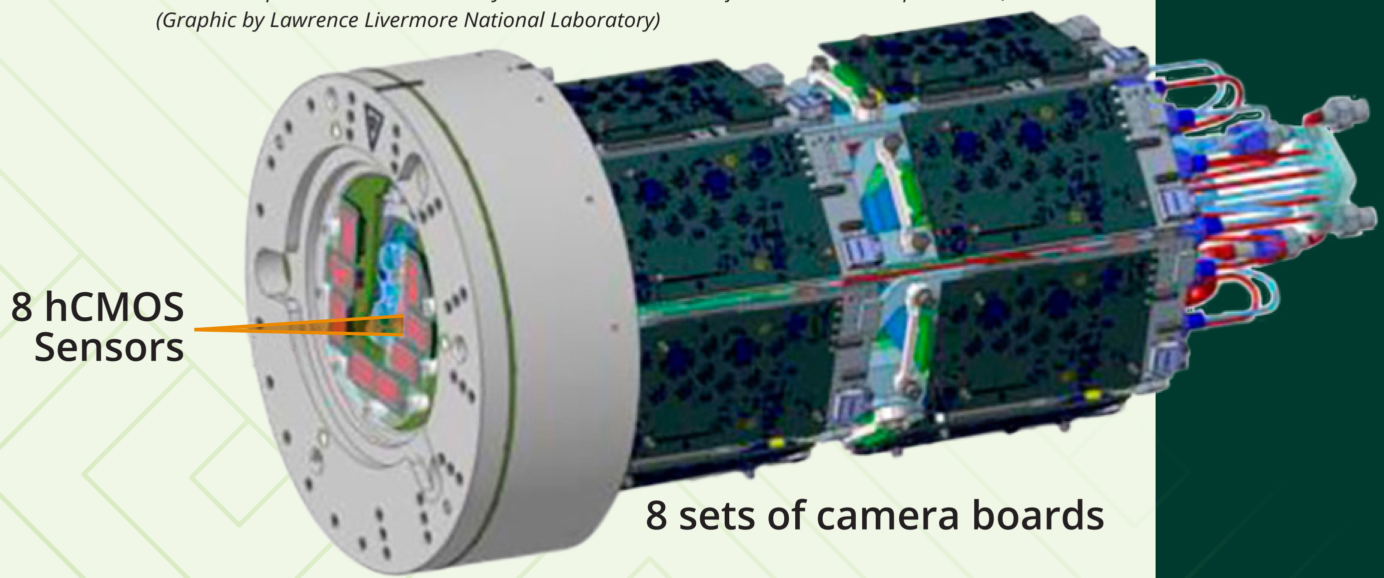
Led by Lawrence Livermore National Laboratory

Co-developers: Sandia, Advance hCMOS systems. Sandia team: Quinn Looker, John Porter, Michael C. Jones, Lu Fang, Gideon Robertson.

Measuring the properties of materials under extreme conditions, such as very high pressures (over 1 million bars), is important for various fields of High Energy Density research. This includes studying the dynamics of the Earth's core and improving fusion ignition at facilities like the National Ignition Facility. To create accurate physical models and simulations, precise information is needed about how materials behave under these extreme conditions.

The key properties of materials—like their strength, how easily they can be compressed, and their ability to conduct heat—are heavily influenced by their structural phase. Therefore, it is crucial to measure not only the density of the materials but also their phase and how they respond to changes in pressure. This comprehensive understanding helps researchers make better predictions and advancements in their work.

FIDDLE (short for Flexible Imaging Diffraction Diagnostic for Laser Experiments) is one of the most complex diagnostics ever fielded at NIF, housing all the electronics, cables, and water lines to support up to eight hybrid CMOS sensors and an x-ray streak camera. (The sensors were developed at Sandia and widely used in NIF Inertial Confinement Fusion experiments.) (Graphic by Lawrence Livermore National Laboratory)



The solution selected as the basis for the new time-resolved detector is the nanosecond-gated hybrid CMOS (hCMOS) sensors from Sandia that can capture multiple frames of diffraction data on a single laser-compression experiment. LDRD investments from the past and other NNSA support allowed scientists and engineers at Sandia to contribute to this effort.

BLEEDING MATERIALS & ENCLOSURES

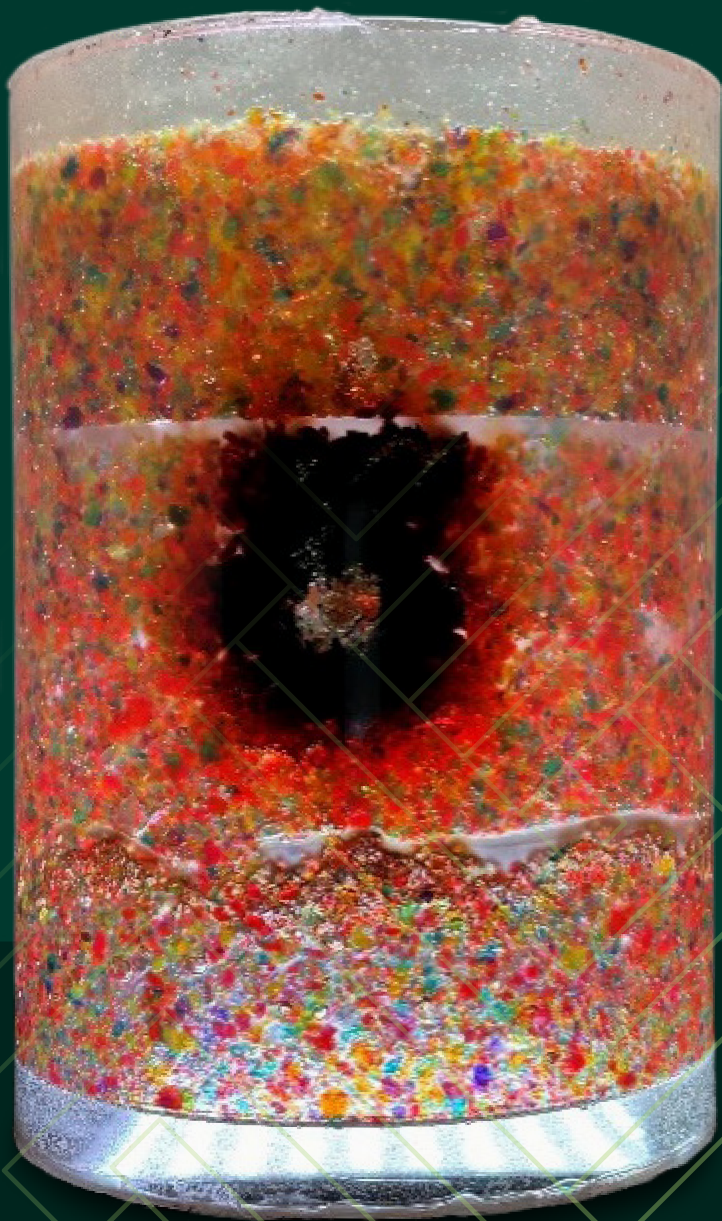
Cody Corbin (PI). Team members: Heidi Smartt, Clayton Curtis.

Tamper-indicating seals are widely used across industries from over-the-counter medication bottles to containers protecting national security materials. The Bleeding Materials & Enclosures product uses a completely new approach to fabricating custom tamper-indicating enclosures using commercial-off-the-shelf materials that allow rapid and conclusive inspections for potential tamper or damage. The "wow" factor of the material is that it irreversibly turns from multi-colored to black upon tamper, and the reaction is visually obvious.

The dramatic color change begins at the site of the damage or penetration and spreads with time, similar to bruising or bleeding. An additional feature is that the multi-colored beads act as a mechanism to prevent counterfeit or substitute, as they randomly form patterns in the material that can be compared before and after deployment. Any damage or penetration will disturb the spatial location of the beads, and an adversary attempting to counterfeit or substitute the enclosure would find it extremely difficult to arrange the beads in the same pattern. All of these features are created using common, affordable materials.

The bruising materials research was funded by Sandia's LDRD program. Further development and device prototyping were funded by the NNSA.

Watch the video.



A container protected with Sandia's "Bleeding Materials & Enclosures" product indicates a tamper attempt. In this image, silicone is used to encapsulate the air-sensitive beads.

PROFESSIONAL FELLOWS

One key indicator of advancement and leadership in the ST&E field is the election of individuals as fellows of professional societies. This recognition signifies success for both the individual researcher and the associated laboratory. Researchers at Sandia have been elected as fellows in more than 25 esteemed scientific and engineering societies, with the highest number of fellows belonging to the societies listed below.

- American Association for the Advancement of Science
- American Chemical Society
- American Institute of Aeronautics and Astronautics
- American Physical Society
- American Society of Mechanical Engineers
- Institute of Electrical and Electronics Engineers
- National Academy of Engineering
- Society for Industrial and Applied Mathematics

NAMED FELLOWS

	SINGLE YEARS			FIVE YEARS		TO DATE*
	FY23	FY24	FY25	FY16-20	FY21-25	FY11-25
TOTAL AWARDS	8	7	9	41	36	118
AWARDS WITH LDRD ROOTS	8	6	7	35	29	95
PERCENTAGE WITH LDRD ROOTS	100%	85%	78%	85%	80%	83%
AVERAGE YEARS FROM FIRST LDRD EXPERIENCE	18.5	14.5	19.7	14.4	16.9	14.5

FELLOWSHIP AWARDS

Read about individuals at Sandia who have been elected fellows of professional societies in the *Workforce Development* section of this Annual Report.

SHORT-TERM METRICS

INTELLECTUAL PROPERTY

PATENTS

Number of U.S. and foreign patents issued in a given FY.

	FY21	FY22	FY23	FY24	FY25
SANDIA PATENTS	120	98	116	116	86
LDRD SUPPORTED	57	44	45	58	33
PERCENTAGE DUE TO LDRD	48%	45%	39%	50%	38%

LDRD supported: Patents issued that would not exist if not for initial work funded by LDRD.

COPYRIGHTS

Number of copyrights created in a given FY.

	FY21	FY22	FY23	FY24	FY25
SANDIA COPYRIGHTS	170	146	135	169	185
LDRD SUPPORTED	34	26	23	45	53
PERCENTAGE DUE TO LDRD	20%	18%	17%	27%	29%

LDRD supported: Copyrights issued that would not exist if not for initial work funded by LDRD.

INVENTION DISCLOSURES

Number of declarations and initial records of an invention (a new device, method, or process developed from study and experimentation) in a given FY.

	FY21	FY22	FY23	FY24	FY25
SANDIA DISCLOSURES	295	280	277	274	270
LDRD SUPPORTED	118	118	120	121	138
PERCENTAGE DUE TO LDRD	40%	42%	43%	44%	51%

LDRD supported: Disclosures issued that would not exist if not for initial work funded by LDRD.

PEER-REVIEWED PUBLICATIONS

Publications

Number of peer-reviewed publications, as a function of publication year.

	FY21	FY22	FY23	FY24	FY25
SANDIA PUBLICATIONS	1493	1456	1372	1291	1252
LDRD SUPPORTED	379	380	408	391	418
PERCENTAGE DUE TO LDRD	25%	26%	30%	30%	33%

LDRD supported: Publications that would not exist if not for initial work funded by LDRD.

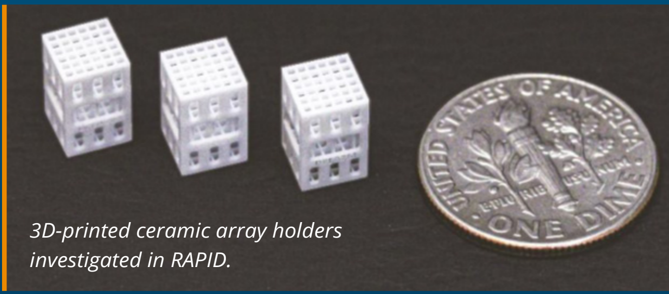
SCIENCE AND ENGINEERING TALENT PIPELINE

Student Interns Supported by LDRD (>10%) at Sandia

Number of graduate and undergraduate students working full- or part-time for the Labs, who charged at least 10% time to LDRD.

	FY21	FY22	FY23	FY24	FY25
GRAD STUDENTS	139	147	158	187	169
UNDERGRAD STUDENTS	84	110	118	129	113
SANDIA R&D STUDENTS	711	841	857	933	878
PERCENTAGE DUE TO LDRD	31%	31%	32%	34%	32%

LDRD IMPACT STORY: ENHANCING ADVANCED MANUFACTURING CAPABILITIES AT SANDIA



3D-printed ceramic array holders investigated in RAPID.

Over the last decade, multiple materials science LDRD projects have steadily built the foundations, tools, and know-how needed to field high-consequence additively manufactured parts and improve national security. What began as fundamental explorations of 3D-printing processes with commercially-available metal and polymer feedstock has grown into a full suite of capabilities—predictive computer models, real-time process controls, new material formulations, advanced inspection methods, and data-driven design tools—that together are reshaping how Sandia makes components for everything from nuclear weapons to power plants.

Laying the groundwork: Understanding printed materials (2014-2016)

Researchers performed comprehensive studies of how stainless steel built layer-by-layer responds to different kinds of loads, including very fast impacts. (Printed steel often outperforms conventionally made steel in strength, thanks to the way its tiny crystal grains and dislocations arrange during the build.) At the same time, teams began to develop computer simulations that reproduce the thermal cycles and residual stresses inside laser-based 3D printing. These early models revealed how temperature gradients drive microstructures—and ultimately strength and toughness—in printed parts.

Postdoctoral Researcher Support

Number of postdoctoral researchers working full- or part-time for the Labs.

	FY21	FY22	FY23	FY24	FY25
SANDIA POSTDOCS	428	459	453	459	486
LDRD SUPPORTED >10%	196	209	231	248	278
PERCENTAGE DUE TO LDRD	46%	46%	51%	54%	57%

LDRD supported: Postdoctoral researchers charging at least 10% time to LDRD.

Postdoctoral Researcher Conversions

Number of conversions from postdoctoral researchers to a member of the staff.

	FY21	FY22	FY23	FY24	FY25
SANDIA CONVERSIONS	61	94	85	30	36
LDRD SUPPORTED >10%	32	42	54	18	19
PERCENTAGE DUE TO LDRD	52%	45%	64%	60%	57%

LDRD supported: Conversion of postdoctoral researchers who charged at least 10% time to LDRD in the fiscal year preceding the conversion.

Improving reliability and expanding the materials palette (2017-2019)

Building on those first simulations, Sandia introduced in situ sensors to monitor temperature and laser absorption as parts grow. This led to methods for spotting pores or other flaws as they form and even responding on the fly to keep a build on track. Parallel work established the first high-throughput, hierarchical finite-element tools to predict how a given defect will influence part performance. By knowing which pores or cracks really matter—and which do not—engineers can move from "inspect everything" to a damage-tolerant approach that speeds up qualification without sacrificing safety.

Research teams also invented new "functional inks" that allow Sandia to print electronics directly onto flexible substrates. These efforts spawned patent applications and promise rapid and flexible electronics production in the future. Concurrently, projects on negative-thermal-expansion composites, high-entropy alloys, and magnetic materials pushed the boundaries of what can be created out of polymers and metal. Sandia scientists learned how to tune feedstock and process parameters to meet performance needs.

From materials to prototypes while advancing automation (2020 - present)

Materials science investment established basic principles and mechanistic understanding of orthogonal or sequential chemistries for fabricating multi-material printed materials. Numerous additive manufacturing (AM) techniques were developed including volumetric solid-state printing, dual-wavelength printing, and lithographic regulation of polymer crystallinity.

Additionally, new techniques were discovered for depolymerization enabling recovery of pristine carbon-fiber and high value electronics under moderate conditions. Recent investments in automated materials synthesis paved the way for advancement in materials discovery and coupled with digital engineering. The first metal AM parts were produced thereafter.

To build on these successful advancements, Sandia is continuing to invest in expanding advanced manufacturing (AdvM) capabilities and to decrease the effort needed to qualify new materials and component designs.

CAMINO
Center for Advanced Manufacturing & Innovation

The Center for Advanced Manufacturing and Innovation (CAMINO) and the new multi-year DREA2M Mission Campaign now ensure additive techniques feed directly into stockpile maintenance and modernization efforts.

OVERALL IMPACT

Capability build-up: Sandia has moved from one-off experiments to productionized software and hardware.

Mission readiness: Multiple Sandia programs now leverage certified AM components.

Workforce and partnerships: Over 50 publications, more than a dozen patents, dozens of academic collaborations, and the training of a new generation of AM specialists have emerged from this decade of investment.

Future promise: By building digital twins that span atoms to full systems, real-time defect mitigation, and data-driven materials discovery, Sandia is positioned to help the United States reap the full benefits of AdvM—for defense, energy, and beyond.

In sum, LDRD seed investments in fundamental understanding, combined with sustained efforts in modeling, sensing, and materials innovation, have transformed additively manufactured parts from a research novelty into solutions that meet Sandia's toughest mission demands.

DREA²M Digitally Realized and Enabled Agile Advanced Manufacturing

The DREA2M LDRD Mission Campaign: Moving from foundational to fielded

Building on the advanced manufacturing (AdvM) discoveries and advancements of LDRD's research foundations, the Digitally Realized and Enabled Agile Advanced Manufacturing (DREA2M) Mission Campaign was launched in January 2025. DREA2M's mission is to enable broader insertion of AdvM by addressing persistent R&D knowledge gaps and see significant acceleration of production realization activities.

As adversaries accelerate their manufacturing capabilities, the U.S. must innovate to maintain its technical edge and respond to emerging threats with speed and agility. DREA2M focuses on eliminating bottlenecks in product realization by targeting AdvM research spanning materials science, process development, sensing, computational modeling, machine learning, and automation. By enabling agile AdvM capabilities, Sandia aims to enable rapid design, qualification, and production of reliable systems for harsh environments, reducing cycle times for nuclear deterrence programs and hypersonic glide bodies by years, and ultimately ensure the U.S. can meet mission needs faster and more effectively and strengthen national security in an increasingly complex global landscape.

DREA2M's broad base of inaugural projects is driving innovation to overcome the limitations of traditional manufacturing methods, such as subtractive machining and manual assembly, which rely heavily on trial-and-error processes, extensive testing, and artisanal expertise. These legacy approaches are time-tested, but can lack flexibility and speed, making them not as optimal for the rapid responsiveness demands of modern deterrence programs.

DREA2M-funded research is enabling advancements in rapid prototyping, reducing reliance on constrained supply chains, and improving manufacturing agility through cutting-edge technologies like real-time sensing, predictive modeling, and automated systems. Among these efforts is the RAPID project, led by principal investigator Remi Dingreville, which is advancing machine learning applications to optimize manufacturing protocols, reducing inefficiencies and enabling faster production cycles.

RAPID: Robust, adaptable production via intelligent data science

This project integrates Scientific Machine Learning (SciML) with Lithography-based Ceramic Manufacturing (LCM) to establish a closed-loop, data-driven framework for determining robust manufacturing parameters of complex 3D-printed ceramic components used in the stockpile (see photo on page 24). To date, the project has successfully executed a high- throughput combinatorial manufacturing campaign designed to rigorously map the critical process-structure-property relationships with LCM. This campaign systematically swept through a high-dimensional design space, varying digital light processing exposure time and energy density during green body formation, followed by modulations in sintering temperature and soak time during thermal post-processing. Complementing this manufacturing effort, extensive multimodal characterization was performed, capturing high-fidelity geometric measurements and full-field mechanical compression data for every printed component.

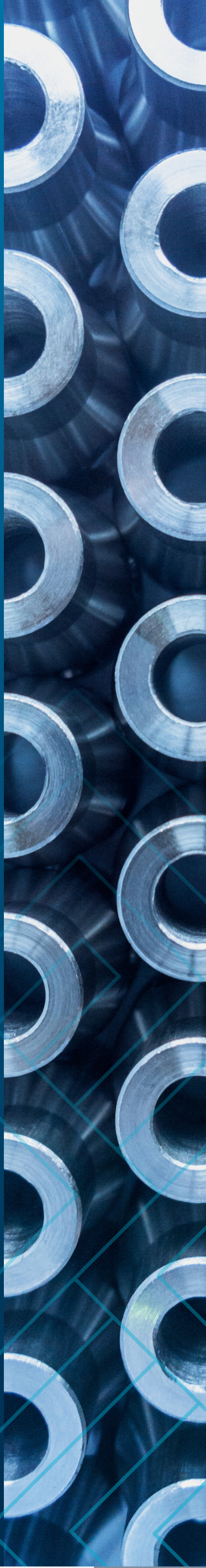
This effort has yielded a massive Process-Structure-Property data cube—a rich, high-dimensional tensor that serves as the ground truth for Sandia's SciML framework. This dense, multimodal dataset is now being utilized to (i) learn fingerprints from this multimodal dataset, and (ii) initialize a Bayesian Optimization framework using these "multimodal-derived" fingerprints.

By applying active learning algorithms to these fingerprints, Sandia is currently identifying the latent correlations between photopolymerization physics (green body) and thermal densification to pinpoint a robust processing window with high statistical confidence.

From the programmatic point of view, this work represents a critical technology transfer milestone for an associated Production Realization Team (PRT).

COOL FACTS > By transitioning from empirical heuristics to SciML-driven process discovery, this project is delivering a pre-validated manufacturing protocol ready for immediate ingestion for production. This direct integration drastically accelerates the PRT's development trajectory, compressing optimization cycles from months to weeks.

By equipping the manufacturing stream with mathematically quantified 'safe' operating zones, the project's results actively mitigate supply chain vulnerability—ensuring that high-fidelity ceramic components can be produced reliably, independent of operator nuance or material variability.



PROJECT HIGHLIGHTS –

MISSION AGILITY

Sandia's LDRD program is organized around three themes: mission agility, technical vitality, and workforce development. Mission agility and technical vitality are closely related but differentiated by the technical readiness levels (TRL) of the research outcomes. The research outcomes in the accomplishments of this section have a higher TRL and could impact Sandia's mission work more quickly.

MISSION CAMPAIGN: DIGITAL ASSURANCE FOR HIGH CONSEQUENCE SYSTEMS (DAHCS)

DAHCS: UNDERSTANDING THE IMPORTANCE OF DIGITAL ASSURANCE IN HIGH CONSEQUENCE SYSTEMS

Digital technologies offer significant benefits in speed, cost, and flexibility, and Sandia strives to reap those benefits, without introducing new system failures—whether adversarial or from unintended behaviors—in our nation's high consequence systems (HCS). Through the Digital Assurance for High Consequence Systems (DAHCS) Mission Campaign, Sandia is focused on ensuring that digital controllers (i.e., cyber-physical embedded systems) within HCS behave as intended and do not weaken the systems.

The mission campaign is creating an integrated ecosystem of tools and rules to help decision-makers assess how much confidence to have in their HCS. This ecosystem must apply across HCS mission spaces, including nuclear deterrence, hypersonics, satellites, and crucial infrastructure.

DAHCS: TACKLING CRITICAL RESEARCH CHALLENGES

The DAHCS Mission Campaign seeks to solve several critical research challenges that are typically addressed in a piecemeal fashion—but much faster than current methods allow. Three of these challenges are:

1. **Digital Composition:** How do we create a simple, convincing, system-level digital assurance argument that clearly describes residual risks? This requires allocating responsibility among components and combining assessment evidence from disparate techniques.

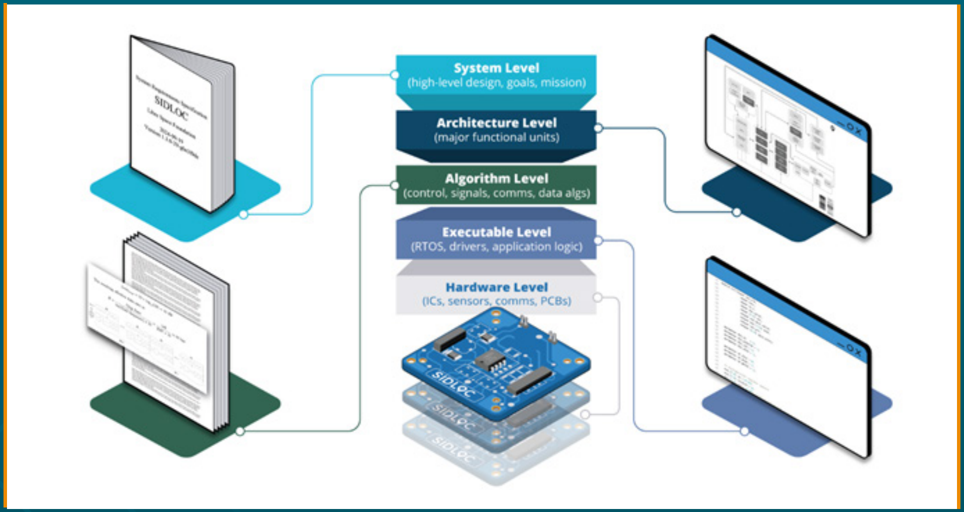
2. **Intelligent Adversary and Hazard Modeling:** How do we explicitly account for the goals, choices, and capabilities of intelligent adversaries when designing or evaluating a system? This understanding is essential for effective resource allocation for rigorous assessment and defense.

3. **Failure Consequence Characterization:** How can we pinpoint which minor digital faults could lead to major failures in a system, along the lines of root cause and impact analysis? This knowledge is essential for preventing small failures from cascading into mission-critical breakdowns.

DAHCS: DEVELOPING A DIGITAL CONTROLLER ECOSYSTEM

LDRD projects funded under DAHCS collaborate closely as an integrated research portfolio to improve Sandia's ability to confidently and rapidly assure the safety, reliability, and security of HCS.

The DAHCS projects are demonstrating outcomes that meaningfully build that ecosystem through shared experiments, shared testbeds, and a shared vision for digital assurance. Most efforts below are focused on a satellite testbed known as the Spacecraft Identification and Localization (SIDLOC) project (*https://sidloc.org/*).



Spacecraft Identification and Localization abstraction levels.

DAHCS: PIONEERING PROJECTS IN DIGITAL ASSURANCE

Focusing on the challenge of digital composition, ***Jabberwocky*** is developing a common language and structure to support easier planning, execution, reporting, and overall effective communication of system-level, multidisciplinary risk assessments. The first year of research has produced a methodology to create a multi-domain DAHCS ontology, which can be used by other DAHCS LDRDs to connect their research efforts.
(PI: Jamie Thorpe, FY25-26)

Addressing the analysis side of this challenge, ***Theorems in Service of Sound Composition, Rapid Modeling, and Scalable Analysis*** developed technology to ensure that requirements that are mathematically proven at the component level still hold when components are integrated in a larger system. This advancement reduces the time and effort needed for analysis, allowing complex systems to be verified much more quickly; on one mission system, it turned an analysis that ran out of memory after eight hours into one that could be completed in a minute. Developed design guidelines, theoretical proofs, and automated tooling are being transitioned to the Advanced Simulation and Computing tool suite.
(PI: John Bender, FY25)

Tying together this first challenge with the second, Intelligent Adversary Modeling, ***Attack Graphs for Digital Assurance*** aims to enable hardening systems against attacks, particularly those like supply chain attacks that target individual components. Building on LDRD

research from the 1990s that developed attack graphs for computer networks, this project is creating a new way to 1) identify single- or multi-component (hardware and software) attack paths in HCS and 2) identify optimal mitigations across multiple attack paths.
(PIs: Laura Swiler, Kasimir Gabert, FY25-26)

These tools require understanding and modeling the system, vulnerabilities, and attacker capabilities. Attack Graphs for Digital Assurance worked with the DAHCS Test & Evaluation Testbed Team (led by Kasimir Gabert) and other DAHCS LDRDs to create deep understanding and modeling of the SIDLOC testbed system. ***Semi-Automated Vulnerability Exploration (SAVE)*** seeks to automate the analysis of system vulnerabilities, validating whether and how attackers can violate system safety, reliability, and security properties. Working with intern Nico Osgnach, SAVE helped create a state machine model of the SIDLOC functionality across its lifetime and is extending the model to include threat models of attackers.
(PIs: Andrew Cox, Karla V. Morris Wright, FY25-27)

Also helping to create multiple types of system models, S***ystem Theoretic Reasoning Across Tiers of Abstraction (STRATA)*** uses Large Language Models to dramatically reduce the time and resources needed to build system models and to uncover unexpected system vulnerabilities. This LDRD team, with intern Ryan Villarreal, is working to understand how different system abstractions impact the effectiveness of control-theory-based vulnerability analysis in high-consequence digital systems. **(PI: Wes Odom, FY25-26)**

To tackle the vulnerabilities that remain, ***Templates for Risk-informed Assurance with Curvature Embeddings (TRACE)*** begins to address the third challenge, helping to prioritize the discovery and mitigation of vulnerabilities. Building from prior LDRD investments, the LDRD team and its three interns, Garrett Allen, Peter Jacobs, and Steven Sleder, created the TRACE software platform. TRACE scans a cyber-physical system, applies advanced mathematics to probabilistically discover potential kill chains, and prioritizes possible mitigations. This project presented and published at the International Conference for Learning Representations, and it identified requirements for future DAHCS testbeds.
(PI: Lekha Patel, FY25)

COOL FACTS > **Collaboratively, the efforts of these DAHCS Mission Campaign LDRD projects are:**

- Dramatically advancing our understanding of digital risks and adversary threats.
- Providing practical tools and methodologies that can be used to make confident decisions about digital technology use across various mission spaces.
- Building an informed workforce that aims to use and expand their networks across Sandia.

As Sandia continues to embrace digital technologies, this research is imperative for designing and safeguarding crucial systems and, ultimately, national security.

ADVANCING OPTICAL EMISSION PREDICTIONS FOR NEXT-GENERATION HYPERSONIC VEHICLES

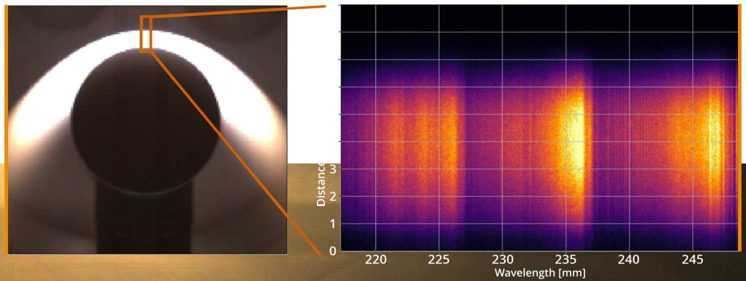
Hypersonic flight conditions, where vehicles travel at extremely high speeds, are unique. At these speeds, chemical reactions happen in the gas surrounding the vehicle, which can be studied using advanced imaging and spectroscopy techniques. To support the performance and safety of hypersonic technologies, Sandia researchers launched a three-year project to develop and validate a model of the optical signals produced during hypersonic flight using new experimental methods in Sandia's Hypersonic Shock Tunnel.

The team successfully integrated several advanced computational codes to predict optical signatures from hypersonic vehicles. They also developed a unique velocimetry technique for measuring hypersonic wakes, which has been adapted for use in multiple projects. Additionally, Sandia established a testing platform for measuring optical emissions from thermal protection system materials, replicating conditions found in actual flight tests.

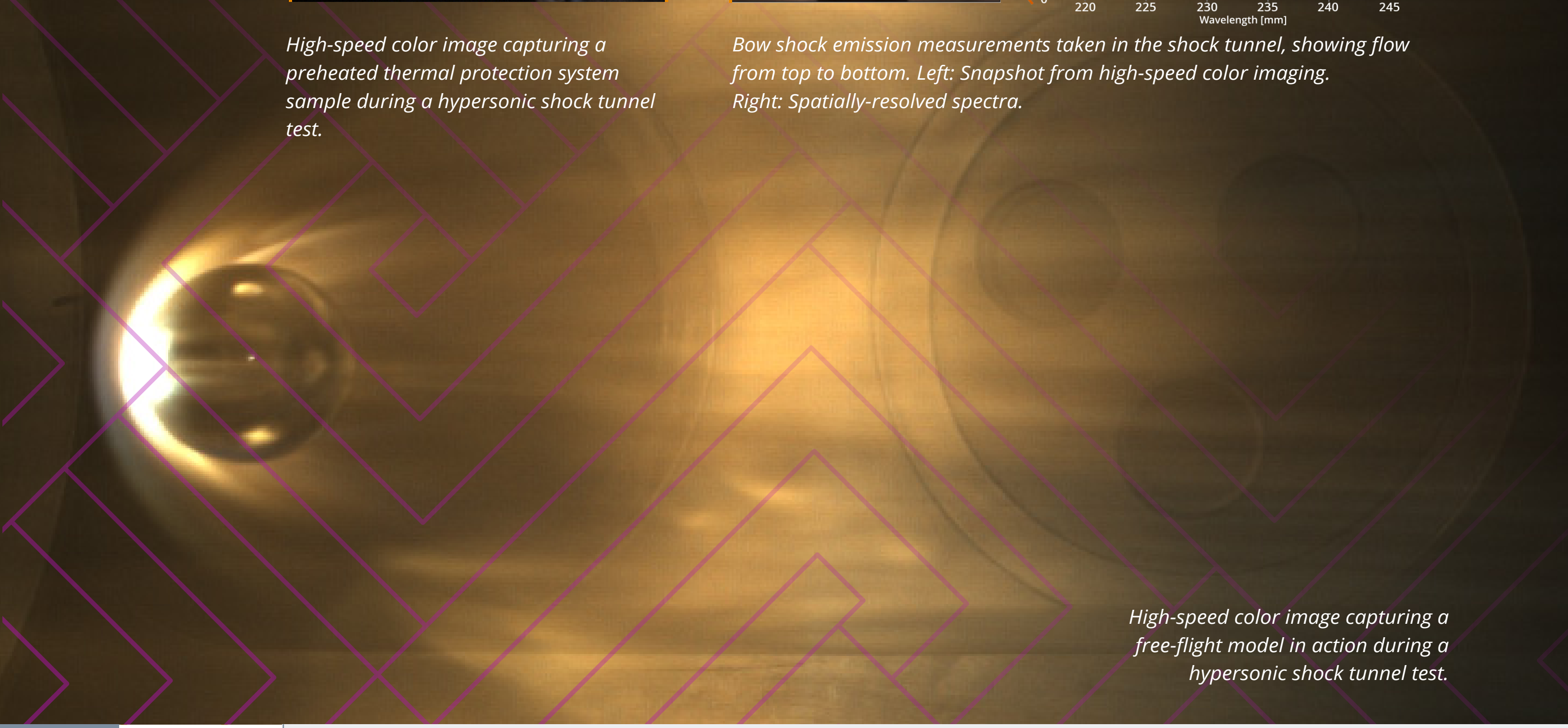
The project has led to journal publications, two invited presentations, and five conference presentations. The innovative work not only enhances Sandia's understanding of the hypersonic environment and gas physics, but also sets the stage for future advancements in the field, ensuring that Sandia remains at the forefront of hypersonic technology development. **(PI: Elijah Rhea Jans)**

READ MORE > *Optics Letters*

High-speed color image capturing a preheated thermal protection system sample during a hypersonic shock tunnel test.



Bow shock emission measurements taken in the shock tunnel, showing flow from top to bottom. Left: Snapshot from high-speed color imaging. Right: Spatially-resolved spectra.



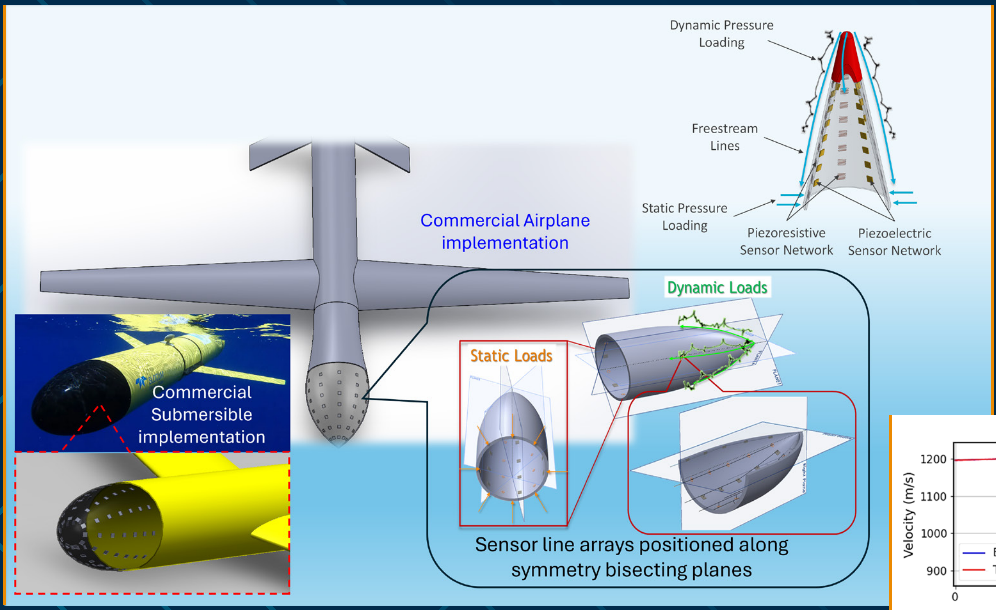
High-speed color image capturing a free-flight model in action during a hypersonic shock tunnel test.

STRENGTHENING NATIONAL SECURITY THROUGH GPS-DENIED MEGASONICS NAVIGATION SYSTEM

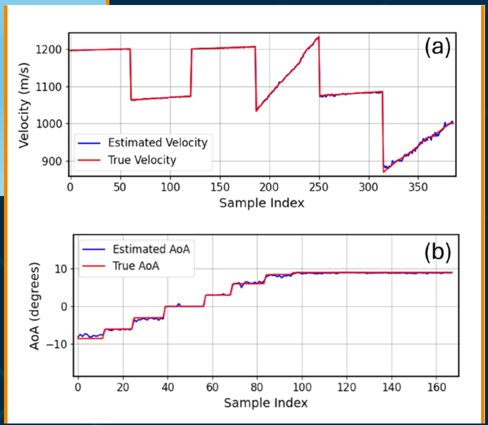
Sandia researchers are tackling a pivotal challenge in navigation technology: the increasing threat of adversaries denying or spoofing GPS signals. This issue can lead to significant targeting errors in delivery vehicles, with potential deviations exceeding 50%. To enhance navigation reliability in these GPS-denied environments, the team has developed an innovative approach that utilizes piezoelectric sensors to monitor turbulent airflow over a vehicle's surface.

By analyzing the vibrations caused by this airflow and strains due to atmospheric loading, Sandia can accurately determine the vehicle's velocity, altitude, and attitude without relying on external signals. This groundbreaking "Megasonics Navigation" method provides a robust alternative to traditional navigation systems.

The successful implementation of this technology could revolutionize autonomous vehicle operations, ensuring precise navigation even in hostile conditions. With the ability to rapidly deploy these solutions, Sandia is paving the way for enhanced national security and operational effectiveness, positioning the nation at the forefront of autonomous delivery vehicle technology. This research promises to improve targeting accuracy and resilience against signal disruptions, ultimately transforming how vehicles navigate in challenging environments. **(PI: Ihab El-Kady)**



Megasonics navigation concept.



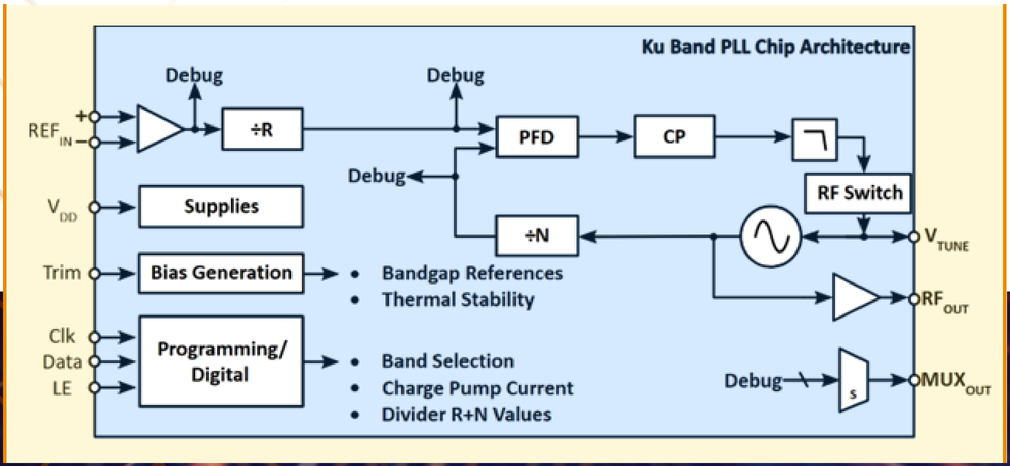
Accuracy estimates of Megsonics navigation system: (a) Veleocity (b) Angle of attack (AoA).

ENHANCING NATIONAL DEFENSE WITH CUSTOM RADIATION-HARDENED RF CIRCUITS

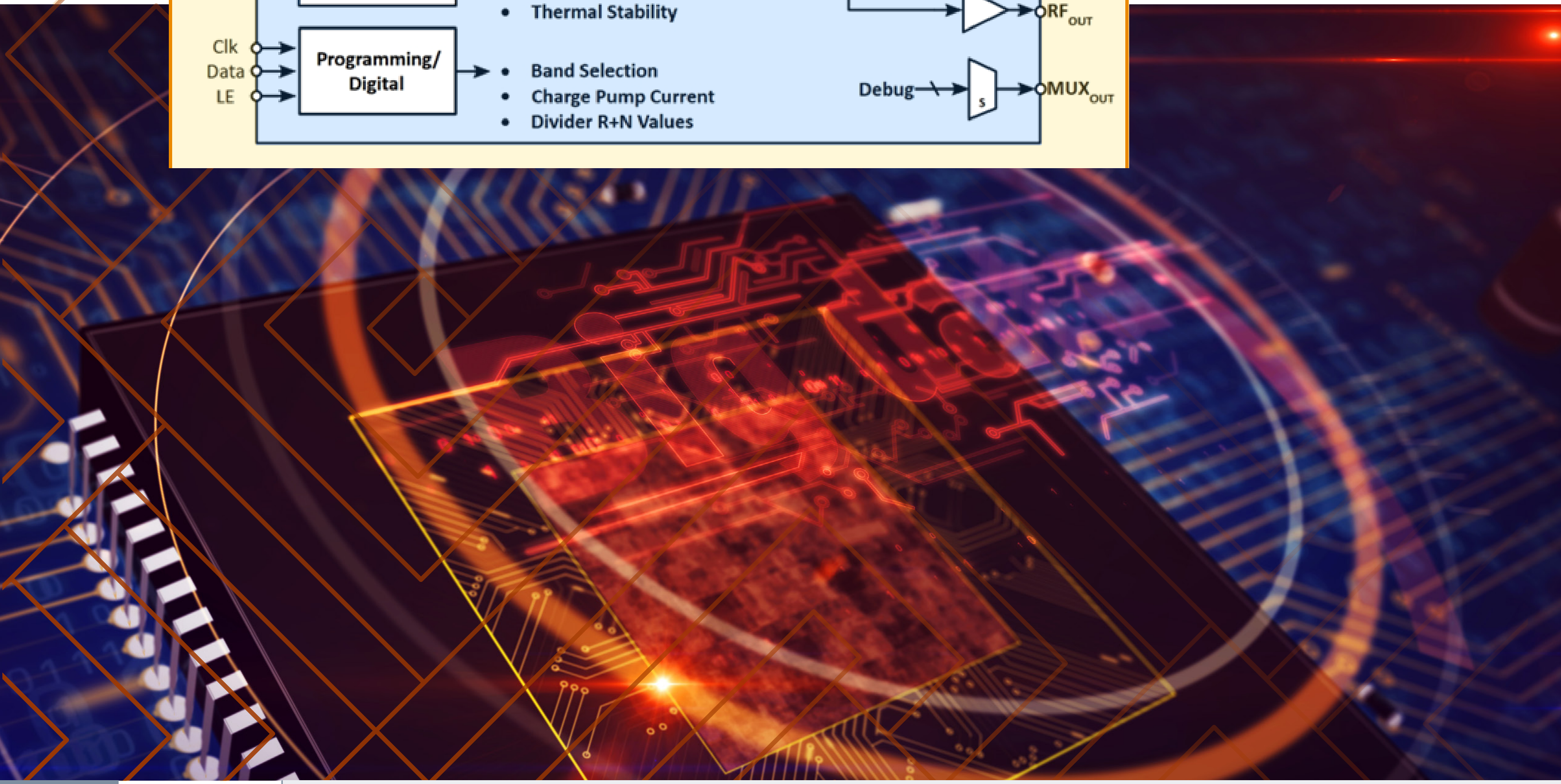
The need for radiation-hardened electronics is vital for national defense applications, as commercial options often fall short of system requirements. To address this gap, Sandia researchers developed a custom Ku-band Phase-Locked Loop (PLL) RF Integrated Circuit using Global Foundries' 45RF CMOS Silicon-On-Insulator process. This innovative PLL meets the demands of higher frequency RF circuits and demonstrates exceptional performance in radiation testing, recovering quickly from high radiation doses.

The team enhanced phase noise performance, creating a highly functional component with low power consumption and fast lock times. Collaboration with Arizona State University, particularly with Jennifer Kitchen and PhD student Liam Nguyen, led to a radiation-hardened Low Dropout Regulator, presented at the HEART conference and in draft for publication.

This LDRD project opens avenues for applications in radar systems currently being designed across Sandia. Continued testing and potential revisions will ensure the PLL meets the rigorous demands of strategic radiation environments, reinforcing Sandia's commitment to advancing radiation-hardened electronics. **(PI: Justine Marie Brenden)**



Block diagram illustrating the architecture of Sandia's Ku-band Phase-Locked Loop, highlighting key components and signal interfaces.



EMPOWERING AUTONOMOUS SYSTEMS FOR DIVERSE REAL-WORLD APPLICATIONS

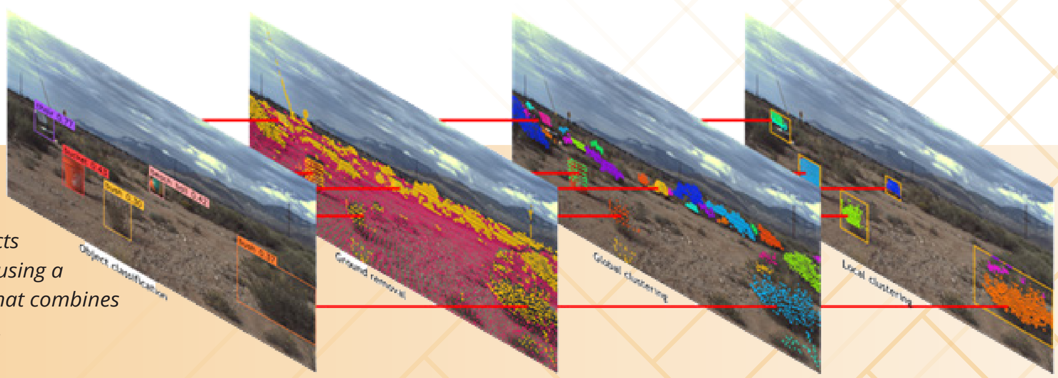
This research enhances uncrewed systems through a new approach to autonomy. The team aimed to improve operations in complex environments by recognizing physical objects, aiding in mapping, navigation, and action planning.

Sandia researchers tested this approach on a four-legged robot, showcasing a multi-modal object perception capability combined with a mapping and navigation technique. Results showed that this approach achieves similar performance to traditional methods while using much less memory, making it advantageous for large-scale environments.

These methods are designed for less structured environments with limited training data. They identify and re-recognize objects via characteristics such as type, color, shape, and size. The team also implemented an autonomy engine, allowing users to define and execute missions based on the system's understanding of its surroundings.

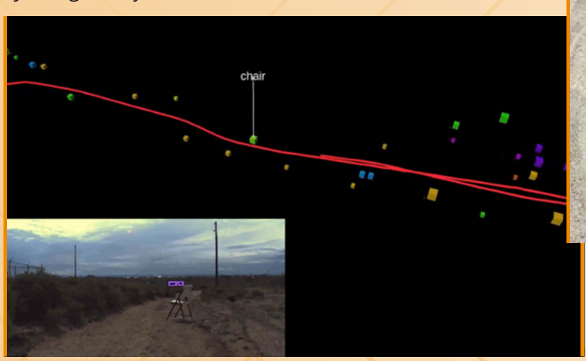
Published in a conference of the American Automatic Control Council, this work can be applied to missions including incident response, physical security, defense, and environmental management. Collaboration with the Georgia Institute of Technology introduced alternative object detection methods, potentially reducing sensor and data processing needs. **(PI: Steve Buerger)**

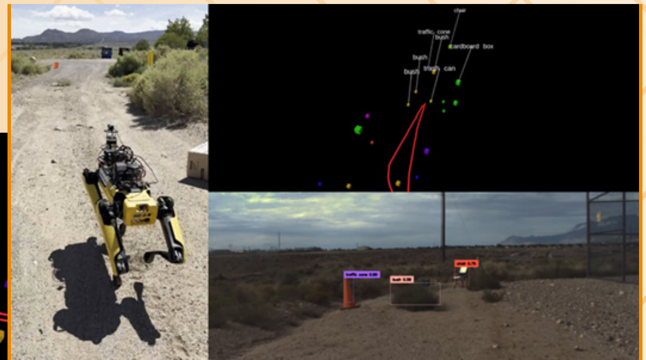
COOL FACT > This advancement positions Sandia's research as a indispensable step toward making autonomous systems more efficient and practical for various applications.



Sandia's object-centric autonomy framework detects objects in its surroundings using a smart, multi-step process that combines data from multiple sensors.

Below: Sandia's object-based autonomy framework builds a map of recognized objects in a test environment by using data from the robot's sensors.





Above: A legged robot navigates through a facility by using objects around it, powered by Sandia's innovative object-based autonomy framework.

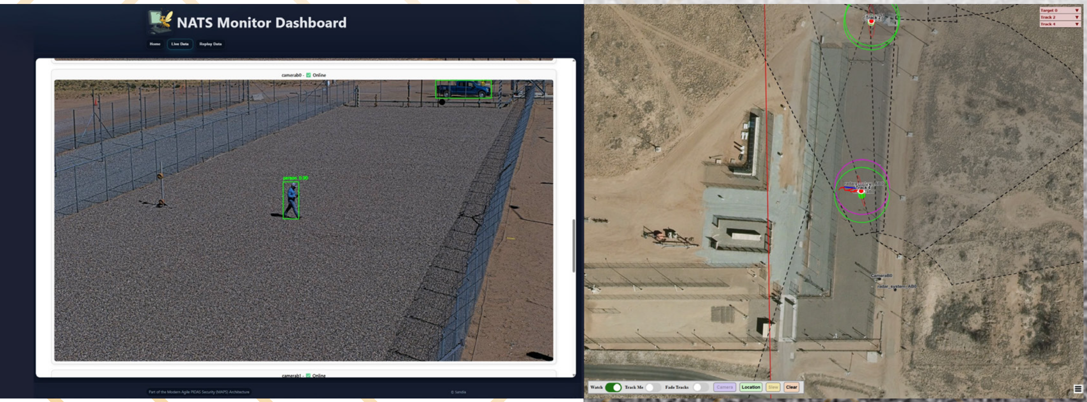
IMPROVING CENTRAL ALARM STATION OPERATOR SITUATIONAL AWARENESS THROUGH MULTI-SENSOR AND MULTI-OBJECT TRACKING

In today's security landscape, enhancing situational awareness is fundamental for effective threat management. This LDRD project focused on improving the capabilities of central alarm station (CAS) operators through the application of advanced algorithms for multi-sensor and multi-object tracking.

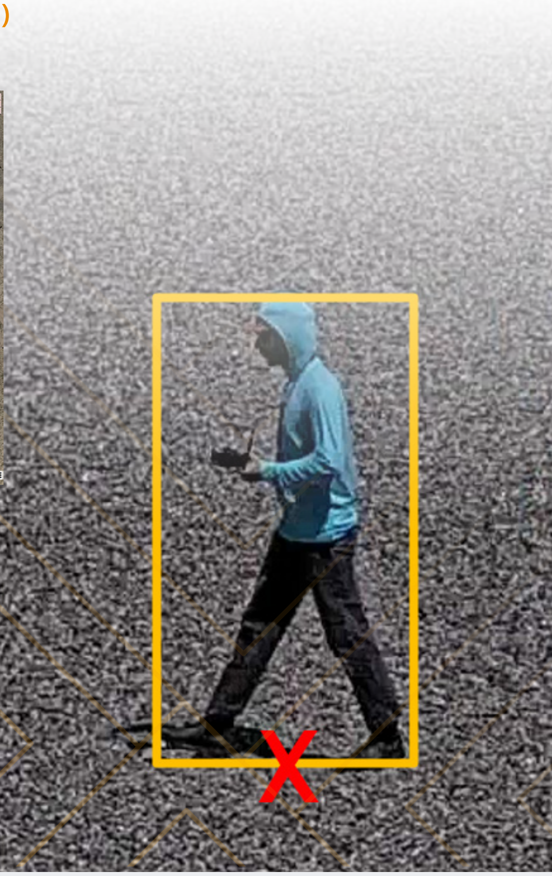
The primary objective was to explore the potential for automated detection systems that could achieve several important outcomes:

1. **Automatic threat detection:** Develop the ability to identify threats from multiple sensors seamlessly.
2. **Precise location tracking:** Accurately determine the locations of detected threats.
3. **Data fusion and correlation:** Integrate and correlate detections from various sensors over time to create a cohesive understanding of the security environment.
4. **Unified situational awareness**: Produce a comprehensive situational awareness map that shows the overall location and movement of all threats and activities from all sensors in a single site map context—alleviating the need for a CAS operator to correlate the overall state of play from disparate sources and viewpoints.

By enhancing the visualization and understanding of unfolding threats, this project aims to improve CAS operators' decision-making capabilities while reducing their workload. Ultimately, these advancements contribute to a more effective physical security system, bolstering the protection of sites worldwide. **(PI: Leo Bynum)**



Above: Detecting people in a live video feed and instantly converting them to a dynamically updated target on a site map in real time.



Right: Using the Sandia algorithm YOLO to detect people in a live video feed, the X at the bottom of the box represents their ground position.

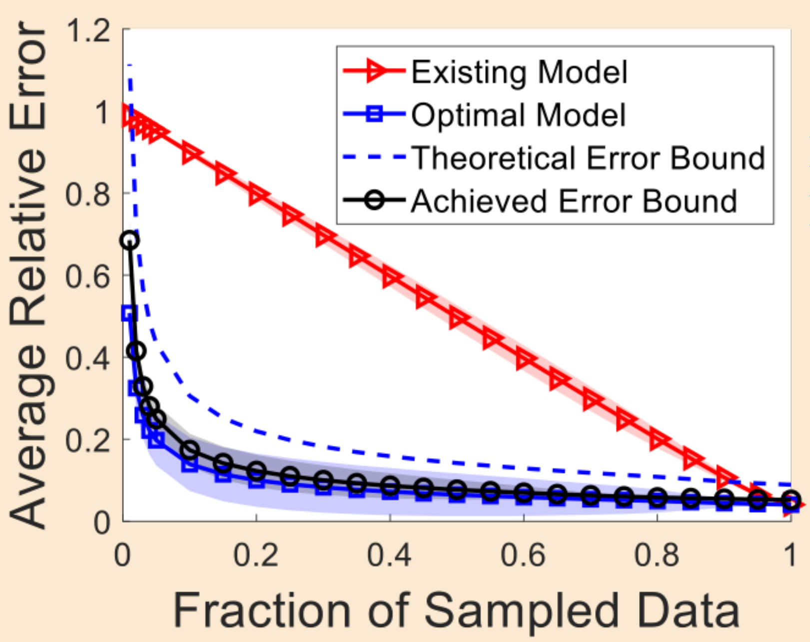
ENHANCING DATA ANALYSIS THROUGH ADVANCED TENSOR MODELING TECHNIQUES

Analyzing large, complex data sets relies on enhancing the reliability of low-rank matrix and tensor models. These models help identify crucial patterns while using fewer variables, thereby improving data analysis efficiency. Researchers on this project developed innovative statistical methodologies for analyzing multidimensional data in applications such as cybersecurity, combustion modeling, radiation transport, and AI. Specifically, they introduced novel approaches to statistical parameter inference, model identifiability, model sensitivity, and near-optimal sampling complexity for various tensor data models and distributions, providing valuable tools for scientists, engineers, and analysts working with multi-way data.

Results of this work were presented at multiple conferences (Joint Mathematics Meeting, Joint Statistical Meetings, SIAM Mathematics of Data Science, Sampling Theory and Applications). **(PI: Danny Dunlavy)**

LEVERAGING NEW TALENT > Collaborations with Florida Atlantic University (Oscar López, Nick Fularczyk), College of William & Mary (Jeremy Myers), New Mexico Institute of Mining and Technology (Jordan Medina), and New Jersey Institute of Technology (Kimmie Harding) led to further theoretical advancements and software implementations in tensor data modeling.

READ MORE > *Information and Inference: A Journal of the IMA*, arXiv (*1*) (*2*) (*3*) (*4*)



The research team's new approach for tensor data modeling using samples of data outperforms the best existing approach and achieves near-optimal modeling performance.

REVOLUTIONIZING PROGRAMMABLE DELAYS FOR ADVANCED TRACKING AND LOCATING SYSTEMS

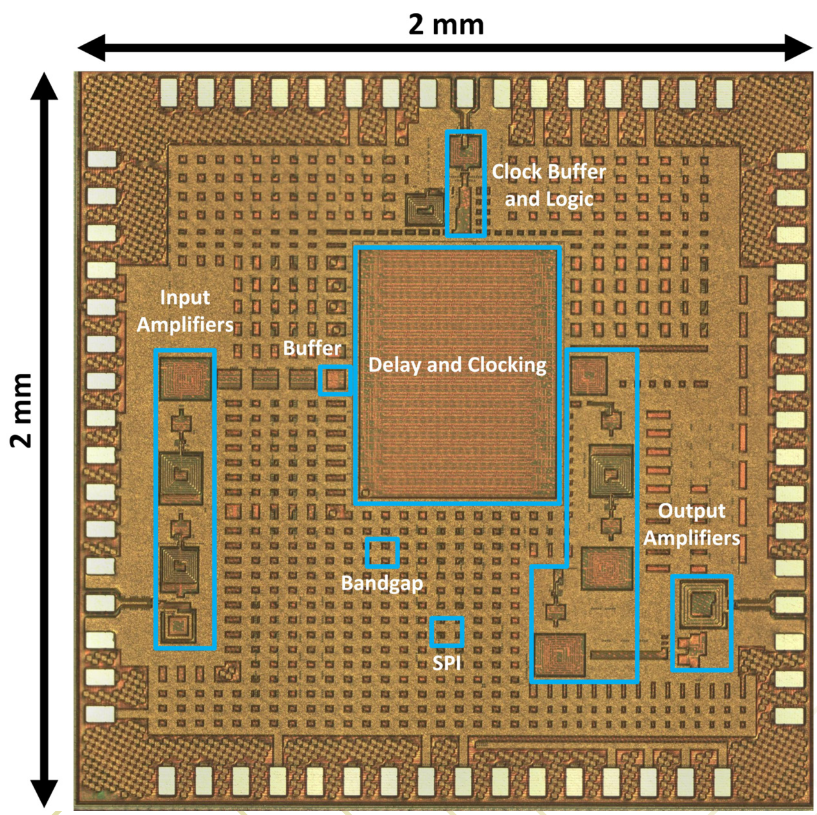
Real-time tracking and locating technologies are core to national security, as they ensure reliable and efficient monitoring of assets. The research conducted by Sandia addresses an important need in technologies including real-time signal manipulation and tagging, tracking, and locating by providing a solution for programmable delays in the RF signal path.

Previously, the maximum programmable delay achievable was just one nanosecond for frequencies above 5.5 GHz, which wasn't enough for many applications. Existing systems had to rely on signal down conversion, leading to inefficiencies in power use, size, and performance.

Sandia researchers have created an innovative programmable delay element that dramatically improves this situation. It offers a delay range of 4.6 to 71.4 ns and operates within a frequency range of 9-11 GHz, all while fitting into a compact area of just 4 mm^2 and consuming only 123 mW of power.

The research breakthroughs open exciting new possibilities for mission-critical applications in tagging, tracking, and locating, as well as real-time signal manipulation. Ultimately, these advancements enhance operational capabilities, making systems more effective and efficient for users in various fields. **(PI: Travis Forbes)**

COOL FACT > By moving away from traditional methods, Sandia achieved a remarkable 65-fold increase in maximum programmable delay and a 39-fold improvement in area efficiency, transforming the landscape of real-time electronic signal manipulation and tracking systems.



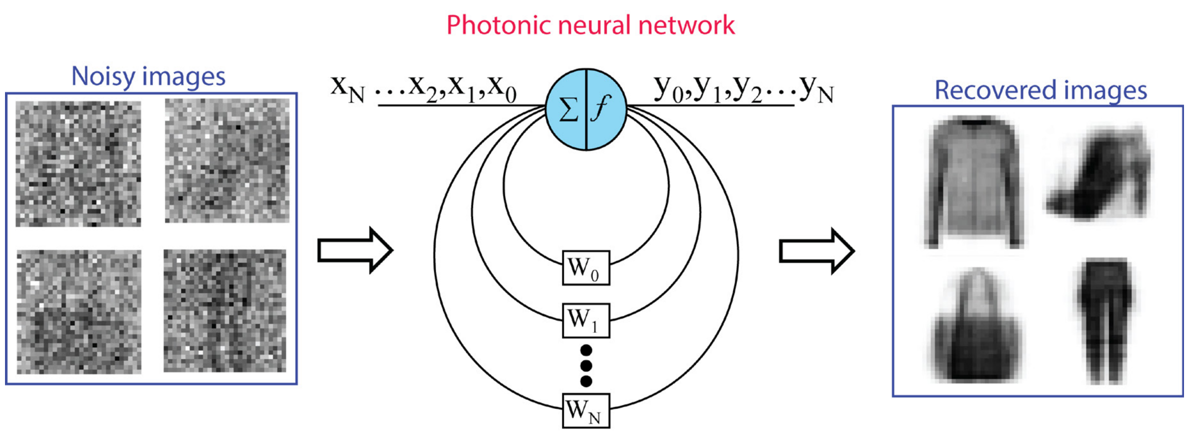
This compact, energy-efficient device revolutionizes applications in real time electronic signal manipulation and advanced tracking technologies.

EVOLVING AI WITH SCALABLE COHERENT PHOTONIC COMPUTING

The extreme growth of AI and scientific computing has created a pressing need for faster, more energy-efficient hardware to process large datasets and complex algorithms. Sandia researchers are addressing this challenge by developing innovative photonic technologies that use light instead of electricity to perform mathematical operations fundamental to neural networks and signal processing. Unlike traditional digital processors, which are limited by energy consumption and latency, Sandia's approach leverages the unique properties of coherent laser light to achieve efficient computation.

The team successfully demonstrated a new photonic matrix-vector multiplier that uses optical delay lines to perform calculations. This technology enables scalable, time-multiplexed computation, reducing hardware requirements while maintaining high performance. Sandia researchers applied this multiplier to implement deep neural networks for tasks such as image classification and noise reduction, achieving accuracy comparable to digital systems.

This work highlights the potential of photonic computing to revolutionize AI, scientific simulations, and communication systems. **(PI: Seth Andrew Fortuna)**



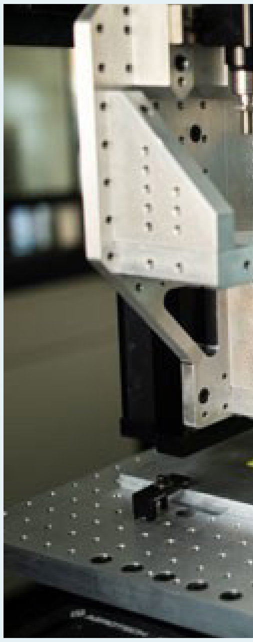
A photonic neural network developed by Sandia researchers uses time-multiplexed coherent laser light to recover images corrupted by noise.

LEVERAGING NEW TALENT > Sandia postdoc Eamonn Hughes helped develop the new scalable coherent photonic computing technology that will allow for the development of smarter AI systems that can analyze data and make decisions more quickly.

ADVANCING MAINTENANCE EFFICIENCY WITH EASY-TO-REMOVE FOAM SOLUTIONS

Driven by the need for effective protection of sensitive electronic components, Sandia researchers explored innovative materials for foam encapsulation that provide safer and more efficient solutions than traditional polyurethane foams, which can damage electronics and complicate repairs and upgrades.

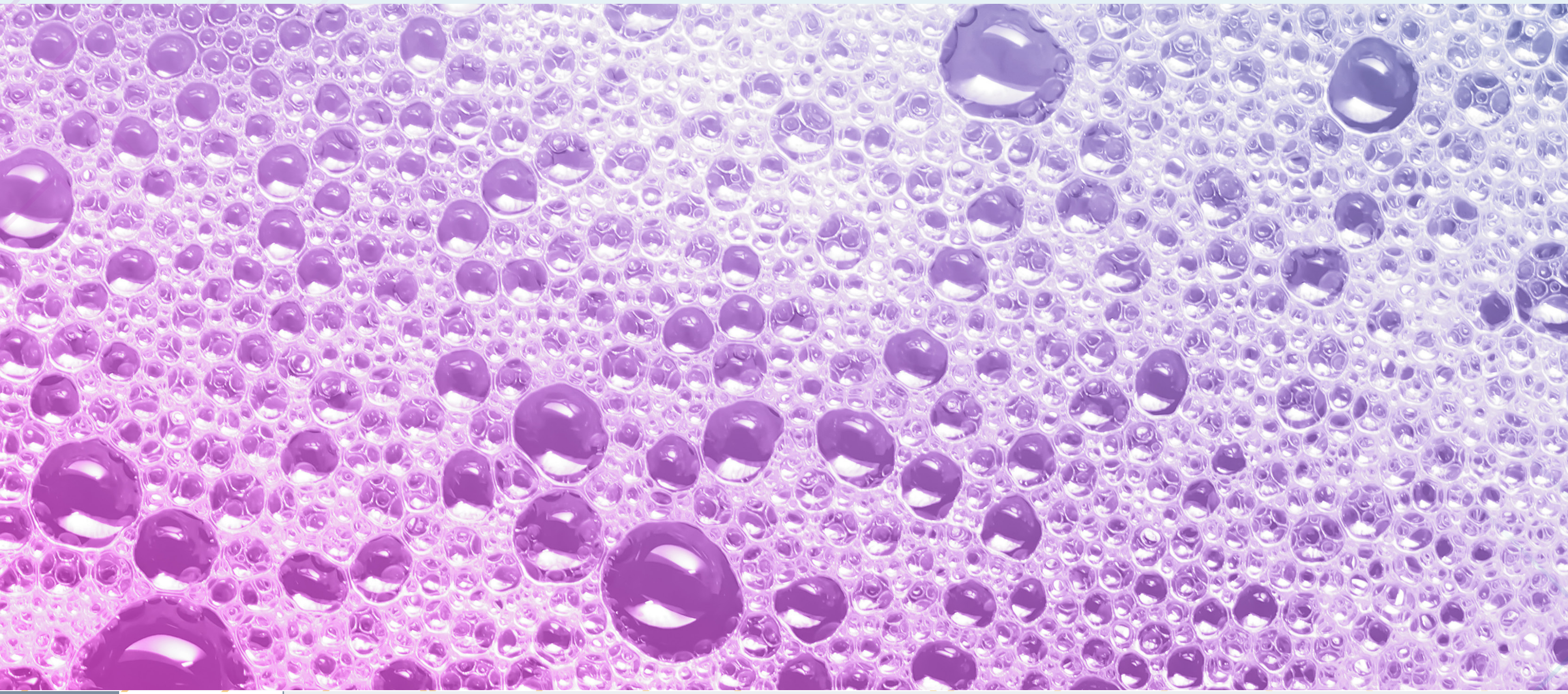
To tackle this issue, the team developed a foam made from poly(dicyclopentadiene) using a technique called frontal polymerization. This method enables the creation of high-performance foams that can be easily removed without the use of harsh chemicals or high temperatures; the catalyst in the process can be tailored to specific properties, making them extremely versatile. To demonstrate the viability of the foam, the team successfully encapsulated a circuit board and later removed the foam with the electronics remaining fully functional.



By simplifying foam removal, Sandia aims to improve operational efficiency and lower costs associated with electronic maintenance and repair. The team has shared their findings at prominent conferences and is actively pursuing further funding opportunities.
(PI: Hayden Fowler)

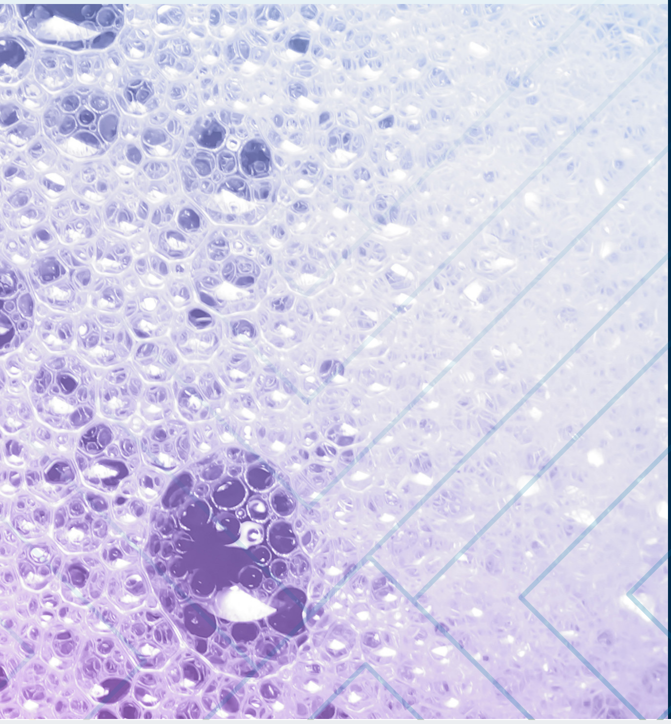
LEVERAGING NEW TALENT > Key contributors, including postdoc-turned-staff Hayden Fowler and postdoc Kylie Van Meter, gained valuable experience, with Fowler transitioning to a staff position.

COOL FACT > This advancement in high-performance removable foam encapsulants can enhance the protection of sensitive electronic components in pivotal systems and benefit a wide variety of industries.



The Advanced Materials Laboratory (AML) is one of seven laboratories that comprise Sandia's Materials Science and Engineering Center. This unique Sandia facility is located on the campus of the University of New Mexico and provides solutions to a wide range of applications. AML has a strong history of partnerships between industry, universities, and the national laboratories.

Sandia PI Hayden Fowler did work on his pivotal LDRD at the AML.



> *"At the Advanced Materials Laboratory, we are not just pushing the boundaries of materials science and advanced manufacturing; we are creating an ecosystem that fosters collaboration, innovation, and discovery. The state-of-the-art facilities and interdisciplinary approach at the lab empowers researchers and ultimately accelerates the pace of scientific breakthroughs."*
>
> *-Hayden Fowler*

GRAND CHALLENGE: Radiation-Hardened Edge Processing (RAD-EDGE)

RAD-EDGE: ACCELERATING REAL-TIME AI WITH ADVANCED ANALOG IN-MEMORY COMPUTING

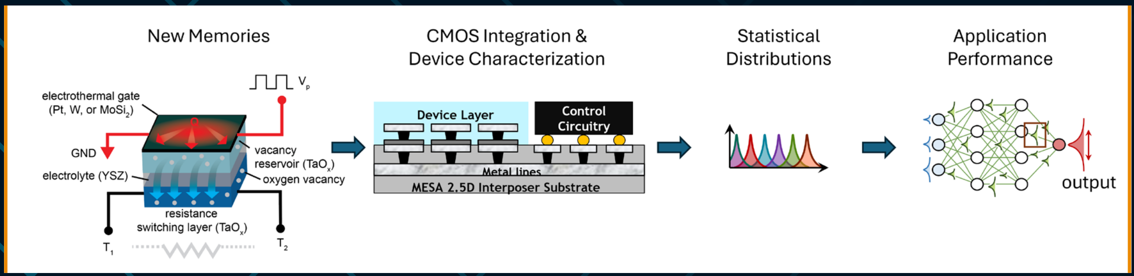
Sandia is advancing computing capabilities in environments where traditional digital systems struggle, such as space missions exposed to radiation. The team developed innovative analog in-memory computing technologies that significantly reduce energy consumption and enable more processing in edge systems. This research, part of the Advanced RAD-EDGE Grand Challenge LDRD initiative, focuses on creating resilient AI computing systems for extreme environments.

Through this project, Sandia researchers have created low-noise, radiation-resistant memory devices and co-design tools for accurate and efficient computations. By leveraging analog computing, the team aims to accelerate data processing for applications like space-based sensing, flight systems, and large language models. Their work shows that analog computing can outperform conventional digital systems, paving the way for more efficient computing solutions in many applications. **(PI: Sapan Agarwal)**

LEVERAGING NEW TALENT > Seven postdocs and 29 interns were supported through this effort, with three hired as staff and one promoted to manager.

COOL FACT > This project resulted in 32 journal and conference papers and generated over $20M in follow-on funding, including support to develop space-ready prototypes from the Department of Defense Microelectronics Commons.

Advanced processing is essential to a broad range of applications.



Sandia researchers have developed tools to go from the invention of new computing devices to application-level performance estimates.

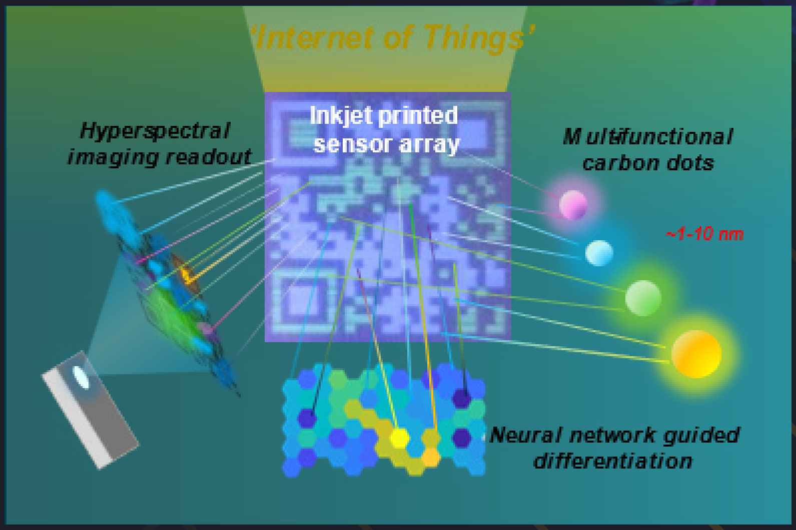
TRANSFORMING THREAT DETECTION WITH INNOVATIVE PRINTABLE SENSING TECHNOLOGIES

Warfighter operational challenges are increasingly complex and constantly evolving where effective threat detection and situational awareness can be limited by traditional methods requiring significant expertise to operate. Sandia researchers developed innovative and low-cost printable sensor arrays with multiplexing-capable sampling that can be integrated into a wide range of settings.

The team, in collaboration with faculty and student researchers from the University of New Mexico, utilized new non-toxic carbon dot materials that feature multiple addressable optical reporter states, allowing for high specificity in detecting different threat species. Printing these materials into barcode arrays allows for the use of changes in spatial patterns, which enhances detection efficacy. This advancement is further supported by cutting-edge hyperspectral optical imaging techniques and machine learning models. Together, this innovative platform opens new pathways for high-throughput and real-time detection for multiple applications utilizing cellphone camera technology.

The research from Sandia, which resulted in publications, patent applications, and conference presentations, is transforming the landscape of threat detection, making it more effective, adaptable and accessible. **(PI: John K. Grey)**

READ MORE > *Nano Letters*, *ACS Sensors*, *Chemistry-A European Journal*



Multi-dimensional information encoding concept for barcode printed sensor design and readout.

REVOLUTIONIZING POINTING AND NAVIGATION BEYOND GPS

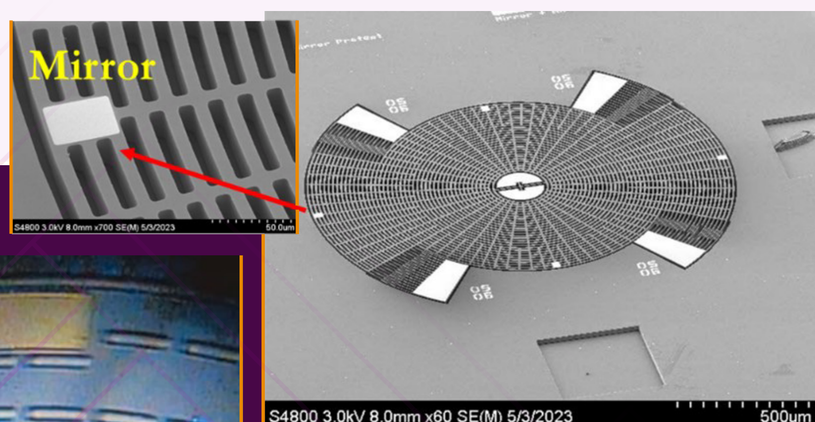
There is a pressing need for more compact navigation systems. Traditional navigation systems are bulky and power-hungry, limiting their applications, so Sandia researchers combined the advantages of microelectromechanical systems—such as their small size and low power consumption—with the enhanced sensitivity and performance of optical readout and created a gyroscope for navigation that is smaller than one cubic inch. This significantly improves versatility compared to existing systems.

Sandia's work, which leveraged expertise from the University of Florida and Stanford to enhance mechanical design and optical modeling, was recognized in academic circles.

This research benefits national security and has already led to follow-on projects funded by the DOE, showcasing Sandia's commitment to advancing technology for consequential mission spaces. **(PI: Alejandro J. Grine)**

COOL FACT > A two-axis vibratory gyroscope developed by the team has an impressive mirror reflectance of 99.2%, allowing for clear optical signal detection. This advancement is opening doors for new applications especially in scenarios where GPS reliance is not feasible.

READ MORE > *International Conference on Optical MEMS and Nanophotonics* (It earned a nomination for a best paper.)



Above: Scanning electron micrograph of Sandia's innovative Optical Microelectromechanical System gyroscope, showcasing a gold mirror designed for precise optical readout.

Left: Microscope image showing the laser spot focused on the mirror edge, with reflected power monitored by a photodiode for enhanced gyroscope performance.

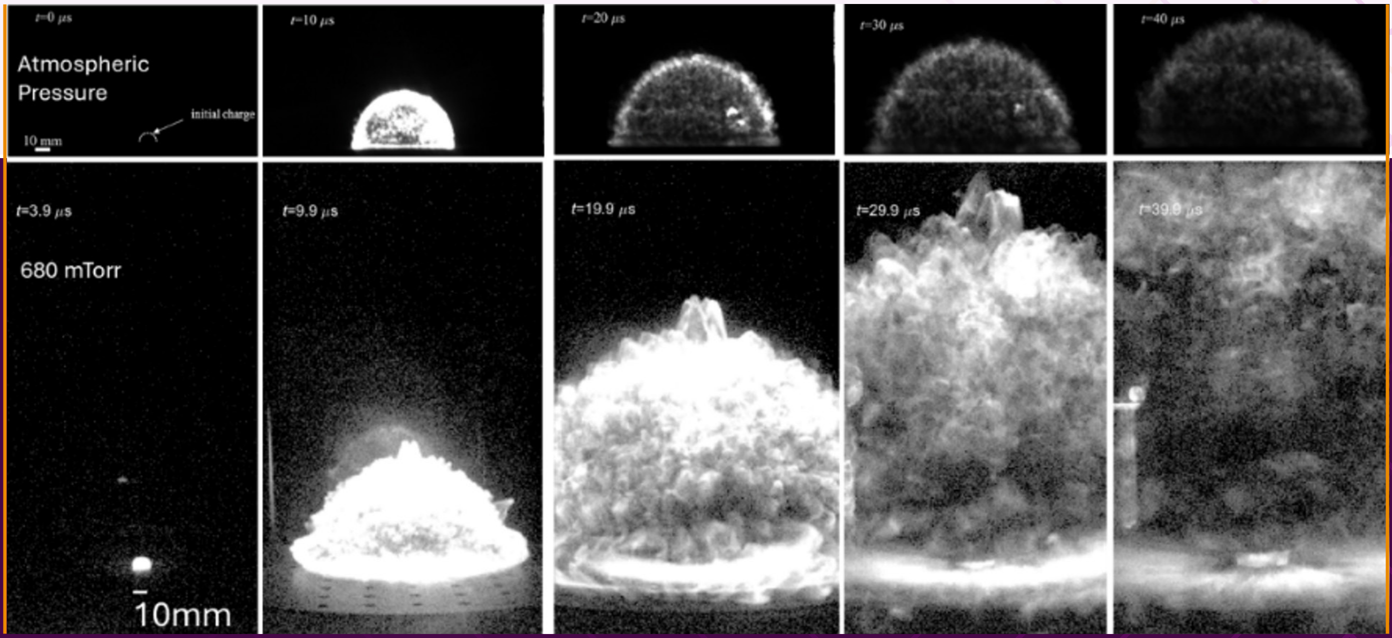
HEIGHTENING UNDERSTANDING OF DETONATION SOOT TO IMPROVE FIREBALL PREDICTIONS

This particle-focused research conducted by Sandia addresses a fundamental challenge: enhancing the understanding of how detonation soot forms and behaves during explosions. This work is vital because it leads to better predictions of particle morphologies and fireball light emission produced by the detonation. Improved models can significantly impact mission areas such as nuclear nonproliferation and explosive emergency response.

Sandia researchers collaborated with experts from the University of Illinois Urbana-Champaign, Purdue, and the University of Florida. The collaborators provided valuable measurements of soot properties and particle diagnostic tools, as well as a new model for estimating particle growth in accelerating flows.

This research, which resulted in journal publications and presentations at numerous conferences, not only advances scientific understanding in the field but also lays the groundwork for future follow-on explosives signatures modeling projects. Through these efforts, Sandia is making strides in both applied and basic sciences, ultimately contributing to higher-confidence modeling of explosive events. **(PI: Adam Les Hammond-Clements)**

LEVERAGING NEW TALENT > Due to his project contributions as a student, Tahir Farrukh joined Sandia as a postdoc appointee and is supporting externally funded follow-on work.



A hemispherical explosive at reduced pressures was used as a representative explosive flow. Lower pressures (bottom row) allowed the fireball to expand unimpeded by air.

IMPROVING DECISION-MAKING USING INCOMPLETE DATA

Making decisions in logistics systems or in other complex situations where information may be incomplete or unclear is challenging. To help with this, a Sandia research team created methods to bring together scattered data and consider operational constraints on the systems involved. They developed models that help figure out the current state of these systems based on the available information and take into account all possible conclusions that can be drawn from the data.

These models alone, however, do not provide sufficient clarity for decision-makers, as they yield many equally plausible inferences. To address this, Sandia researchers focused on quantifying the uncertainty associated with these models using an interpretable and easy-to-compute hierarchical model of uncertainty. Understanding this uncertainty is key for determining how to reduce it effectively. The team then explored how to prioritize additional information that could minimize uncertainty, guiding new data collection efforts and highlighting which unknowns drive inference uncertainty.

The insights gained can inform logistics operations planning, enhance infrastructure protection, and improve data reconciliation methods. The research led to advancements in the open-source Pyomo algebraic modeling language and will empower decision-makers with clearer insights despite incomplete data. **(PI: Emma Savannah Johnson)**

LEVERAGING NEW TALENT > The project provided experience for four student interns, three of whom continue to work at Sandia.

DEVELOPING NEW AND IMPROVED SAFETY TECHNOLOGY FOR NUCLEAR WEAPONS

The Time-Resolved Elastodynamic Discrimination (TRUE-D) project was launched to improve safety systems for new nuclear weapons, aiming to make them more cost-effective and faster to develop. This research led to the creation of new materials and design insights that help control signals and power transmission for weapon operation. The TRUE-D technology offers a reliable alternative to traditional, more complex mechanical safety systems.

Two B61-12 joint test assemblies loaded on an F-35 aircraft for a flight test on Aug. 19, 2025. (Photo by Craig Fritz)

Sandia successfully tested TRUE-D flight hardware on the SkyFox flight demonstrator, showing promising results that could influence future nuclear programs. This project, in collaboration with the Weapon Technology Program under the NNSA, is working towards integrating TRUE-D into advanced safety systems. Overall, these advancements enhance national security by ensuring that nuclear weapons are safer and more efficient to operate. **(PI: Rick A. Kellogg)**

BOOSTING THREAT DETECTION IN DENSE TREES USING POLARIMETRIC RADAR

Sandia's research focuses on improving the detection of potential threats in cluttered environments, particularly in dense tree areas. The aim is to enhance situational awareness and increase analyst efficiency by reducing false alarms compared to existing single-polarization synthetic aperture radar (SAR) algorithms.

To achieve this, Sandia researchers have developed a novel automated target detection pipeline that utilizes polarimetric SAR (PolSAR). This advanced technology provides imaging capabilities in any weather and at any time, while also offering insights into the scattering physics of the observed regions. This allows for better differentiation between man-made objects and natural features.

The detection process begins with the extraction of polarimetric and texture-based features to identify regions with dense tree cover. The team then pairs polarimetric anomaly maps with Sandia's Focus of Attention algorithm to make initial detections. These detections are further refined and classified using a support vector machine classifier, which assesses features to separate man-made objects and natural features.

The results demonstrate that PolSAR enhances detection capabilities, yielding high-confidence results while substantially reducing false alarms. This advancement supports analysts in providing superior situational awareness. **(PI: Mindi Koudelka)**

ACCELERATING INFECTION DIAGNOSIS THROUGH RAPID DIAGNOSTIC TECHNOLOGY

There is a need for faster and more effective infection detection, particularly because of challenges posed by novel pathogens like SARS-CoV-2 in 2019. Current diagnostic methods often depend on prior knowledge of the specific pathogen, which can delay diagnosis, public health responses, and treatment decisions. To overcome these limitations, Sandia researchers are developing a new, agent-agnostic diagnostic technology that can quickly identify infections without needing to know the pathogen in advance.

The team leveraged outcomes from a previous LDRD project that utilized electromagnetic array technology with host response biomarker detection to develop a multi-mode assay that can rapidly distinguish between bacterial and viral infections based on a panel of host protein and RNA biomarkers. This capability will provide important insights during the early stages of an outbreak, enabling timely public health interventions even before targeted assays become available for scientists and clinicians. Ultimately, this research has the potential to create a portable diagnostic tool that can transform how infections are detected and managed, enhancing public health responses to emerging threats. **(PI: Betty Bosano Mangadu)**

SUPPORTING APPROPRIATE TRUST IN AI: UNDERSTANDING USER PERCEPTIONS AND PERFORMANCE

With the increasing use of AI tools to support high-consequence decision making, it's crucial to identify effective ways to help users to calibrate their trust in those tools. Much of the prior literature on trust in AI assumes that more trust is better, without considering the potential negative effects of inappropriate trust.

In this project, the Sandia researchers developed a novel model of trust in AI and designed an experiment to test interactions between user characteristics, task characteristics, and model characteristics with respect to appropriate and inappropriate trust. The experiment manipulated the transparency and interactivity of an algorithm used to support a seismic data analysis task. A key finding revealed that participants' perceptions of an algorithm's trustworthiness often did not correlate with actual performance improvements. For instance, when participants could change the algorithm's parameters, they often made choices that aligned the algorithm with their own incorrect assumptions about the data, leading to an erroneous output. The participants had high trust in the algorithm when it agreed with them, even though they were wrong.

These findings address an major gap in the prior research and emphasize the need for careful design in AI systems to prevent unwarranted perceptions of trustworthiness. **(PI: Laura Matzen)**

ENHANCING DECISION-MAKING THROUGH EFFECTIVE UNCERTAINTY VISUALIZATION TECHNIQUES

In the event of a radiological accident or attack, understanding the radiological environment is imperative for emergency response. The DOE's Nuclear Emergency Support Team (NEST) creates data products to guide responders in making informed decisions, such as where to evacuate residents, and this Sandia project aimed to minimize the potential for decision errors by improving the visualization of uncertainty.

Visualizations are effective for conveying complex information but can be misinterpreted. To help with this, researchers conducted systematic experiments to assess how visual cues influence risk perception in hazard maps, focusing on both non-experts evaluating wildfire risks and NEST team members assessing radiological risks. The findings revealed that different visual encodings can consistently alter risk perception for both groups.

The team produced publications and developed an online tool that models human visual processing, enabling rapid, objective evaluations of NEST data products. This tool ensures that vital information is conveyed efficiently without biasing risk perception. Ultimately, this research aims to equip decision-makers with the best information to protect the public during emergencies. **(PI: Laura Matzen)**

COOL FACT > The results from this project were presented to the New Mexico State Legislature to advocate for standardizing the state's wildfire evacuation maps.

TRANSFORMING LITHIUM BATTERIES FOR SAFER, HIGH-EFFICIENCY ENERGY STORAGE SOLUTIONS

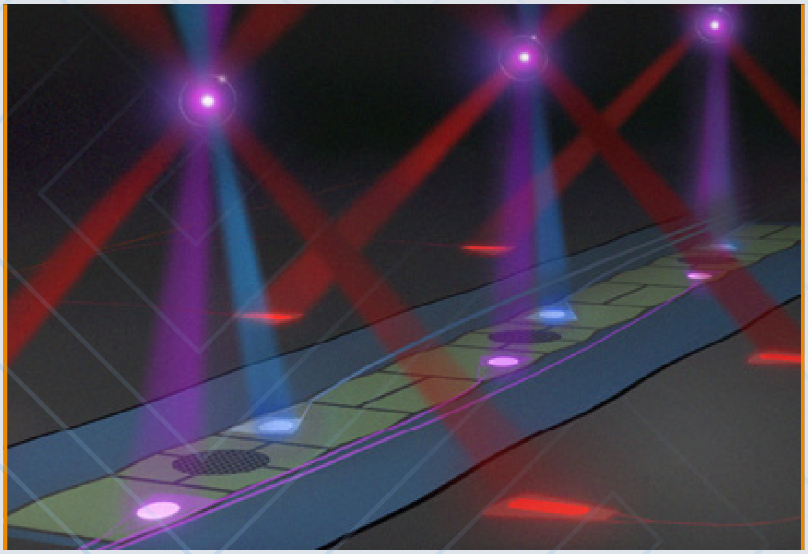
Applications from personal electronics to national security utilize lithium (Li) batteries. Li can provide significantly higher energy density than traditional graphite anodes, but safety concerns, such as the formation of Li dendrites, have limited its use to single-use batteries. These dendrites can cause short circuits and catastrophic failures.

To tackle these challenges, Sandia researchers studied the impact of copper crystal orientation on Li plating in high concentration liquid electrolytes, discovering that tuning the copper structure can improve performance. They also explored ion implantation to prevent dendrites from penetrating lithium lanthanum zirconate (LLZO) solid electrolytes, enhancing safety.

ADVANCING PORTABLE OPTICAL CLOCKS FOR ENHANCED NAVIGATION AND SECURITY

Portable optical atomic clocks are necessary for timing, communications, infrastructure, and navigation applications. Traditional high-performance clocks are often too large and power-hungry for field use, making portable solutions a priority for U.S. government research agencies.

A Sandia LDRD team focused on this need demonstrated the physics component of an optical clock with impressive frequency stability. This innovative clock utilizes trapped ions, specifically Yb-171, as frequency references. The team integrated photonic components, such as waveguides and diffraction gratings, into the ion trap, allowing for a compact and robust system that operates at room temperature and can withstand environmental changes.



Conceptual image depicting the ion trap with integrated optics, highlighting how lasers interact with the ions to enhance clock performance/stability.

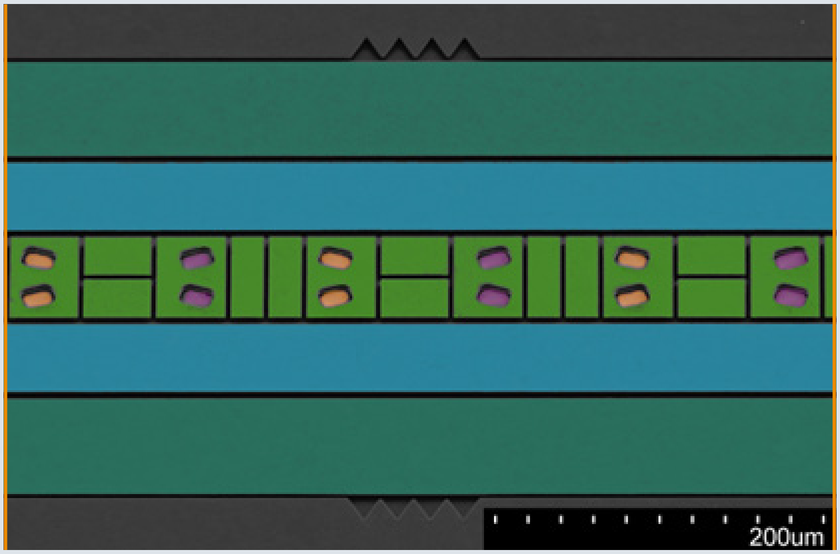
Additionally, the team investigated radiation damage through molecular dynamics simulations, revealing that defect concentrations along grain boundaries affect stability. In a related study published in *Nature Materials*, Sandia and University of Texas at Austin researchers demonstrated a synthesis method to generate zirconium oxide at grain boundaries in LLZO, suppressing dendrite growth and improving electrochemical . This innovative approach offers a scalable solution to enhance the safety and efficiency of all-solid-state batteries, paving the way for broader adoption. **(PI: Josefine D. McBrayer)**

READ MORE > *Nature Materials*, *Journal of Power Sources*

The development of a portable optical atomic clock holds important implications for inertial navigation, particularly in areas where GPS signals are unavailable, enhancing national security capabilities. With further advancements, this technology could lead to a fully deployable clock system with low size, weight, and power.

The team presented their work at the Southwest Quantum Information and Technology, and the findings are being submitted to *Nature Photonics*. **(PI: Hayden McGuinness)**

LEVERAGING NEW TALENT > Postdocs Joonhyuk Kwon and Tharon Morrison conducted experiments under the supervision of Hayden McGuinness, collaborating with David Leibrandt from UCLA, a leading expert in optical clocks.



Scanning electron microscope imagine, in false color, of the ion trap used to probe the frequency reference ions.

TRANSFORMING ENERGY EFFICIENCY WITH INNOVATIVE MINNEALLOY MAGNETIC MATERIALS

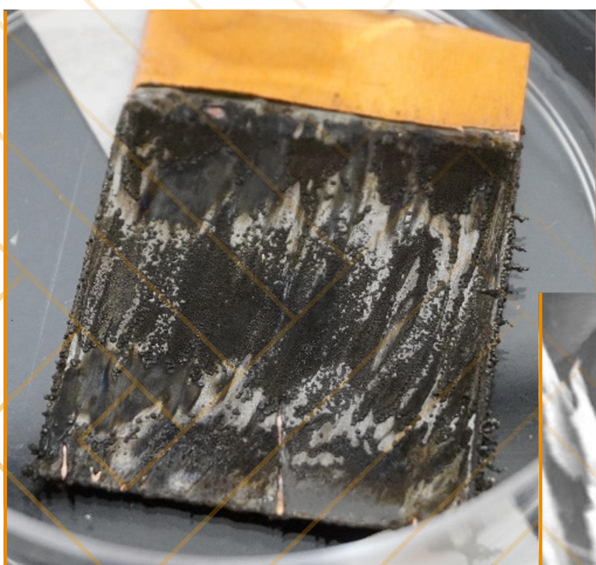
Sandia developed a groundbreaking soft magnetic material that addresses the modern electrical systems need for more efficient transformer cores and inductors. Minnealloy, composed of iron, nitrogen, and carbon, can outperform traditional electrical steel by transferring more power with less energy loss. This innovation is significant as it does not rely on critical materials, ensuring a secure supply chain.

The team fabricated Minnealloy using three scalable methods: melt-spinning, powder precursors, and electrodeposition. Each method has unique advantages; melt-spinning allows precise control over material structure, while powder precursor routes enable larger batch production. Electrodeposition is the most cost-effective option, though it lacks control over grain structure.

Sandia researchers presented their work at IEEE Magnetism and Magnetic Materials conferences and the DOE Office of Electricity, highlighting Minnealloy's potential for secure, high-power transformers. **(PI: Andrew S. Padgett)**

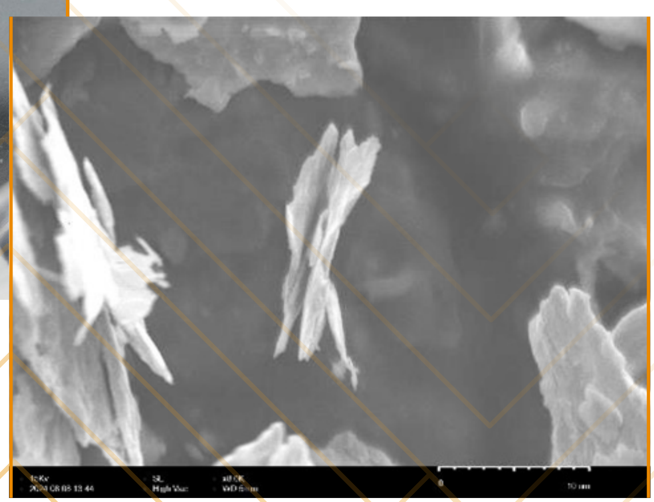
READ MORE > *AIP Advances*

COOL FACT > Ongoing collaborations with the DOE and industry partners will accelerate Minnealloy's commercialization, promising important impacts on the energy sector. $2.8M was awarded by the DOE to continue development through 2027.



Left: Powder precursor iron-carbon platelets. These particles are produced industrially and geometrically optimized for conversion to Minnealloy.

Below: Minnealloy thin film electrodeposited on a copper sheet. This process is low-energy and inexpensive.



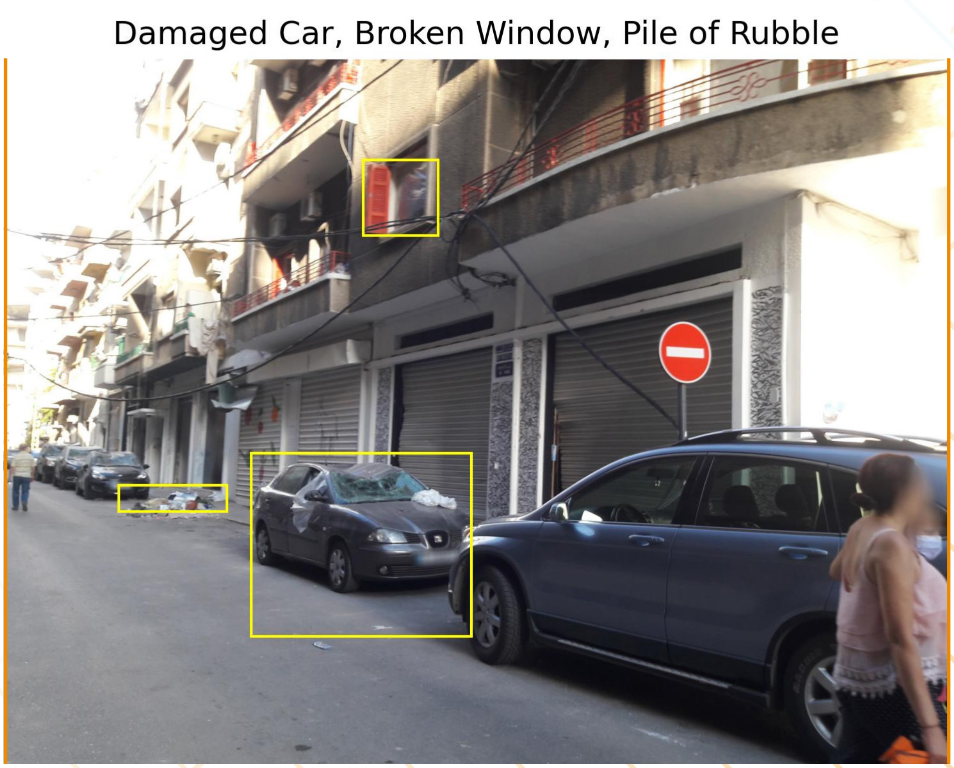
EVOLVING QUALITATIVE DATA INTO TRUSTWORTHY INSIGHTS USING GENERATIVE AI

Qualitative data from sources like news articles and social media are abundant, but it often lacks the reliability needed for accurate analysis. So, a Sandia LDRD team created PARADIGM, a computational framework aimed at transforming the qualitative data into quantitative insights using generative AI (GenAI) models, particularly in the realm of multimodal data fusion. For their test case, the research team focused on estimating the explosive yield of the Beirut blast from August 2020, utilizing various data sources, including synthetic aperture radar (SAR), crater images, seismographs, and social media images.

Employing vision language models (VLM), the team assessed structural damage in images and generated probabilistic damage evaluations linked to blast overpressure. By fusing estimates from different data sources through a Bayesian fractional posterior framework, the team estimated the explosive yield to be between 0.34 and 0.48 kilotons of TNT equivalent. Interestingly, the analysis revealed that ground-level images processed by VLMs were deemed more reliable than SAR data.

The project also investigated the use of knowledge graphs to validate the outputs of GenAI models and applied conformal predictions to enhance their performance. In addition, the researchers developed a new computational environment to facilitate the training and application of GenAI models, showcasing the potential of advanced technologies in improving data analysis and decision-making in pivotal situations. **(PI: Jaideep Ray)**

READ MORE > arXiv



A VLM detecting and describing damage in Beirut. The damage was classified into eight categories and converted into blast over-pressure estimates for that location.

UPGRADING QUANTUM SYSTEMS THROUGH INNOVATIVE ION TRAP INTEGRATION

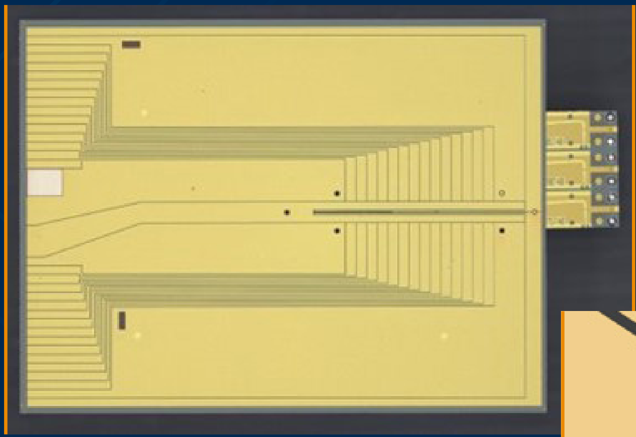
Sandia addressed important challenges in improving quantum systems, especially for quantum computers and atomic clocks. Current technologies struggle to combine ion traps and photonic circuits, which are essential for boosting performance and making these systems larger and more efficient. This project aimed to get around the limitations of traditional methods by developing a new approach that keeps these components on separate chips.

Paving the way for more efficient quantum systems, Sandia researchers achieved precise alignment within one micrometer between a photonic integrated circuit chip and an ion trap chip. The benefits realized from this research extend to enhancing the design and functionality of ion traps, which could lead to significant advancements in quantum technology.

This research aligns with national interests by enabling the integration of diverse technologies, ultimately contributing to the growth and sustainability of the quantum computing field. This work was presented at a national conference on atomic physics. (PI: Melissa Revelle)

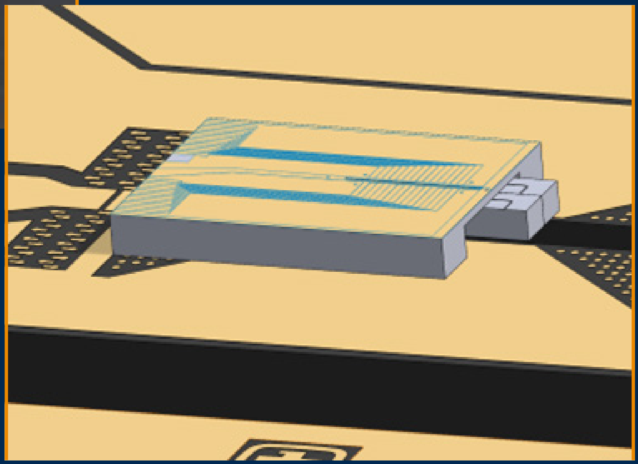
LEVERAGING NEW TALENT > The team benefitted from Theala Redhouse, an early career technologist, and two summer interns.

COOL FACT > Sandia's innovative strategy of keeping the components on separate chips provides more design options and makes the manufacturing process easier, ultimately helping to advance the capabilities of quantum technology.



Left: Image of the Chimera trap with the waveguide chiplet attached to the back. The output grating coupler is seen in the center of the trap slot as a small green dot.

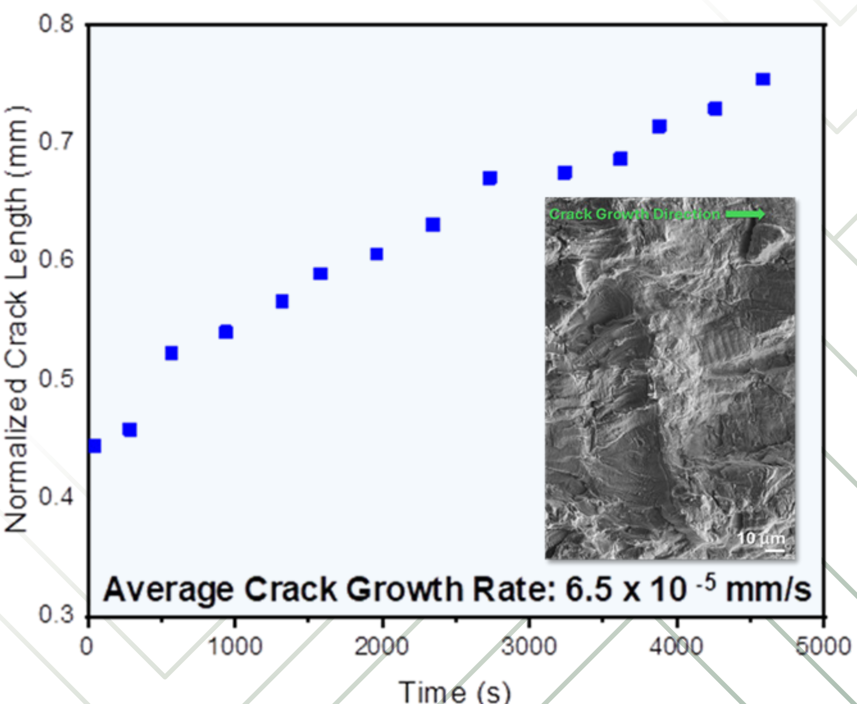
Below: Solidworks drawing of the final trap configuration. There is a large cutout in the backside of the ion trap which allows for a photonic circuit chiplet to be inserted and attached to the back of the trap.



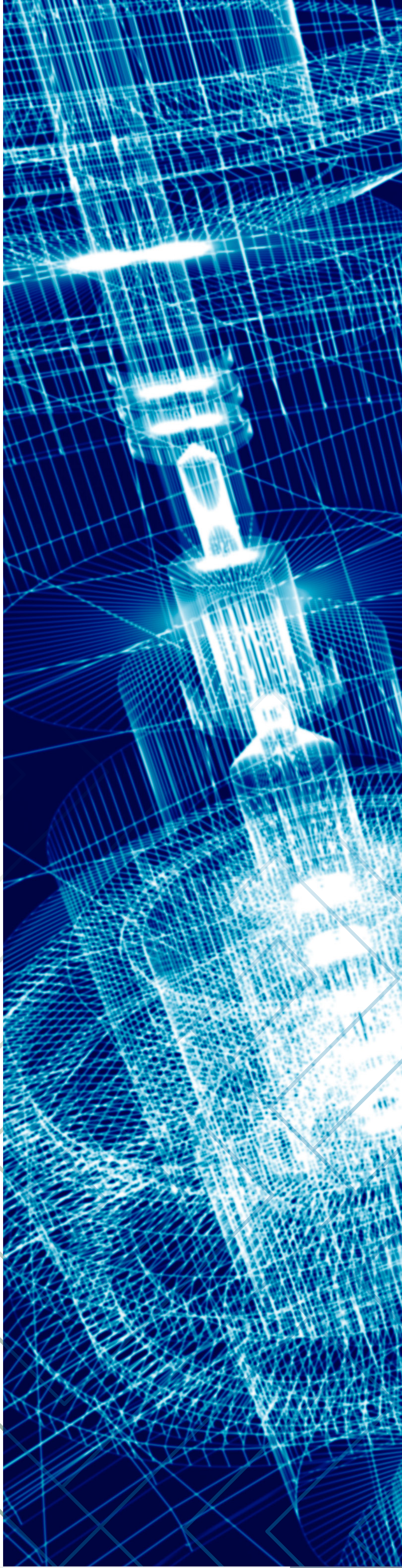
STRENGTHENING REACTOR RELIABILITY WITH ADVANCED MEASUREMENT TECHNIQUES

Next-generation nuclear reactors, particularly molten salt reactors, require materials that can withstand extreme conditions, but current methods for measuring environmentally assisted cracking are inadequate. To enhance safety and reliability, Sandia researchers developed a novel approach combining in-situ direct current potential drop techniques with high-temperature fittings and innovative sample designs. This work achieved the first-ever in-situ crack growth rate measurement for steel in a molten salt environment, specifically using a sodium nitrate/potassium nitrate salt solution at 340°C, which was validated by detailed post-test imaging.

The new measurement capability accelerates material evaluation, providing insights into degradation mechanisms. Collaborations have expanded, including proposed work with Lawrence Livermore National Laboratory on molten salt corrosion. The findings will be presented at distinguished conferences, such as the Electrochemical Society Annual Meeting and the Materials Society Annual Meeting, highlighting Sandia's commitment to advancing materials science in extreme conditions and contributing to safer, more reliable nuclear energy solutions. **(PI: Rebecca F. Schaller)**



The graph displays crack growth in molten nitrate salts, totaling approximately 0.33 mm, with an inset image showing fatigue bands indicating growth.



FROM THE ARCTIC TO INDUSTRY: THE WIDE-REACHING APPLICATIONS OF SANDIA'S DUAL COMB SPECTROSCOPY SYSTEM

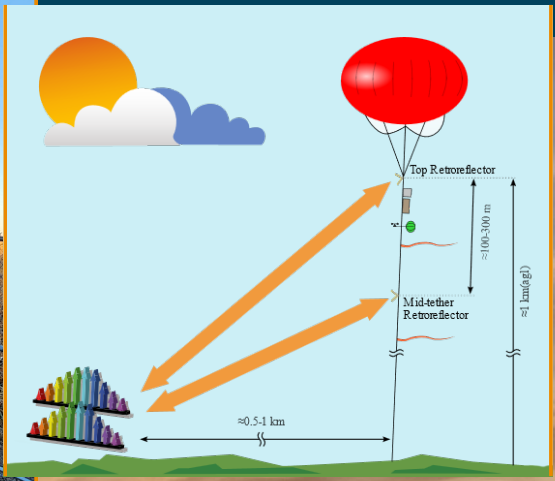
There is a need for effective greenhouse gas (GHG) monitoring, driven by the impact of climate change on national security and infrastructure. Current sensors are limited to either single-point continuous monitoring or intermittent measurements on kilometer scales using airborne or satellite systems. To bridge this gap, Sandia developed a dual comb spectroscopy (DCS) system capable of continuous GHG monitoring over kilometer scales. In collaboration with the National Institute of Standards and Technology (NIST), Sandia demonstrated vertical DCS measurements of water, methane, and carbon dioxide using a tethered balloon, marking the first extended-period vertical GHG monitoring with DCS.

This breakthrough enables precise measurement of GHG concentrations in the troposphere, such as in the Arctic, where it is possible to measure methane emissions released from melting permafrost. Beyond GHG monitoring, DCS technology has potential applications in industrial leak detection, chemical threat identification, and high-speed chemical reaction monitoring. Follow-on projects being led by Truman Fellow Daniel Herman include the mid-infrared DCS development and quantum-enhanced DCS for improved chemical threat detection. **(Co-PIs: Peter Schwindt and Roger Ding)**

COOL FACT > The innovative DCS system is smaller, lighter, and more energy-efficient than previous DCS technologies and has successfully measured methane concentrations over a 1.3 km path.

Left: Picture of the telescope that launches the laser light to the tethered balloon flying during DCS measurements.

Below: Schematic showing the broadband light of two frequency combs for DCS being sent to retroreflectors on a tethered balloon.



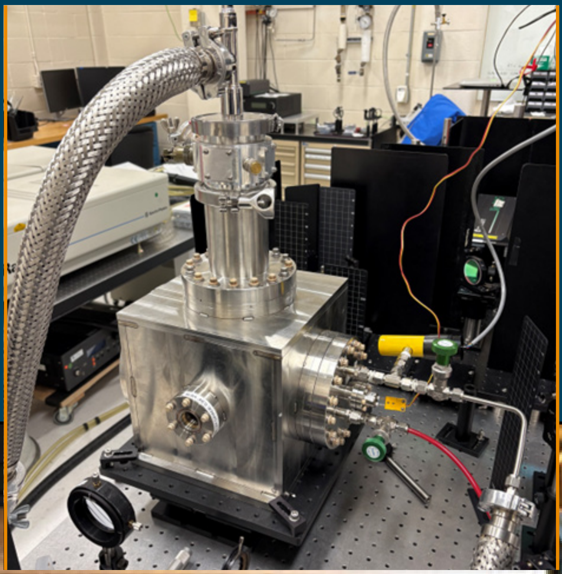
Picture of the tethered balloon flying during DCS measurements at the DOE Atmospheric Radiation Measurement site near Lamont, OK.

IMPROVING HYPERSONIC AIRFLOW ANALYSIS FOR MODERN DEFENSE APPLICATIONS

Precise gas temperature measurements are integral for advancing hypersonic technology and ensuring the success and safety of related missions. In Sandia's Mach 14 Hypersonic Wind Tunnel facility, accurately measuring these temperatures using advanced optical techniques is challenging, so a Sandia team addressed this ground capability gap during a six-month LDRD project.

The team established measurement and spectral fitting procedures to extract temperature data from experimental images, and their innovative approach resulted in the development of a novel Rayleigh scattering technique that has been demonstrated in benchtop environments relevant to wind tunnel operation. Initial tests have shown promising results, with accuracy and precision within 8%. Findings from this work will be presented at the American Institute of Aeronautics and Astronautics SciTech 2026 conference.

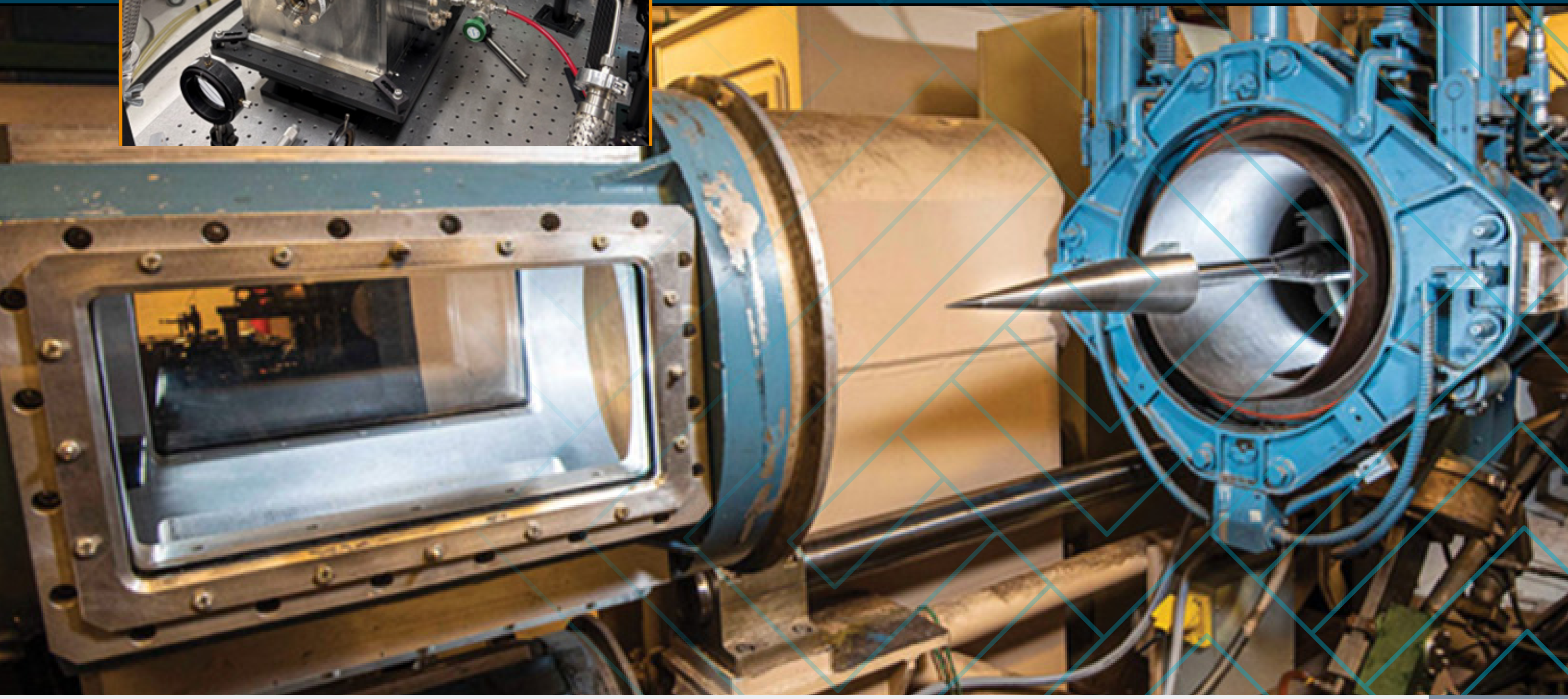
Looking ahead, Sandia researchers are exploring various methods to further improve measurement precision and capability. This technique holds the potential to become a vital tool for blowdown-to-vacuum wind tunnel facilities. **(PI: Will Charles Bowman Senior)**



COOL FACT > Applying this new Rayleigh scattering technique in the Hypersonic Wind Tunnel will improve understanding of the complicated airflows at hypersonic speeds, which are important for modern missile delivery systems.

Left: Benchtop experiment for technique characterization.

Below: Sandia's Hypersonic Wind Tunnel facility.

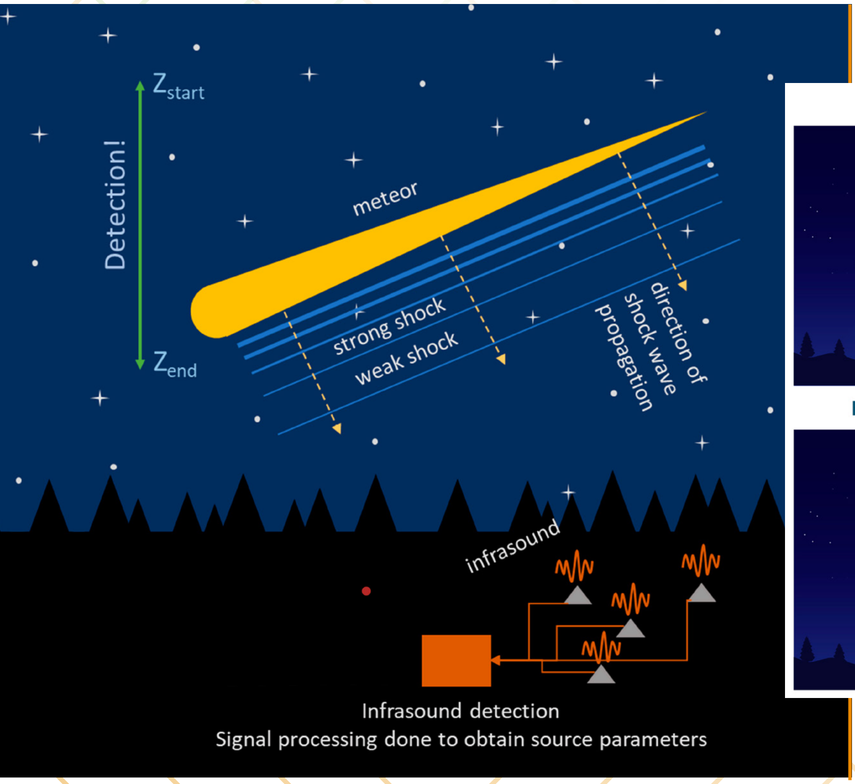


BOLSTERING NATIONAL DEFENSE BY MONITORING AND CHARACTERIZING NATURAL AND ARTIFICIAL HYPERSONIC OBJECTS

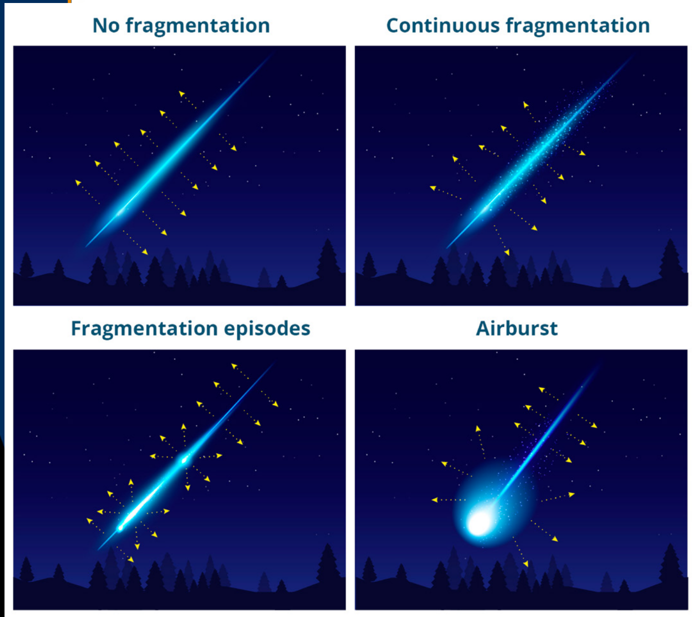
National security and planetary defense hinge on distinguishing natural meteoroids from objects of artificial origin. Sandia rose to this challenge by harnessing natural fireballs as real-world hypersonic test flights. By analyzing infrasound—low frequency acoustic signals—generated as these objects race through the upper atmosphere, the team refined how these waves reveal energy release and source characteristics. The team built software that analyzes light emissions to pinpoint fragmentation, developed adaptive array processing methods to extract faint signals, and created a trajectory model that factors entry angle to improve event locations. Sandia interns processed vast datasets, and collaborations with universities supported analytical capabilities. To lay a lasting foundation, Sandia researchers assembled comprehensive archives of past fireball records, merging digitized historical data with matched optical-acoustic observations. The team published ten peer-reviewed papers—including one featured on a journal cover—and released two open-source software packages. Follow-on projects funded by non-LDRD sponsors are already building upon these methods for real-world applications. **(PI: Elizabeth A. Silber)**

READ MORE > *Atmosphere*, *The Astronomical Journal* (*1*) (*2*) (*3*) (*4*), *Remote Sensing*, *Pure and Applied Geophysics*, *Data* (*1*) (*2*), *Seismological Research Letters*

COOL FACT > The results of this project strengthen global surveillance, help verify treaties, and improve quick response planning through better understanding of hypersonic objects.



Visualizing how a meteor's shock wave produces infrasound, which is then processed to determine source parameters.



Visualizing how fragmentation affects the observable light and acoustic signature of a high-speed atmospheric object.

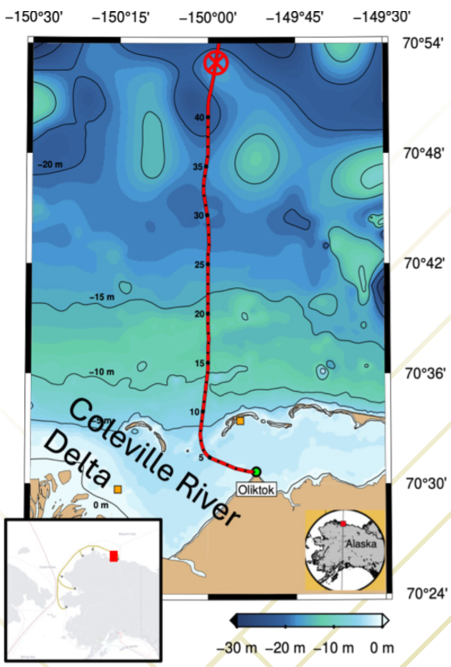
REPURPOSING FIBER-OPTIC CABLES FOR ARCTIC MONITORING

There is an urgent need to understand the Arctic environment and its impact on ecosystems, infrastructure, and national security. The Permafrost Distributed Acoustic and Temperature Sensing LDRD team repurposed a 42-kilometer submarine dark fiber-optic cable near Oliktok Point, Alaska, extending into the Beaufort Sea. Using advanced laser technology, Sandia developed a system that combines distributed acoustic sensing and distributed temperature sensing on a single fiber. This system provides continuous, high-resolution monitoring of seismic activity, seasonal sea-ice behavior, and subsurface temperature changes.

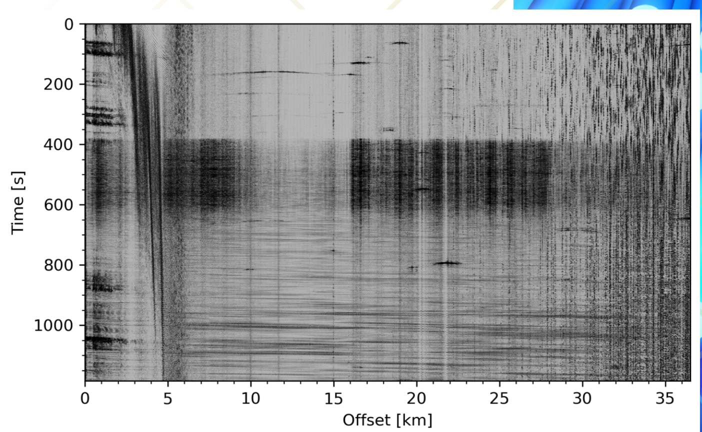
The research uncovered ice-bearing submarine permafrost layers, persistent thermal anomalies potentially linked to fluid and gas seepage, and detailed icequake event data. These findings highlight the untapped potential of existing telecommunications cables for Arctic remote monitoring and beyond, offering valuable insights into subsurface seismic and thermal structures, while addressing national security concerns. Collaborations with the University of Texas at Austin and the University of Washington were core to the project's success.
(PI: Christian Stanciu)

READ MORE > *Scientific American*, *Sandia Lab News*, *KUNM*

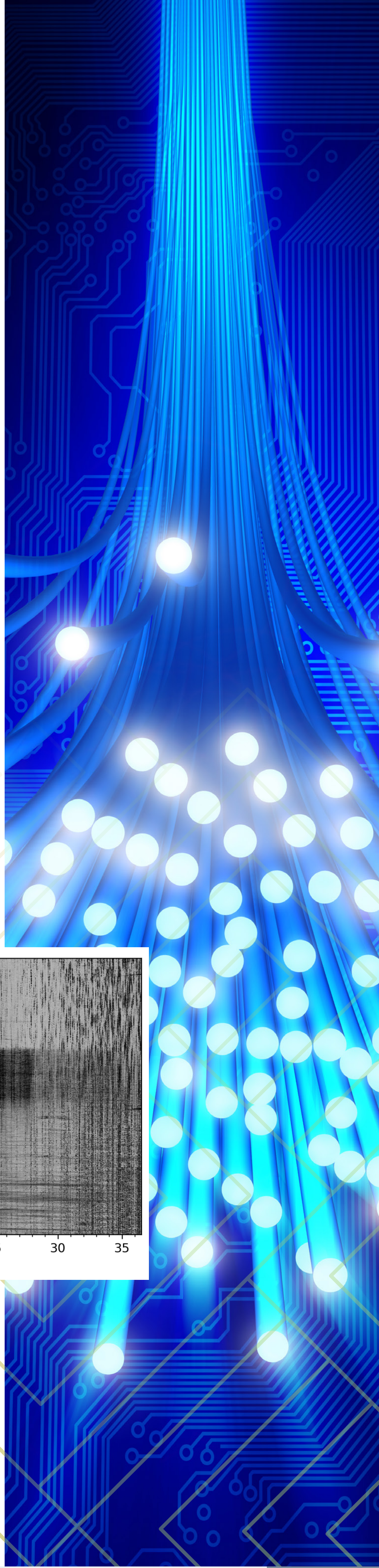
COOL FACT > With over 10 million people reached through publications, conferences, and media, this work is driving innovation across Sandia's mission areas, including global security and nuclear threat detection.



Map showing the fiber optic cable used for Arctic monitoring extending offshore from Oliktok Point into the Beaufort Sea.



Seismic waves from the Kamchatka M8.8 earthquake, recorded using the Alaska fiber-optic cable.



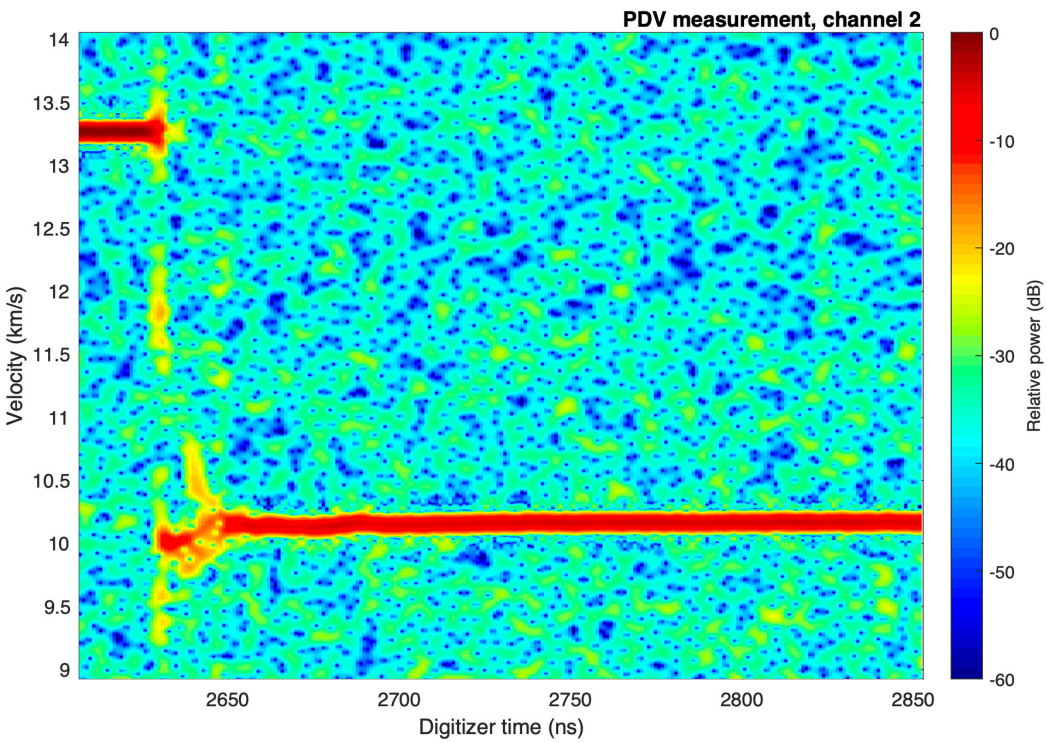
ADVANCING FLUID BEHAVIOR MODELS FOR NATIONAL SECURITY MISSIONS

Understanding how fluids behave under extreme pressure and temperature is fundamental for national security science. The simulations used by the NNSA need accurate predictions of how materials mix when subjected to shock waves, but many existing models overlook viscosity. To address this issue, Sandia researchers created a new experimental setup that measures how a shock wave behaves in fused silica using advanced techniques.

Working with the University of Colorado Boulder, Sandia brought together scientists, graduate interns, and students to enhance their research. The LDRD team also conducted detailed calculations to estimate viscosity and incorporated a new viscosity model into their hydrodynamics code. This allowed them to run simulations that helped design their experiments. Additionally, they achieved the first high-pressure measurements of pure fused silica viscosity, providing valuable data on how viscosity changes under pressure.

As a result, Sandia can now accurately calculate the viscosity of fluids and plasmas at high pressures and temperatures. This information will be integrated into hydrodynamic and magnetohydrodynamic models that support fusion research and high energy density experiments, ultimately benefiting national security missions. **(PI: Joshua P. Townsend)**

READ MORE > *Physics of Plasmas*



Representative Photonic Doppler Velocimetry trace of viscosity experiments show decaying envelope of velocities at short time due to viscous effects.

GRAND CHALLENGE: Enabling Rapid Flight Integration of Advanced Hypersonic Thermal Protection System Materials (TPS)

TPS: TRANSFORMING THERMAL PROTECTION SYSTEMS ANALYSIS FOR NEXT-GENERATION HYPERSONIC VEHICLES

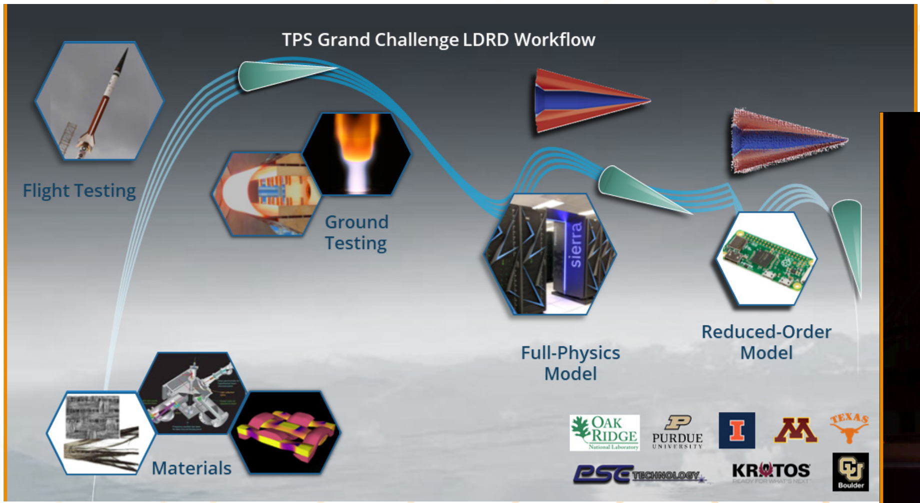
Hypersonic glide vehicles operate at extreme speeds and temperatures, so it is imperative that the materials withstand harsh conditions. To meet this need, Sandia researchers are *enhancing the performance analysis of advanced thermal protection system (TPS) materials*. Over three years, the team investigated three types of carbon-based and two types of carbon-silicon carbide materials, producing hundreds of samples for testing in collaboration with eight external partners.

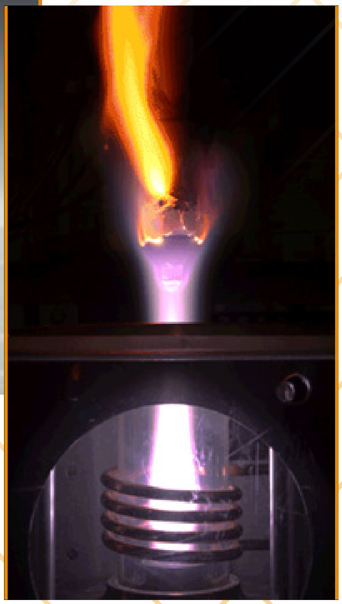
The team developed a model that simulates the thermal protection system's performance throughout a hypersonic vehicle's flight trajectory. By combining experimental data with advanced modeling techniques, the team accurately predicted how these materials respond to extreme heat and pressure. Innovative testing methods, including ablation experiments in specialized environments, validated these predictions.

In 2025, extensive flight test data was collected, allowing the team to create a framework for understanding uncertainties in material properties and ablation responses during flight. More samples are expected in 2026. **(PI: Justin L. Wagner)**

READ MORE > *The Journal of Physical Chemistry C*, *Aerospace Research Central*

COOL FACT > Sandia developed a reduced order model that is 25,000 times faster than the full-order model while maintaining 90% accuracy. This advancement will enable real-time analysis on desktop systems and potentially onboard future hypersonic vehicles.





Above: Illustration of the Thermal Protection Systems Grand Challenge workflow capturing major research thrusts spanning materials science through systems predictions. External partners listed on bottom-right.

Right: Engineers test a heat-shield material in an inductively coupled plasma torch. The plasma can reach temperatures hotter than the surface of the sun, replicating the intense heat of hypersonic flight. (Photo by Craig Fritz)

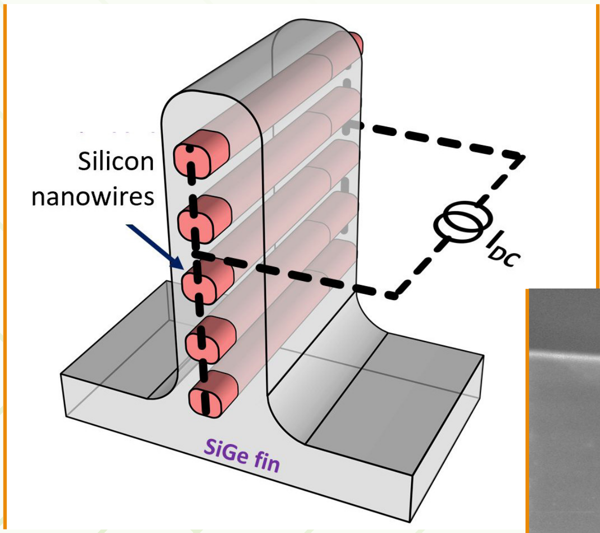
REVOLUTIONIZING DEFENSE AND COMMUNICATIONS WITH SELF-AMPLIFIED RESONATORS

High-performance, integrated resonators that operate in the super-high frequency range would benefit numerous mission applications across defense, aerospace, and telecommunications areas. To meet this need, Sandia took an innovative approach and created the self-amplified resonator (SANR). The significance of this research lies in its potential to revolutionize technology by enabling integrated, on-chip resonators that dramatically reduce size, weight, and power consumption compared to existing solutions.

Collaborations with external partners, including the University of Florida and companies like Applied Materials and Axcelis Technologies, have been core to the project's success. Together, they demonstrated self-amplification in new resonators made from a layered material of silicon and silicon germanium at low frequencies.

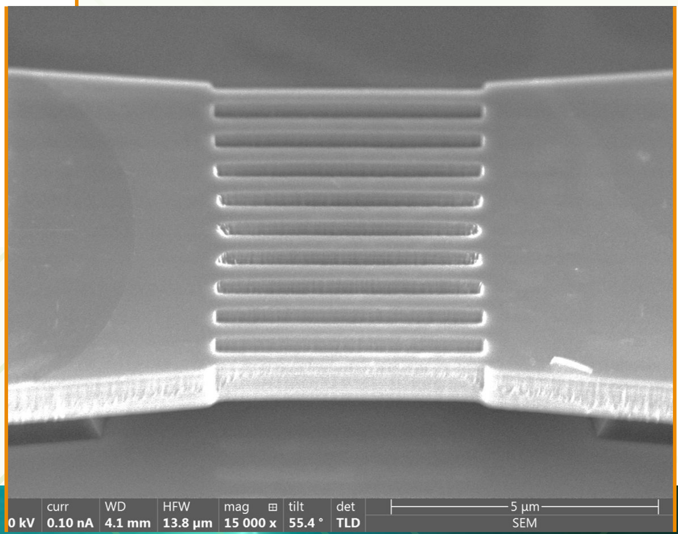
The implications of this work extend to mission areas such as tactical positioning, navigation, and timing, as well as advancements in 6G communications and phased array radars. A follow-on LDRD project will continue to explore the transformative potential of this research. **(PI: George T. Wang)**

COOL FACT > A U.S. patent for the groundbreaking self-amplified resonator technology was awarded in 2025.



Left: SANR design consisting of a silicon germanium nanofin with embedded silicon nanowires.

Below: Image of a fabricated SANR with 10 nanofins.

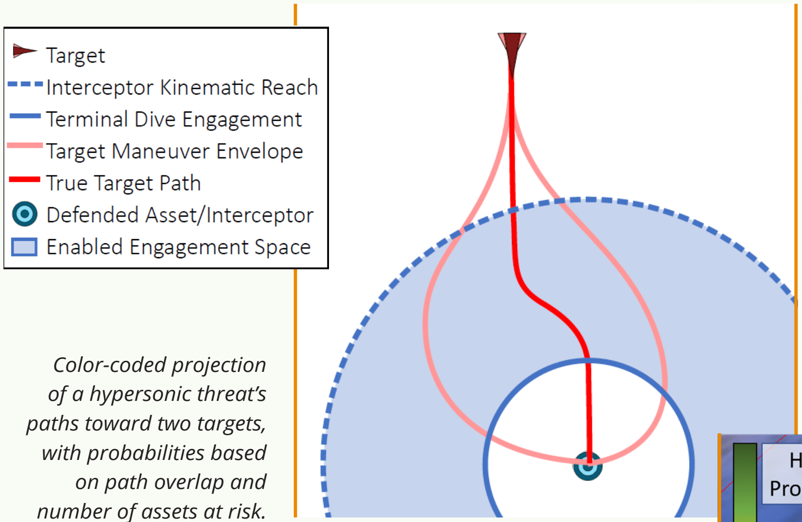


FORTIFYING FIRE CONTROL ALGORITHMS FOR COOPERATIVE HYPERSONIC TARGET PREDICTION AND INTERCEPTION

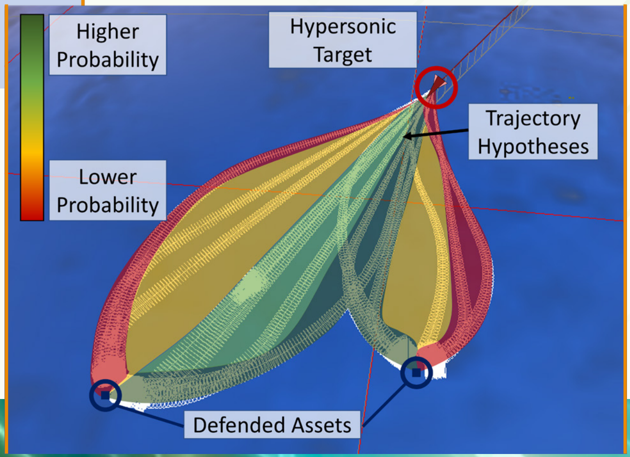
Hypersonic weapons pose a challenge to missile defense systems due to their extreme speed, unpredictable maneuvers, and aimpoint ambiguity. To meet this threat, Sandia researchers developed a fire control algorithm that forecasts multiple possible flight paths, selects probabilistic intercept points during launch, and continuously updates guidance commands for multiple simultaneous interceptors in flight.

Using the high-fidelity Ascent simulation environment, the team evaluated the algorithm in a realistic point defense scenario with varying numbers of interceptors. Results demonstrated the algorithm's computational feasibility and showed how it compares to existing methods. The findings also provide valuable insights into hypersonic trajectories and maneuvers, identifying which are most challenging to counter. This strategically positions Sandia in supporting national priorities, including Golden Dome and space-based interceptors.

The Missile Defense Agency is interested in this work for two future projects, specifically since the algorithm is interceptor-independent and adaptable to various missile defense systems. Future efforts will explore alternative interceptor models, scenarios with multiple defended assets, and refined weighting schemes. **(PI: Landon Clark Willey)**



Color-coded projection of a hypersonic threat's paths toward two targets, with probabilities based on path overlap and number of assets at risk.



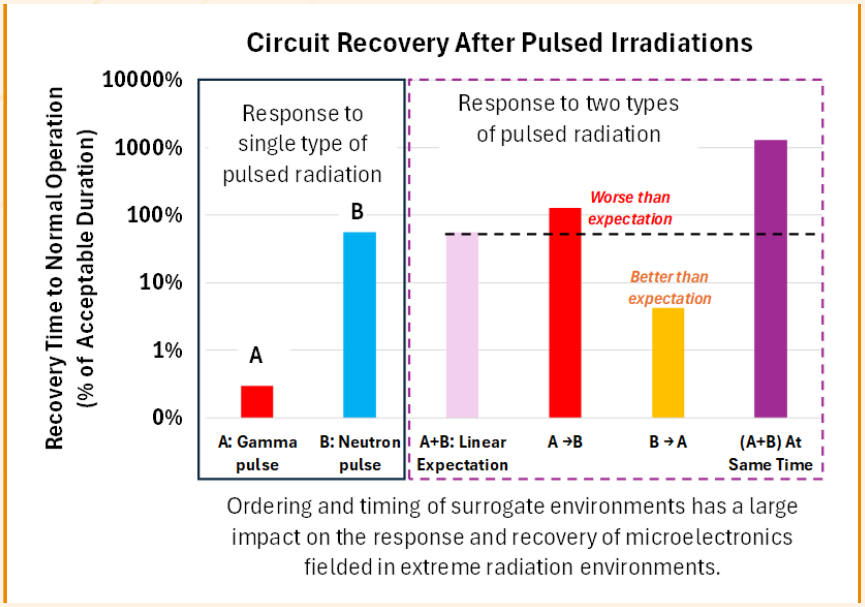
Side-by-side comparison of aimpoint selection methods including traditional, literature-based, and Sandia's multi-hypothesis approach for defending an asset from a hypersonic threat.

ADVANCING UNDERSTANDING OF COMBINED RADIATION EFFECTS ON CRITICAL MICROELECTRONICS

Understanding the resilience of microelectronics in harsh environments is essential for ensuring the reliability of technology used in applications for national security and space exploration. Sandia researchers have been actively investigating how microelectronics, particularly silicon and gallium-arsenide transistors, respond to combined neutron and gamma radiation environments. This work is imperative as it helps predict how these components will perform in real-world scenarios where they may face multiple types of radiation simultaneously.

The team produced a series of impactful studies, publications, and multiple conference presentations that delve into various aspects of radiation effects on these transistors. For instance, one study explores enhanced annealing processes in high dose rate environments, while another focuses on the response of radiation-hardened optical data converters. The research also includes innovative modeling techniques to simulate the synergistic effects of radiation, providing valuable insights into the degradation mechanisms of these technologies.

This work not only contributes to scientific knowledge but also supports national security initiatives by ensuring that technologies can withstand the rigors of their operational environments. **(PI: Joshua Young)**



Observation of synergistic recovery behavior after combined surrogate neutron and gamma irradiation.

OPTIMIZING ONBOARD COMPUTING FOR AUTONOMOUS VEHICLES WITH ANALOG COMPUTING

Many autonomous and semi-autonomous systems operate with limited onboard power, restricting the applications that can be solved onboard. Current systems often rely on simpler operations or offload tasks to a base station, increasing computation time and vulnerability to jamming. To achieve true autonomy, addressing energy consumption in onboard computing is imperative.

To tackle this issue, Sandia researchers developed energy-efficient methods for matrix-vector multiplication, a key operation for many applications, using analog computing. This approach leverages the physical properties of circuits to perform calculations, making it more efficient than traditional digital systems. However, analog computing introduces challenges due to circuit-level imperfections that limit precision, leading research toward applications that can tolerate low precision.

To support applications requiring higher precision, such as advanced optimization algorithms for guidance, navigation, and control, Sandia researchers devised a new approach. By dividing calculations between analog and digital components and modifying algorithms to address the challenges of analog computing, the team showed that optimization algorithms could effectively use analog hardware, achieving significant energy savings. This advance will enable future systems to perform these tasks entirely onboard. **(PI: Ben Feinberg)**

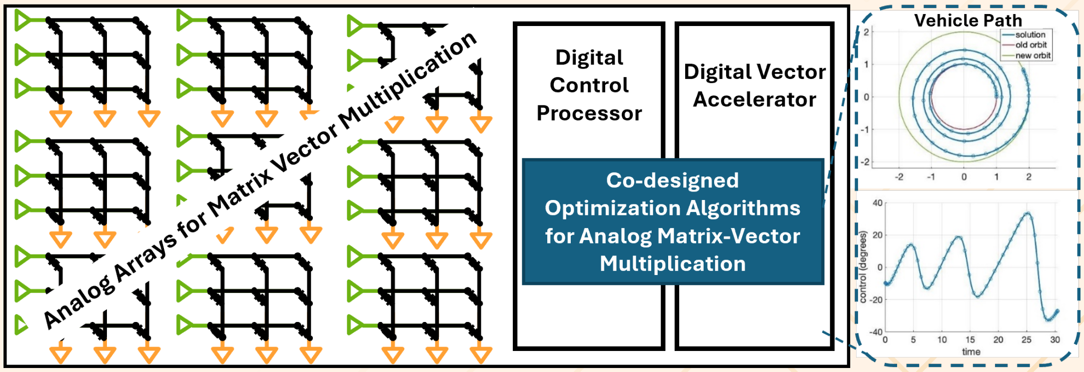
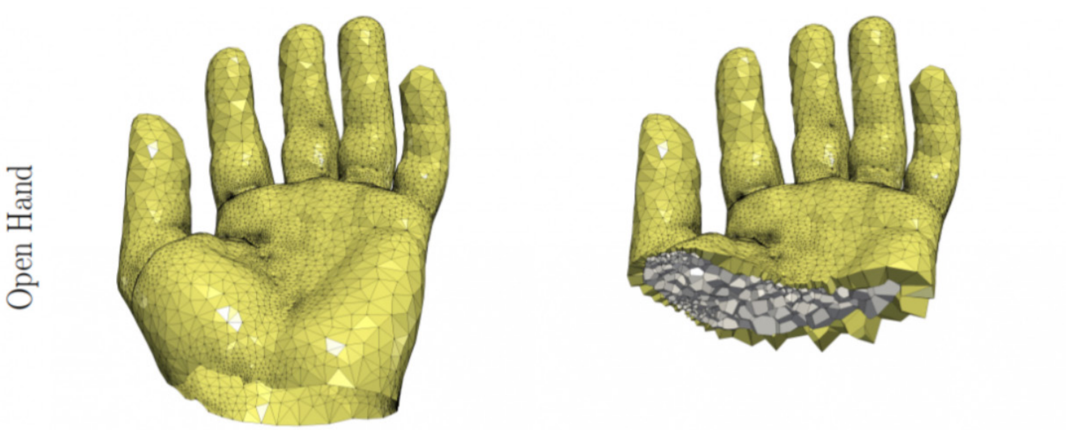


Illustration of a hybrid computing system that enhances energy efficiency when determining an optimal trajectory for transitioning between two orbits using both analog and digital components.

ACCELERATING NUCLEAR DESIGN THROUGH A REVOLUTIONARY MESHING TECHNIQUE

Creating computer-aided design (CAD) models for new nuclear design components is indispensable to the design process. Preparing the models for simulation takes months due to the complex process of breaking them into smaller pieces, or "meshing." Each mesh cell must meet specific geometric requirements to ensure accurate simulations, but existing methods often produce low-quality meshes that require extensive manual adjustments, slowing down the ability to innovate.

This LDRD team created a new a methodology that can drastically reduce the component design-to-simulate cycle and provide confidence in parallel meshing. The new mesher builds on the strengths of the previous VoroCrust tool but addresses its limitations. It automates the meshing process, ensuring high-quality meshes that are tailored to the needs of ND simulations. By using advanced geometric techniques, Sandia can efficiently identify nearby geometric objects and manage the order of adding mesh cells, even in complex areas with sharp curves. This new approach reduces the time and effort needed for model preparation, allowing the design and testing of ND components to be accelerated. Ultimately, this project enhances Sandia's mission by streamlining the development process, improving simulation accuracy, and supporting timely advancements in nuclear deterrence technology.
(PI: Mohamed Ebeida)



Q_{min}	$\theta_{<30}\%$	$\theta_{>90}\%$	$V_6\%$	$d_H(\times 10^{-2})$	$d_{RMS}(\times 10^{-3})$	ρ_{max}	$T^{\updownarrow}$	$T^{\downarrow\downarrow}$
0.13	8	18	39	0.884	1.42	16.598	105	151

VoroCrust is the first provably correct algorithm for conforming Voronoi meshing of non-convex and non-manifold domains with guarantees on the quality of both surface and volume elements. The new mesher designed in this LDRD project has all of VoroCrust's good qualities, improves where issues were encountered before, and places simulation points where the physics needs them.

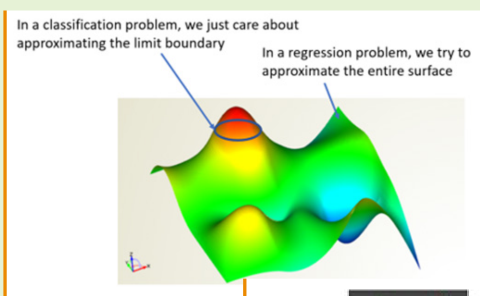
OVERCOMING THE CURSE OF DIMENSIONALITY: A FRAMEWORK FOR EFFECTIVE DECISION-MAKING IN NUCLEAR DETERRENCE APPLICATIONS

When a simulation or experiment involves many input parameters, the “curse of dimensionality” precludes a full exploration of the response of the system to all of the possible combinations of inputs. This LDRD project addresses this vital challenge through the development of active learning methods to classify conditions as ‘safe’ or ‘unsafe, in the presence of uncertain variables.

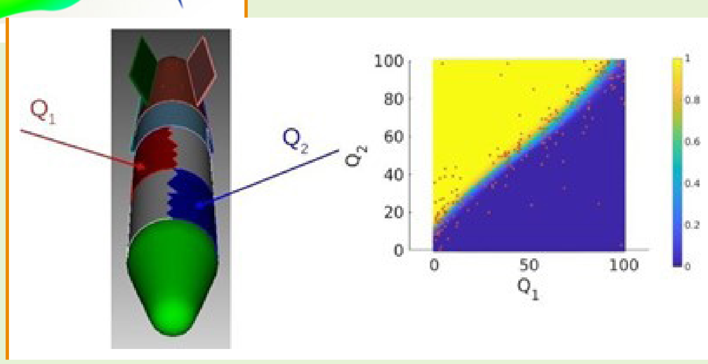
To tackle the curse of dimensionality, the team explored four different strategies to efficiently identify these boundaries, tested on specific mathematical examples. They also introduced a transfer learning framework that allows knowledge from one model to enhance another, saving time and resources. Additionally, Sandia researchers implemented advanced techniques to find rare failure conditions, ensuring comprehensive safety assessments.

To visualize complex data, the team employed methods that make it easier to understand how decisions are made. This research improves how decision boundaries are estimated, ultimately enhancing safety and reliability in engineering designs. The findings pave the way for more effective decision-making processes in key applications, showcasing Sandia’s commitment to advancing technology for national security. **(PI: Tim Walsh)**

READ MORE > *Structural and Multidisciplinary Optimization*, *IEEE Open Journal of Control Systems*, *AIAA Aviation Forum and ASCEND Conference*, *IEEE Conference on Decision and Control*



Comparison of classification and regression approaches: While regression struggles with high-dimensional data by attempting to fit a continuous output, classification simplifies the problem by defining clear boundaries between categories.



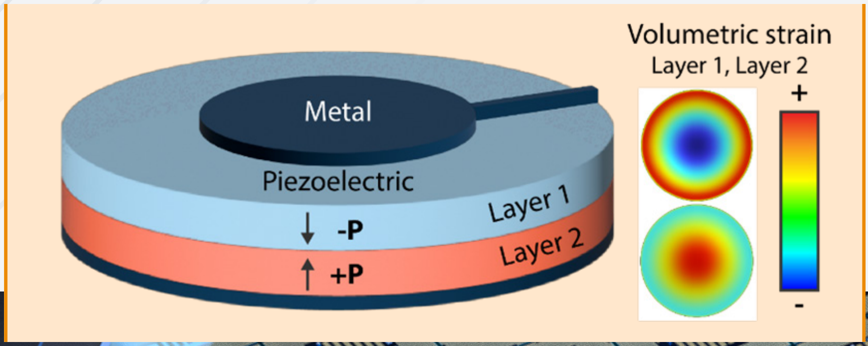
(Left) uBOMB geometry of fictitious reentry vehicle. The red and blue panels are prescribed a heat flux Q. (Right) The decision boundary obtained using support vector machines, where the red dots indicate the simulations required to obtain the interpolated solution.

TINY TECH, BIG IMPACT: IMPROVING PIEZOELECTRIC DEVICES FOR NATIONAL SECURITY

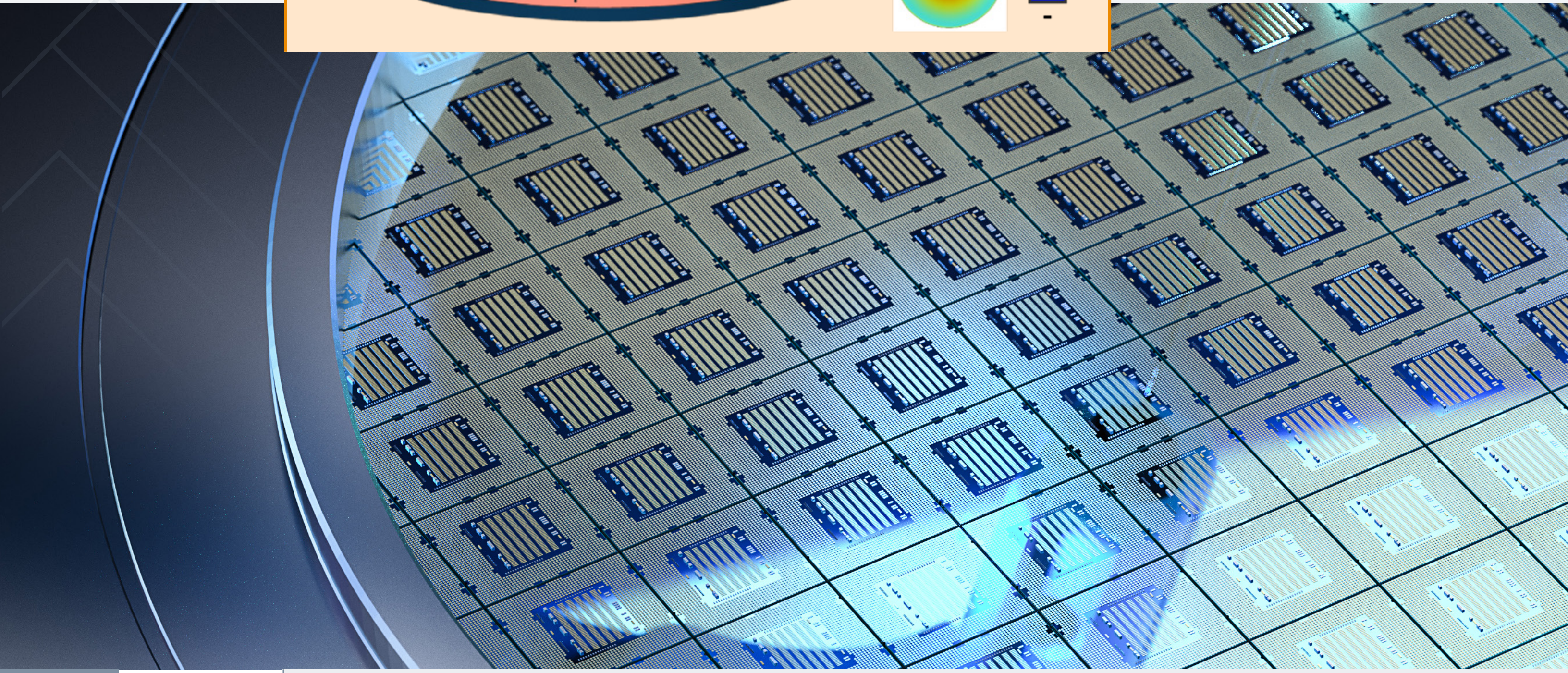
Piezoelectric MEMS (micro-electromechanical systems) are miniature devices that generate a small electrical charge when subjected to pressure or strain in response to an applied electric field. Researchers are exploring their potential to enhance operational capabilities and support infrastructure in national security contexts. Utilizing strategic poling, this LDRD project team aligned layers of alternating polarity, which enhances electrical and mechanical coupling. This innovative approach mitigates charge cancellation during transduction, a common issue with conventional unipolar piezoelectric films, and improves displacement during actuation performance. Additionally, the team is investigating how the approach can be rapidly deployed into state-of-the-art manufacturing to showcase how a processing change can result in a higher performing piezoelectric MEMS.

This research has the potential to significantly improve technologies like piezoelectric-based radio frequency filters, electro-optic modulators, and pressure sensors. Advancements in this area are not only integral for improving industrial applications but also align closely with national security needs, making the project highly relevant for technology transfer to various industries. **(PI: Giovanni Esteves)**

COOL FACT > Outcomes from this project helped to obtain follow-on funding from the Defense Advanced Research Projects Agency and push piezoelectric bimorphs into micron scale.



Strategically poled transducer that achieves higher sensitivity than unipolar transducers by incorporating alternately poled layers to complement the anticipated stress during operation.



EVOLVING SEMICONDUCTOR TECHNOLOGY FOR NATIONAL SECURITY APPLICATIONS

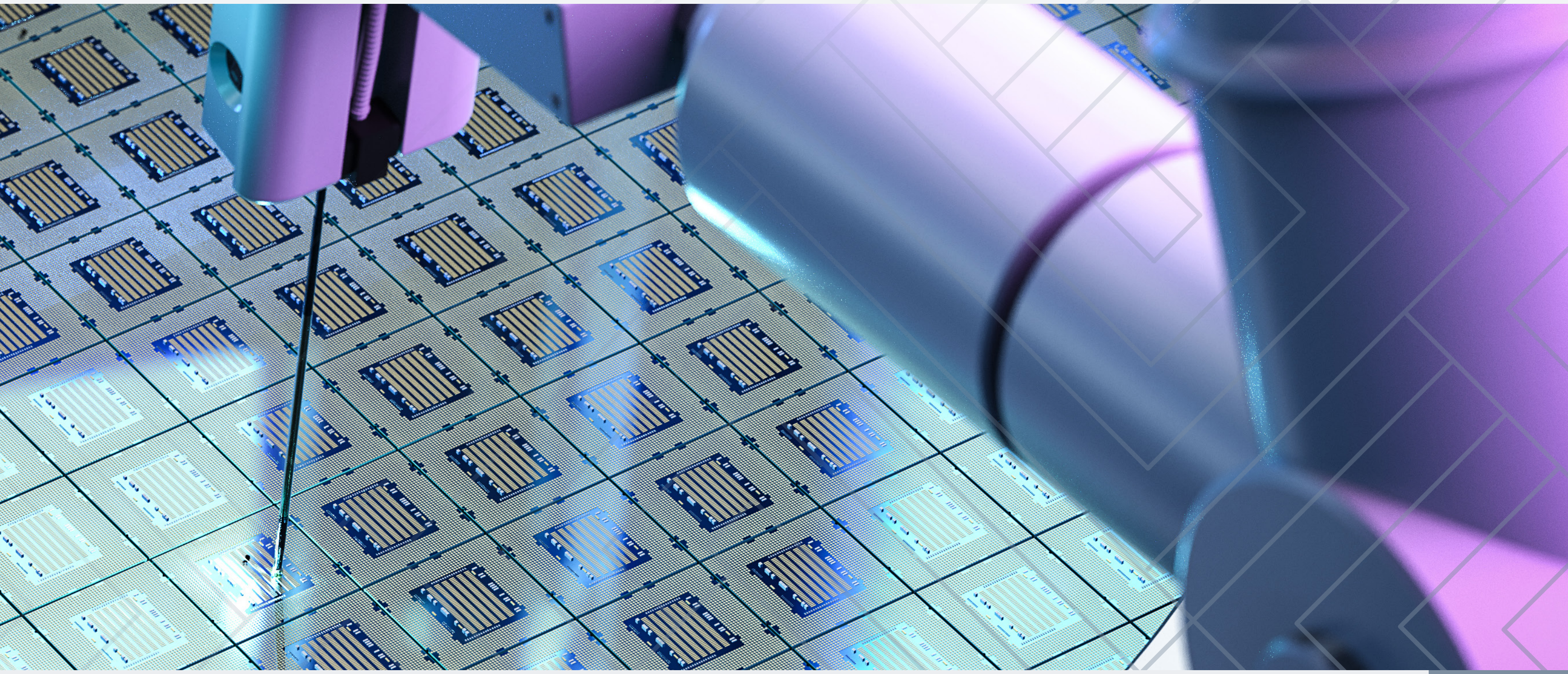
With the goal of enhancing the reliability and performance of microelectronics in the face of radiation challenges, LDRD researchers have made significant strides in developing non-volatile, radiation-hard ferroelectric memory using innovative materials such as hafnium oxide and hafnium zirconium oxide. This advancement is being integrated into Sandia's trusted radiation-hardened fabrication facility, specifically within the MESA CMOS technology.

The team is focused on creating a robust backup technology that ensures the availability of reliable microelectronics in a global landscape where supply is limited. By achieving a higher level of radiation hardness, Sandia aims to fill a critical technology gap for national defense systems that require durable, non-volatile memory solutions. The integration of ferroelectric memory into existing processes not only mitigates risks associated with future developments but also positions Sandia at the forefront of semiconductor technology.

This work has pushed ferroelectric memory with FeRAM at the 200 mm wafer scale and generated both binary and 32-state ferroelectric tunnel junctions, demonstrating advanced capabilities in memory device engineering. Sandia researchers are actively testing and characterizing these new materials to understand their performance under radiation exposure. This work has already been showcased at a conference, highlighting its significance in advancing the field.

Looking ahead, Sandia plans to advance this research with follow-on projects aimed at developing supporting circuitry for the ferroelectric memory cells, further solidifying its commitment to innovation in microelectronics. **(PI: Michael David Henry)**

LEVERAGING NEW TALENT > Sandia Hruby Fellow Samantha Jaszewski and PI Michael David Henry partnered together to orient her proposal on radiation effects of ferroelectric hafnium zirconium oxide to this LDRD project.



DESIGNING Z PLATFORMS FOR TRANSFORMATIVE OPACITY RESEARCH

Understanding opacity is crucial for various applications, including national security and astrophysics, as it governs how radiation travels through materials. However, current opacity measurements have not been tested at the extreme temperatures and densities that are essential for advancing scientific knowledge in these areas.

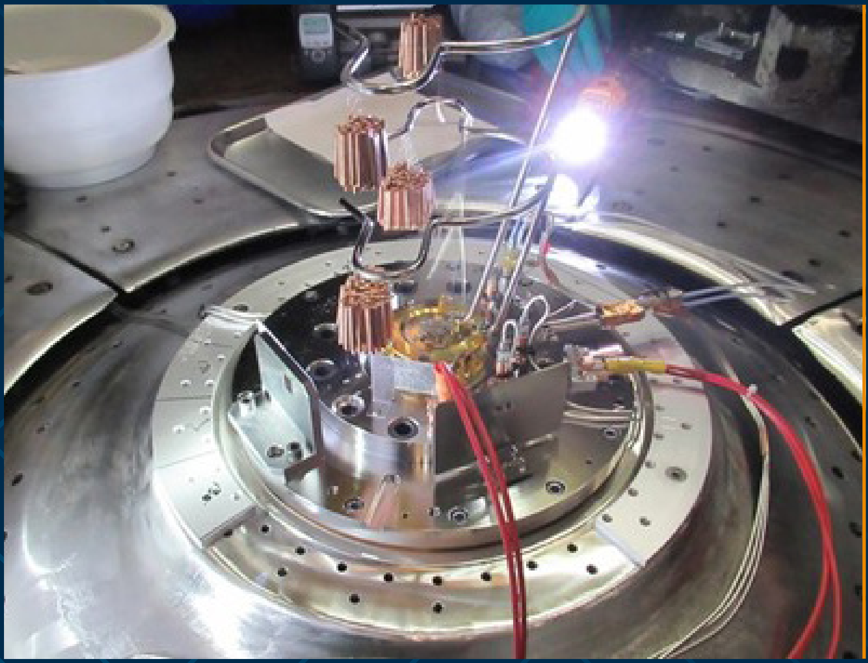
The successful execution of these experiments is enhancing the understanding of opacity in high-energy density environments and strengthening collaboration among national laboratories.

Sandia researchers are taking a novel approach using the Z Facility to benchmark opacity in conditions far beyond previous measurements.

By utilizing spectral simulations, the team has studied challenges associated with novel designs and laid out remaining questions to finalize design points.

The experiments involve embedding opacity samples within the brightest x-ray source on Earth, heating them to extreme conditions, and measuring either their emission or absorption or both.

The project is training scientists in this new research, including a promising student from the University of Nevada, Reno, to ensure a new generation of researchers is prepared to tackle challenges in the field. Ultimately, this research will contribute to national security efforts and improve materials assessments critical for stockpile stewardship. **(PI: Guillaume Loisel)**



Opacity target being installed inside the center section of the Z machine by a Sandia employee.

COOL FACT >

Utilizing novel extreme-conditions schemes would produce unprecedented data on opacity, which is vital for refining theoretical models and maintaining the relevance and cross-comparison capability of the Z Facility alongside ignition-enabled platforms at the National Ignition Facility.

TRANSFORMING SIGNAL PROCESSING FOR ENHANCED NATIONAL SECURITY COMMUNICATIONS

Improving signal processing technologies is imperative for national security and advanced communications. By enhancing optomechanical Brillouin interactions through acoustoelectrically active devices, Sandia researchers are developing new systems that can process signals more efficiently and effectively. This research focuses on integrating acoustoelectric effects with optomechanical processes for the first time, which enables dynamic control over phonon dissipation rates, an important factor influencing the performance of Brillouin-photonic devices.

The team has created innovative structures that leverage the strengths of both optical and acoustic technologies. By applying direct current electric fields, Sandia researchers can enhance phonon amplification and mitigate unwanted energy loss, leading to improvements in devices such as Brillouin amplifiers and acousto-optic modulators. These advancements could result in amplifiers with dramatically increased gain and microwave generators with substantially reduced noise, thus enhancing overall system performance.

Collaborating with universities and securing follow-on funding from the Defense Advanced Research Projects Agency (DARPA) and the Advanced Research Projects Agency-Energy (ARPA-E), the team has made substantial progress in this area.

Among the notable accomplishments, the team has created a device that can boost sound signals by more than 60 decibels, which is a record high for this kind of technology. They also made it much easier to control light signals by lowering the voltage needed to change the light's properties—making it 46 times more efficient than before. The research not only promises to enhance microsystem sensors and optoelectronic devices but also aligns with Sandia's mission to support national security through innovative technology. **(PI: Nils Otterstrom)**

READ MORE > *Physical Review Applied*, *Physical Review X*, *Nature Photonics*, *Frontiers in Optics + Laser Science*, *CLEO: Applications and Technology*, *Nature Communications*

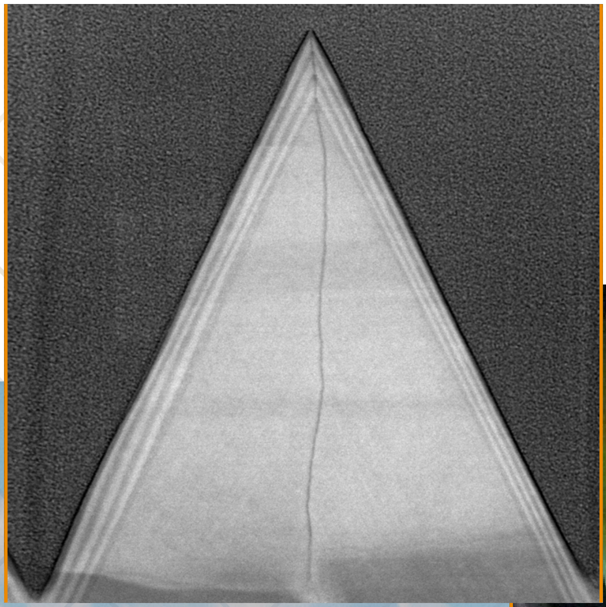
COOL FACT > This work represents an important advancement in the field of optomechanics and acoustoelectrics, paving the way for future developments in integrated photonic systems and advanced signal processing technologies.

IMPROVING NAVIGATION ACCURACY THROUGH ADVANCED SEMICONDUCTOR LASER TECHNOLOGY

Many quantum sensors, such as gyroscopes and magnetometers, rely on multiple lasers operating at various optical wavelengths, but the lack of available semiconductor lasers in this range has limited their capabilities. Sandia researchers are filling that gap by developing new semiconductor laser technology that operates at green, yellow, and orange wavelengths.

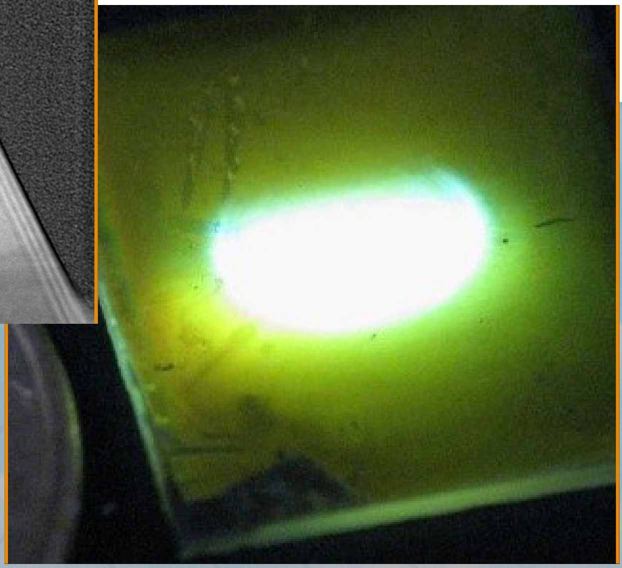
The team overcame the issue of crystal defects and successfully grew indium gallium nitride crystals on specially designed gallium nitride nano-ridges. Their innovative method resulted in low-defect-density light emitters, paving the way for efficient yellow-wavelength lasers. **(PI: Darwin Serkland)**

COOL FACT > This groundbreaking work promises to enhance the capabilities of future quantum sensors and expand the possibilities in various mission-critical applications that had to previously rely on GPS signals.



Left: Transmission Electron Microscope image of indium gallium nitride crystalline quantum wells (20 atoms thick) that efficiently emit yellow photons.

Below: Bright yellow photoluminescence from non-planar nano-structured indium gallium nitride epitaxial semiconductor crystals.



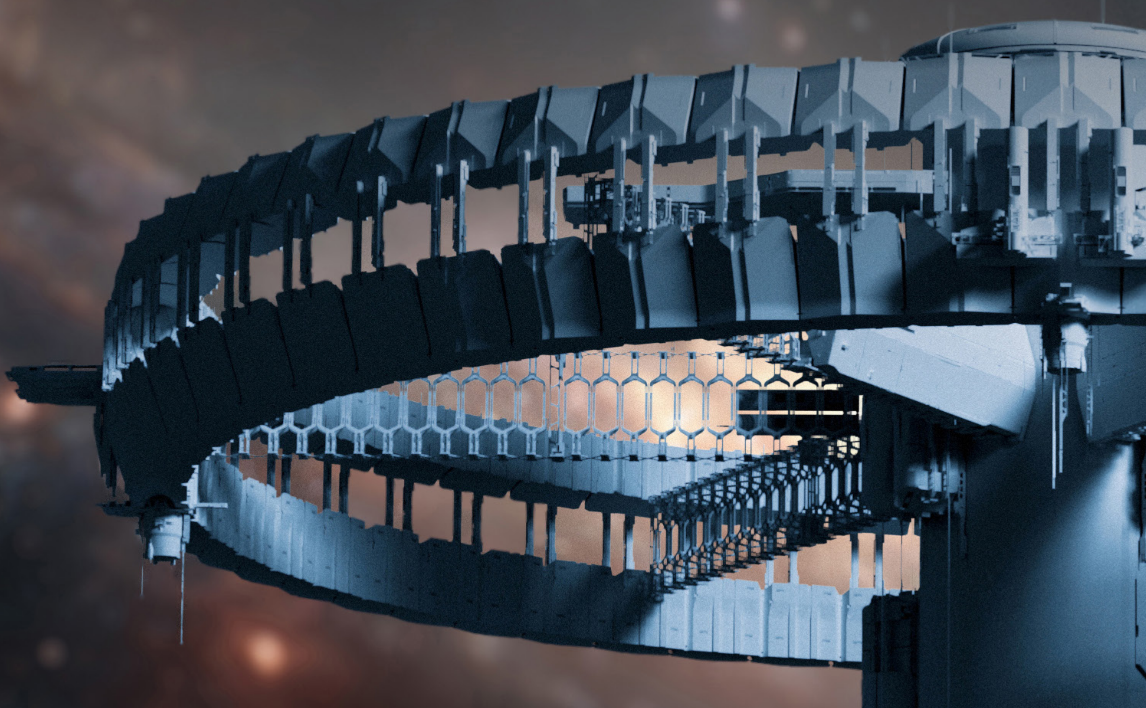
BOOSTING GAS SWITCH RELIABILITY THROUGH COMPREHENSIVE TESTING

High voltage gas switches are vital components in pulsed-power systems so understanding the likelihood of pre-fires—unintended discharges that can disrupt operations—is pivotal for ensuring safety and efficiency in these systems. In this project focused on improving the switch reliability, the team's analysis revealed that traditional statistical methods underestimate the low-probability tail of the data, which is important for predicting pre-fires. This finding emphasizes the need for extensive testing beyond the typical range of 500 to 1,000 shots to accurately assess these low-probability events. Additionally, the housing of the switches was found to significantly affect the self-break voltage distribution, with older housings showing greater variability. However, inconsistencies in tracking housing effects across tests introduced variability in the results. Sandia researchers also observed unexpected results regarding conditioning effects, indicating that factors beyond conditioning may influence switch performance. The presence of numerous low dropouts—unexplained voltage failures—was noted, which are key for scaling to larger systems.

Gaining a deeper understanding of these low dropouts is crucial for evaluating how gas selection impacts the performance of large pulsed-power systems, ultimately enhancing their reliability and efficiency. **(PI: Justin Smith)**

COOL FACT > Sandia researchers tested various gases and energy levels over approximately 10,000 shots to evaluate how self-break voltage distributions change over the switches' lifetimes.

MISSION CAMPAIGN: SCIENCE AND TE
RESILIENCE FOR CONTESTED SPACE (



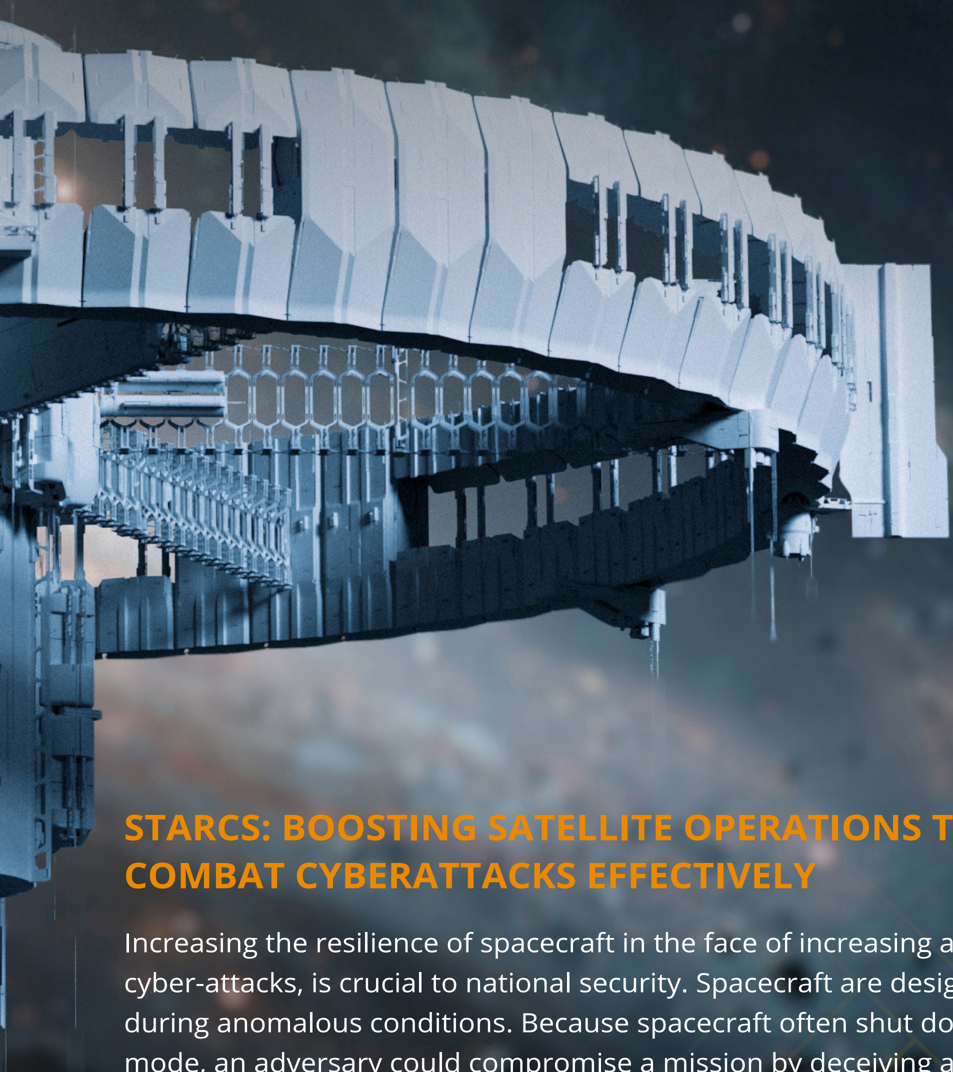
STARCS: DESIGNING EFFECTIVE EXPERIMENTS TO INCREASE SPACE SYSTEM RESILIENCE

The U.S. government depends on space systems for government and commercial applications. As access to space becomes more attainable for private companies and other nations, threats to the nation's space systems are increasing. Recognizing it is impossible to prevent all attacks, the space community seeks to complement security with resilience technologies. Sandia's Science and Technology for Advancing
the Resilience in Contested Space (STARCS) Mission Campaign is focused on that need.

To measure the effectiveness of any developed resilient technologies, in-flight experiments on spacecraft in realistic conditions need to be conducted, so the STARCS team developed a rigorous seven-step methodology for designing qualitative in-flight cyber resilience experiments. These integrate statistical methods with advanced cyber experimentation techniques, allowing for effective measurement of new technologies' impact.

Insights from this methodology will inform future testing efforts, ensuring that space systems can withstand evolving threats. This methodology can also be applied to other important areas, such as infrastructure and high-consequence systems, enhancing national security. **(PI: Meghan Anne Sahakian)**

CHNOLOGY ADVANCING STARCS)



STARCS: BOOSTING SATELLITE OPERATIONS TO COMBAT CYBERATTACKS EFFECTIVELY

Increasing the resilience of spacecraft in the face of increasing adversarial threats, particularly cyber-attacks, is crucial to national security. Spacecraft are designed to revert to a safe mode during anomalous conditions. Because spacecraft often shut down mission payloads in safe mode, an adversary could compromise a mission by deceiving an operator or the spacecraft itself into entering a safe mode.

Sandia researchers have introduced architectural enhancements to NASA's Core Flight System to mitigate this sort of mission disruption. First, a service autonomously reduces the attack surface by loading libraries based on the state of the spacecraft. Second, an onboard machine learning-based anomaly detector monitors the internal communications of the spacecraft. Lastly, a rules engine, operated by a designer or an autonomous agent, can take further action based on internal messages. The team has validated this system through hardware-in-the-loop experiments, demonstrating its ability to maintain mission continuity during deception, and avoiding the mission disruption that would happen using traditional safe mode.

This project is maximizing the success of satellite-hosted payloads under adverse conditions, including cyber threats and filling a critical gap in automated responses to cyber events. This advancement, which is vital for national security applications, provides greater resilience against anomalous space vehicles and ensures mission success even in uncertain security environments. **(PI: David Pollock)**

STARCS: DEVELOPING ADVANCED MODELS FOR PROTECTING SOLAR CELLS

To enhance the resilience of solar cells, Sandia researchers are developing advanced modeling capabilities that can analyze the full dynamics of laser damage, including physical stress, electrical performance degradation, and subsurface damage. By identifying potential weak points in solar cell designs, the team is creating a rapid modeling environment that can adapt to various laser parameters, such as pulse duration and energy deposition.

Current methods rely on empirical approaches that test specific hardware under certain conditions, limiting the understanding of broader threats. Sandia researchers are establishing a comprehensive physics-based model within the SIERRA software, allowing for the simulation of light-matter interactions in solar cells. This model will simplify complex chemical processes into manageable parameters, enabling the team to explore design modifications that enhance protection.

By improving the understanding and mitigation of vulnerabilities, Sandia's work will bolster the resilience of the nation's strategic assets against adversarial threats.
(PI: Seth Melgaard)

STARCS: INCREASING SATELLITE RESILIENCE AGAINST LASER DAZZLE WITH EVENT-BASED IMAGING

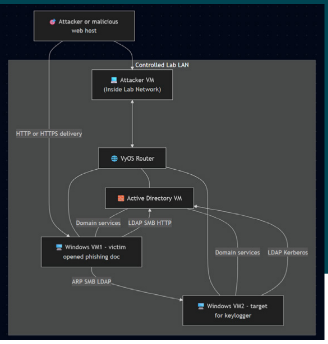
Space monitoring missions must cover vast distances and capture rapid events at rates above ten thousand measurements per second. Conventional cameras overwhelm storage, deliver limited brightness range and drain power. Sandia researchers are investigating event-based sensors that record only significant brightness changes per pixel, cutting data by orders of magnitude, using under 0.1 watts and spanning 120-decibel dynamic range with microsecond responsiveness.

Laser dazzling can blind conventional imagers by flooding pixels with intense light. Sandia researchers developed algorithms that detect and remove dazzling pulses by analyzing the timing patterns of brightness changes or matching change templates. The team integrated these methods into a real-time processing pipeline.

STARCS: SECURING SPACE INFRASTRUCTURE THROUGH DATA-DRIVEN DIGITAL TWIN MODELING

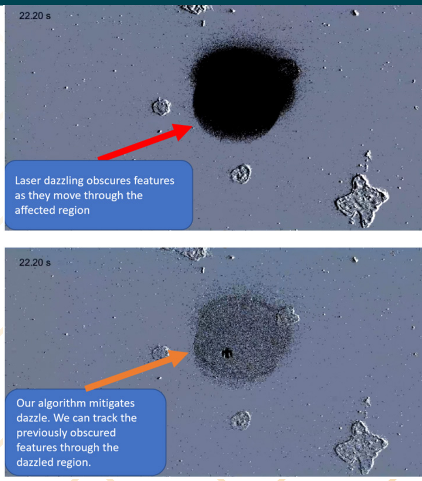
Satellite ground stations are the most vulnerable point in space missions, facing continuous cyber threats that can disrupt communications, damage satellites, and compromise vital data. Sandia researchers recognized that traditional security methods are insufficient for these unique challenges and set out to build data-driven tools for better risk and resilience analysis.

Over two years, the team created an integrated suite of capabilities: automated generation of digital twins for ground station networks, real-time threat intelligence collection tailored to space operations, and impact-analysis tools that quantify mission risk. These elements feed into automated assurance cases, giving decision-makers clear, evidence-based guidance on when and how to apply security updates or modify network configurations.



The research strengthens national security by fortifying space infrastructure, reducing the risk of mission disruption, and enabling rapid, informed decisions during pivotal satellite passes. Sandls open datasets and reference architectures set the stage for continued advances in space cybersecurity and broader critical-infrastructure protection. **(PI: Tim Ortiz)**

Left: Visual diagram illustrating network layout with attack steps overlaid, integrated with digital twin modeling and threat intelligence alerts.



Before (top) and after (bottom) masking dazzling pulses in the event stream, revealing the Thunderbird target inside the previously blinded area.

Laboratory tests with simulated dazzle and targets showed that the processing pipeline could filter out dazzling flashes and restore visibility of underlying targets. The work also revealed hardware limitations in off-the-shelf sensors, such as data bottlenecks and lingering pulse artifacts.

The team is preparing a demonstration for another capstone project. The demonstration uses a chopped visible laser to simulate dazzle and runs on an Advanced Micro Devices Versal VCK190 platform. Filtered events, target features, and velocities will display on a ground-computer stand-in.
(PI: Bjorn Kjellstrand)

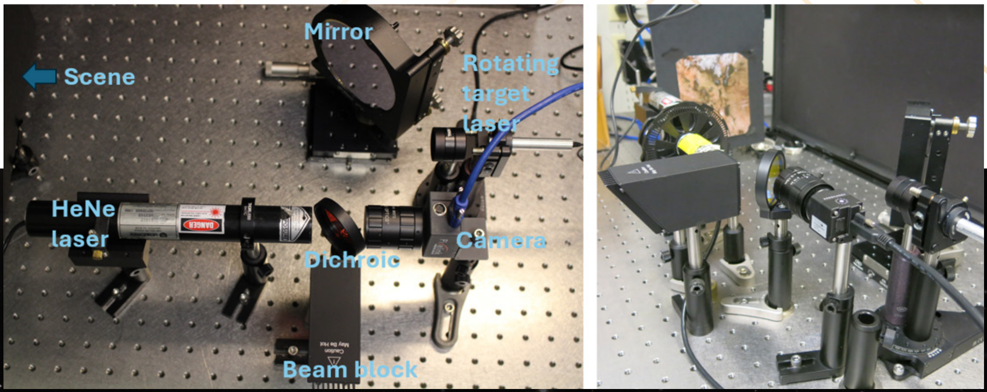


Photo of tabletop setup. Event-based sensors view a target behind a dichroic mirror as a chopper creates pulsed laser dazzling.

PROJECT HIGHLIGHTS –

TECHNICAL VITALITY

LDRD is essential to maintaining the Labs' scientific vitality and Sandia, as the nation's most diverse national security laboratory, is uniquely equipped to tackle groundbreaking, interdisciplinary research. Researchers collaborate across a broad spectrum of disciplines and achieve research breakthroughs, which enables national security technology to be transferred to industry, commercialized under licensing agreements, and brought to market for the U.S. public good.

The LDRD accomplishments in this section highlight research outcomes that extend knowledge in the scientific field or have the potential to provide a new capability for Sandia in the future.

MISSION CAMPAIGN: ASSURED SURVIVABILITY AND AGILITY WITH PULSED POWER (ASAP)

ASAP: DEVELOPING A BETTER WAY TO MANAGE DEBRIS ON THE Z MACHINE

During z-pinch experiments on Sandia's Z machine, explosive debris can damage/contaminate expensive and difficult to source hardware. Debris shield bump and trough structures are 1'-diameter, ring-shaped features machined around Z's five, 10'-diameter, cone-shaped, stainless steel, magnetically insulated transmission lines (MITL). These features catch debris on the MITLs, preventing it from reaching valuable components. This results in reduced hardware damage and improved refurbishment efforts. Exposure to hazardous material is also reduced by simply disposing of the contaminated parts. These improvements contribute to a more reliable machine. However, the extra parts required to incorporate debris shield bumps on the MITLs increase the cost of each Z shot, and there are concerns that debris shield bumps may cause some electrical current and data to be lost, motivating the search for a better and more cost-effective solution.

This work explored a revision to the debris shield bump design in use today, but at a smaller radius, with an additional thin inner MITL region, near the target (see pink oval in Fig. 1). This design change aims to reduce debris and its energy and directs more debris downward, improving disposal methods. The resulting geometry is predicted to improve overall performance. Upcoming tests on the Z machine will evaluate the new design.
(PI: Daniel Ignacio Headley)

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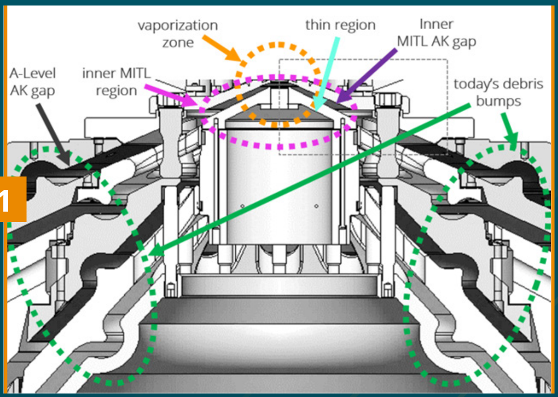

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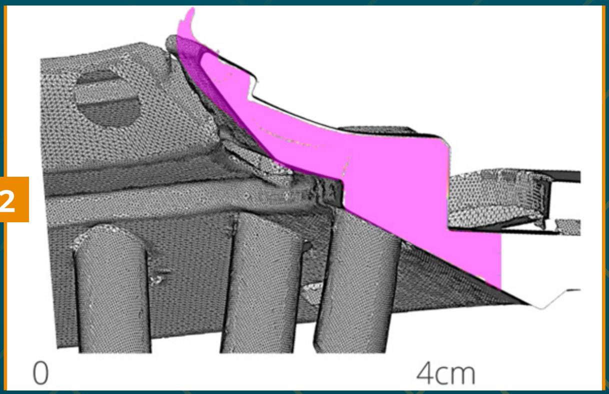

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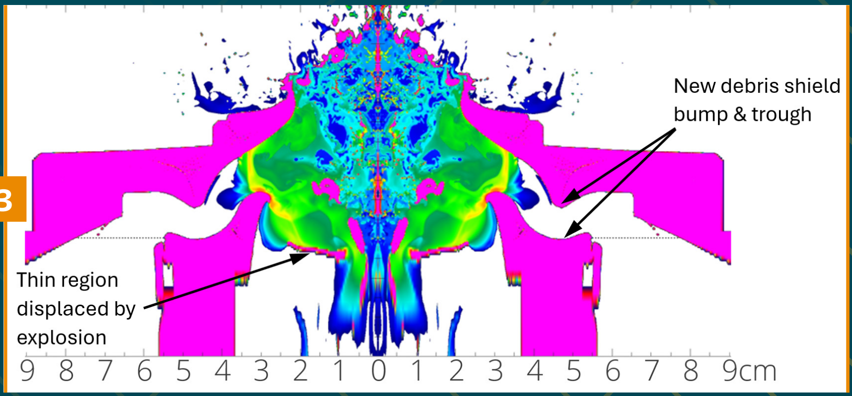


Fig 1. Cross-section of the MITLs. A new debris bumps and thin conductor are proposed within the inner MITL region.

Fig. 2. Post-shot hardware (grey mesh), 3D optical scan cross-section. CTH-predicted deformation overlaid in transparent pink, center axis at left.

Fig. 3. CTH simulation of a Z experiment; the new bump concept at 4.5 cm; thin conductor vents debris downward.

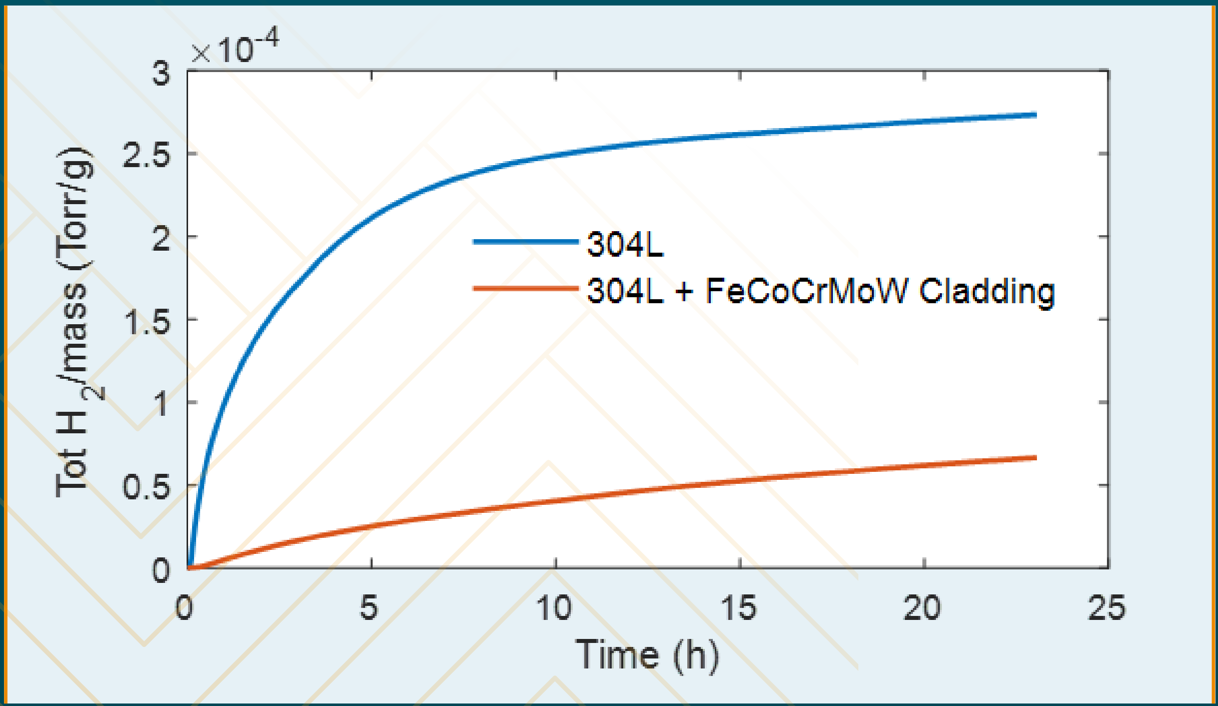
ASAP: IMPROVING ENERGY EFFICIENCY IN PULSED POWER SYSTEMS WITH NEW MATERIALS

Sandia's research is tackling important issues in materials science, particularly how hydrogen behaves in high entropy alloys (HEA) used in pulsed power systems. The goal is to reduce energy loss in these systems caused by hydrogen getting into gaps and forming plasma. To achieve this, the team is developing a new cladding material that has a higher melting temperature than regular steel, lower electrical conductivity to better manage electrical currents, and less ability to absorb hydrogen. (Cladding is the protective layer made from HEA that is applied to components in pulsed power systems to improve their performance and durability, particularly in relation to hydrogen behavior and energy efficiency.)

The new HEA is made from a mix of cobalt, chromium, iron, molybdenum, and tungsten, and it shows very low hydrogen solubility, making it a great choice for cladding. This material not only works well with steel but also has a high melting point and useful electrical properties. Future work will focus on solving challenges related to additive manufacturing to improve how this material performs in pulsed power applications.

This innovative work, which could greatly improve how energy is delivered in pulsed power systems, was done in collaboration with Ames National Laboratory and presented at the Pulsed Power and Plasma Science conference in Berlin. **(PI: Michael J. Abere)**

READ MORE > *Scripta Materialia*



Isothermal temperature programmed desorption analysis hydrogen solubility within the noise of the cladding material compared to steel.

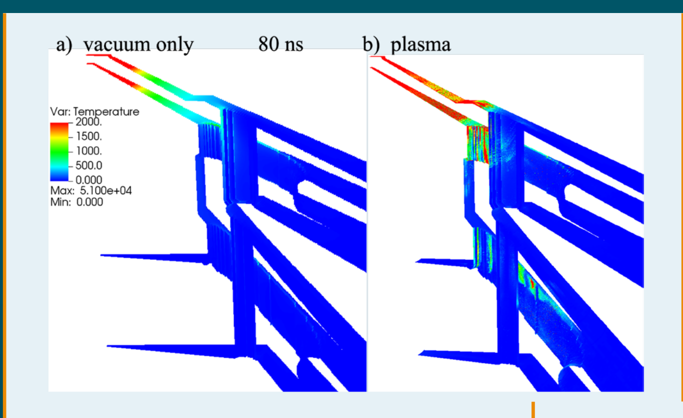
ASAP: OPTIMIZING ENERGY EFFICIENCY IN THE Z ACCELERATOR FOR NATIONAL SECURITY

In the Z Accelerator, a top facility for high-energy experiments, high current densities can create surface plasmas on the electrodes, which divert the current away from its intended target and cause a significant loss of energy. Understanding and optimizing how current flows in the "current adder" area is essential for improving the accelerator's performance and efficiency.

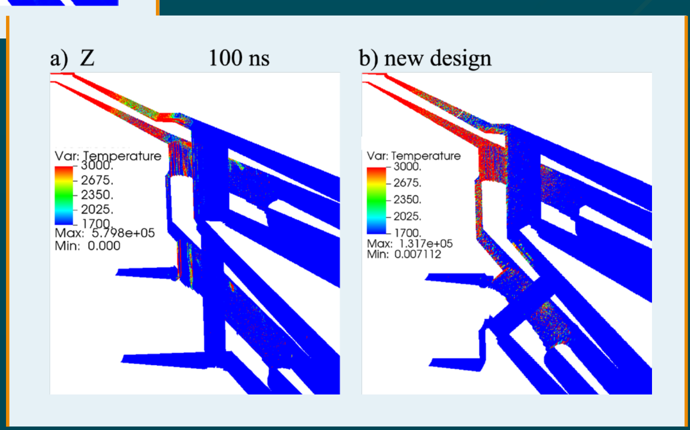
To tackle this issue, Sandia researchers used large-scale 3D simulations to study how these plasmas form and impact current flow. They discovered that uninsulated electrons are the initial cause of current loss, followed by conduction caused by the plasma. By adjusting the position and orientation of certain components in the current adder, the team aims to reduce these energy losses.

This research supports future upgrades by allowing Sandia to deliver higher peak currents with better load inductances and will advance experiments that require precise energy delivery, which can lead to important scientific breakthroughs in high-energy density physics. **(PI: Nicki Bennett)**

COOL FACT > Improving the performance of the Z Accelerator has significant implications for national security, as it enhances the reliability of experiments related to nuclear deterrence and other defense technologies.



The baseline surface temperatures (a) increase when bombarded by charged particles (b).

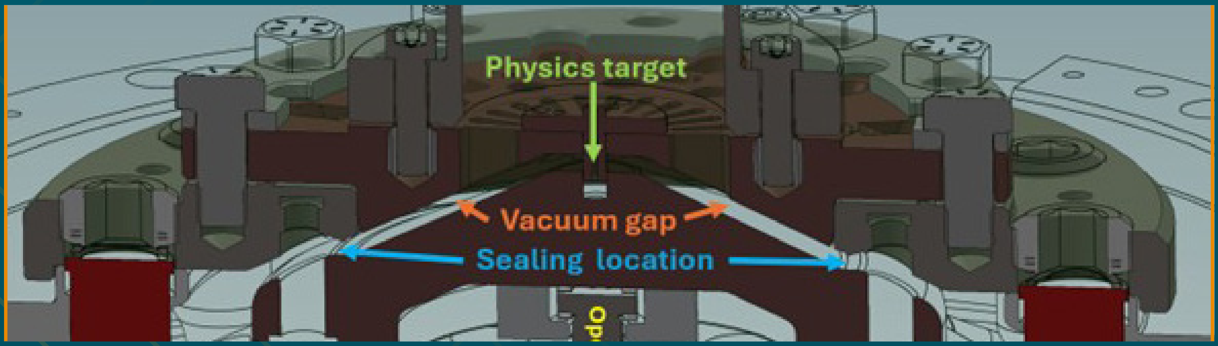


A new hardware design (b) reduces surface temperatures compared to the original design (a).

ASAP: ENHANCING CURRENT DELIVERY USING INNOVATIVE VACUUM CASSETTE TECHNOLOGY

The Z Facility delivers tens of millions of amperes of current to physics targets using a vacuum transmission line made of two conductors separated by a vacuum gap. When these conductors heat due to the high current, contaminants can outgas into the vacuum. This can result in plasma formation within the gap due to the high voltage between the conductors, allowing current to cross the gap instead of reaching the target. To reduce plasma formation, it's important to minimize contamination on the electrodes. One method is to hold the electrodes at ultra-high vacuum for weeks without ever re-exposing them to air.

Sandia has developed a new technology called the vacuum cassette, which is intended to provide the cleanest high-current electrodes ever fielded on the Z Facility. Once assembled, the vacuum cassette keeps the electrodes isolated within a vacuum environment, where they can be cleaned through vacuum baking and extended pumping. After cleaning, the cassette remains under ultra-high vacuum during handling and installation. The electrodes are only briefly exposed to Z's less ideal vacuum for about one second before current delivery. This ensures the electrodes are never exposed to air, reducing contaminant-related plasma formation and improving current delivery to the target. Two Z Facility experiments are planned for 2026 to test the effectiveness of the vacuum cassette. (PI: Thomas J. Awe)



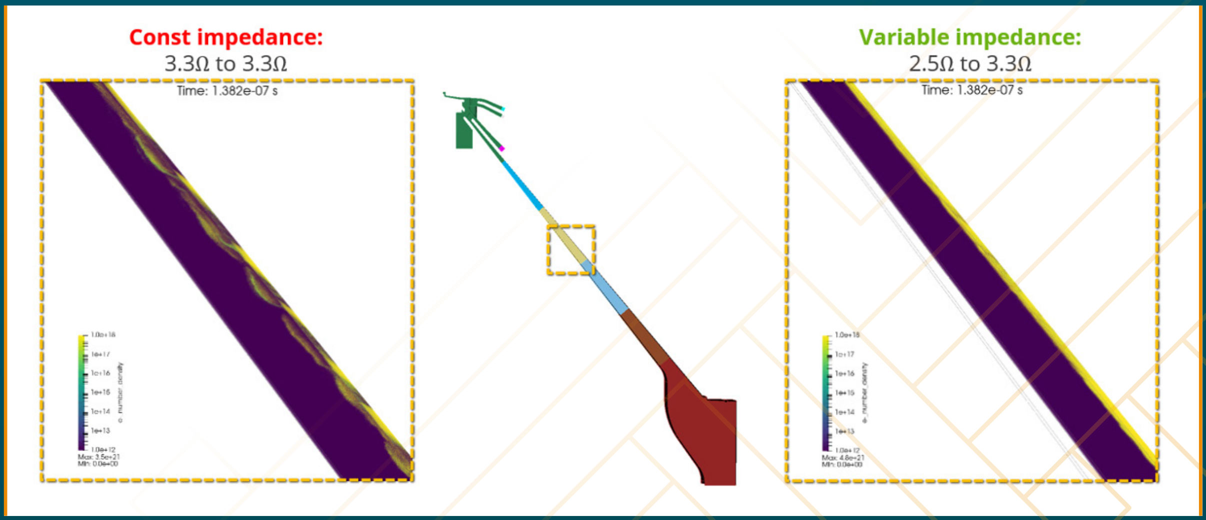
Vacuum cassette hardware installed in the Z Facility. Within the seal, electrodes are held at ultra-high vacuum before the experiment to reduced electrode contamination.

ASAP: INNOVATIVE TRANSMISSION LINE DESIGNS FOR FUTURE PULSED POWER SYSTEMS

Sandia is addressing the need for enhanced current delivery in pulsed power systems, which is vital for national security and scientific advancements. The conventional design approach of using constant geometric impedance magnetically-insulated transmission lines (MITL) are increasingly restrictive, limiting operational efficiency and necessitating larger, costlier accelerator components.

In collaboration with the University of Rochester, Sandia explored variable-impedance MITLs to increase current delivery within a smaller machine footprint through more efficient designs while enhancing safety by lowering voltage requirements. Extensive simulation studies using circuit and electromagnetic particle-in-cell (Empire) codes evaluated designs for the Z Accelerator and next-generation pulsed power facility. The team identified promising designs maintaining effective magnetic insulation, essential for safe operation, and quantified performance in terms of current gains and safety metrics.

This work resulted in one journal submission and multiple presentations at conferences including the 11th International Workshop on the Mechanisms of Vacuum Arcs and a spotlight at the 2024 Sandia Emeritus Meeting. The findings suggest that variable-impedance MITLs could enhance pulsed power technology, providing strategic options for future facilities at practical costs. **(PI: David Sirajuddin)**



Variable-impedance MITLs can improve magnetic insulation, preventing electrons (yellow) from shunting gaps (purple) more effectively than constant-impedance versions, leading to more efficient power flow.

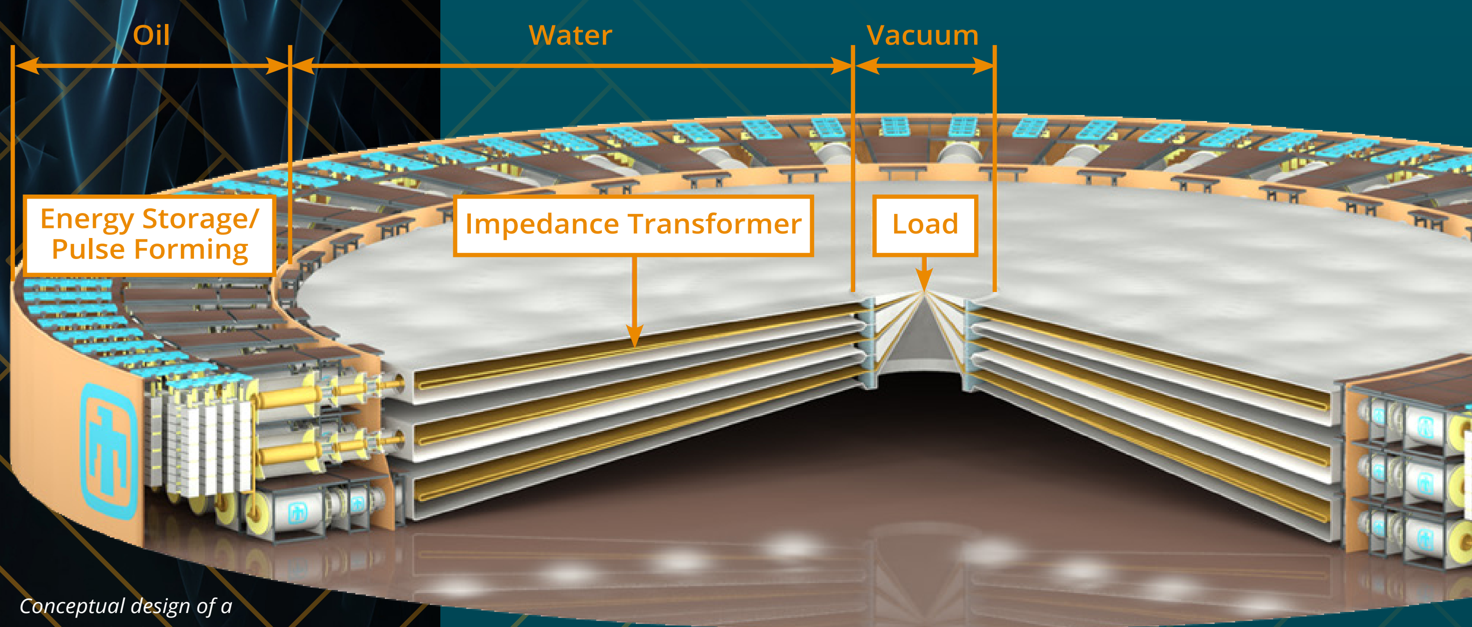
ASAP: EVALUATING NEXT-GEN PULSED POWER ARCHITECTURES FOR DYNAMIC MATERIALS PROPERTIES EXPERIMENTS

Evaluating the ability of future pulsed power accelerators to conduct dynamic materials properties experiments is vital for the NNSA's Stockpile Stewardship Program. These experiments require precise control over output pulse timing and shape.

Sandia researchers developed circuit models to evaluate asynchronous pulse generation in the energy storage and pulse forming regions of the accelerator. This allows for the creation of tailored current pulses essential for assessing material properties under dynamic conditions. The team created 2D transmission line mesh models of the impedance transformers to evaluate the effects of asymmetrical drive from the pulse-forming lines.

To improve the experiment design process, Sandia implemented automated optimization and machine learning techniques. These innovations include an optimization method that automates circuit model runs, varying machine parameters to achieve the desired current pulse shape. Additionally, a machine learning method using a deep neural network has been developed eliminating the need for iterative circuit simulations altogether.

This project enabled Sandia researchers to identify key capabilities of next-gen pulsed power architectures to ensure that they can effectively support dynamic materials properties experiments. (PI: Brian Thomas Hutsel)



Conceptual design of a future pulsed power accelerator evaluated for pulse-shaping capabilities.

INVESTIGATING NANOSCALE PROCESS THAT UNDERLIE THE IGNITION OF REACTIVE MATERIALS

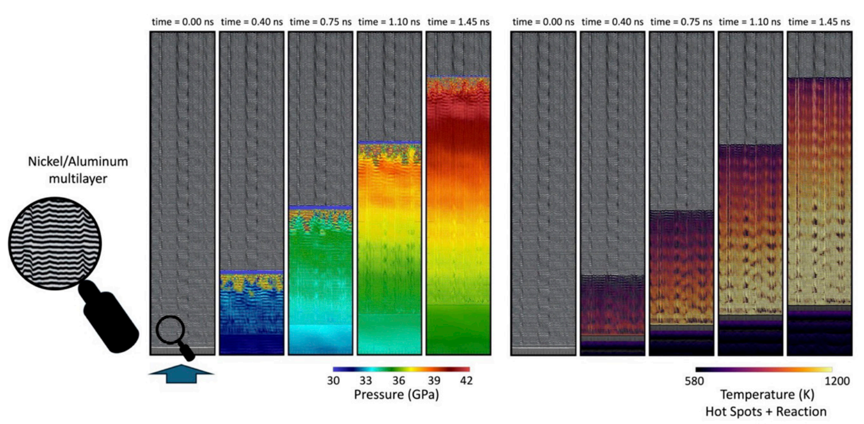
Reactive multilayers are materials that can ignite at certain points and create intense heat and light through self-sustaining reactions. Understandably, these are of interest for advanced power sources. In collaboration with researchers from Georgia Tech, MIT, Purdue, and the University of Colorado, this LDRD project focused on how to reliably ignite metallic nanolaminates when they are subjected to extreme pressure and strain during high-speed impacts.

The team used fast measurement techniques, such as Doppler velocimetry and synchrotron X-ray diffraction, to discover that these reactions can happen within one microsecond after being shocked. Factors like shear force, surface roughness, and the angle of the impact also affect ignition.

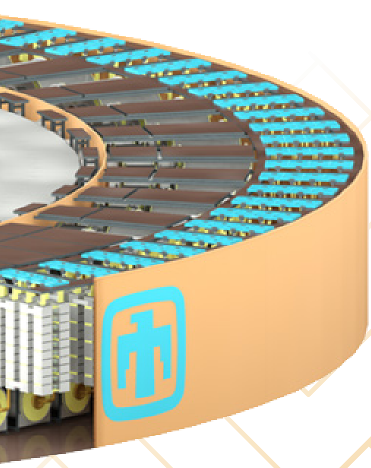
Detailed simulations were conducted to study how these factors influence the start of reactions. Their results showed that shock-induced chemical reactions can occur in nickel-aluminum nanolaminates, involving the formation of hotspots within the solid material.

This work is important for developing new reactive materials and improving designs for applications that require precise ignition under high-stress conditions. **(PI: David P. Adams)**

READ MORE > *Journal of Applied Physics* (*1*) (*2*), *ACS Applied Materials & Interfaces*, and *Combustion & Flame*



Time-resolved shock wave propagation in a reactive nickel-aluminum multilayer. Exothermic reactions increase the shock pressure (left) and temperature (right).



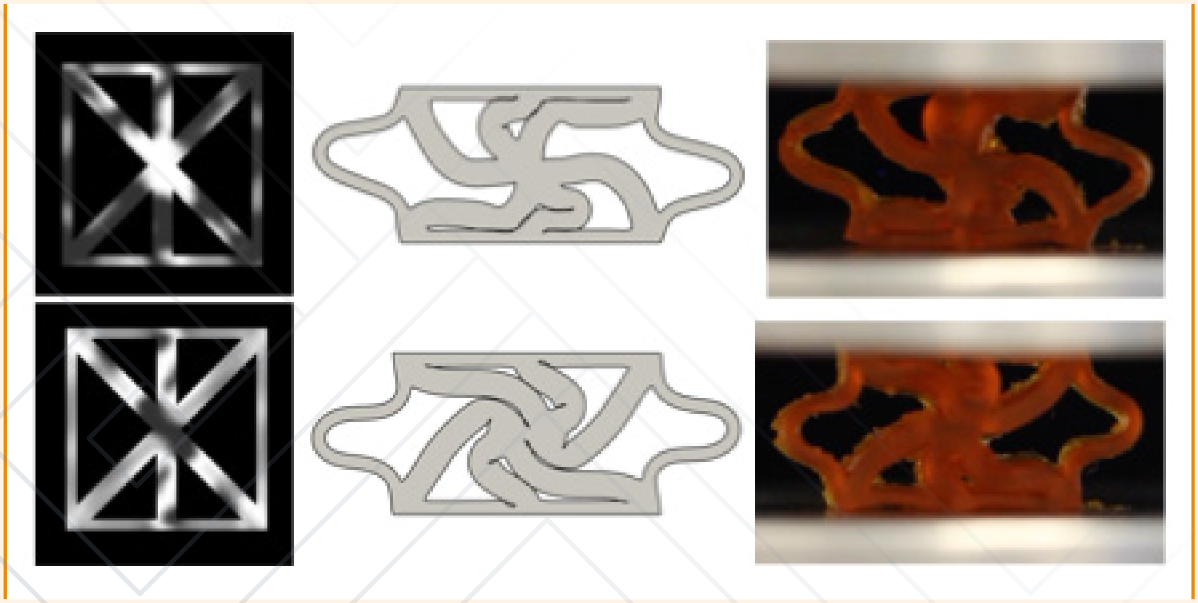
REIMAGINING THE POTENTIAL OF ADDITIVE MANUFACTURING THROUGH COMPUTATIONAL DESIGN

Additive manufacturing (AM) is transforming engineering design by allowing for precise control over intricate geometric features and material properties. However, current design approaches fail to fully leverage this potential. To address this gap, Sandia researchers initiated an LDRD project to rethink design strategies for AM by focusing on how small features can be engineered to buckle and make contact, allowing components to adapt to multiple environments.

The central hypothesis was that by incorporating advanced modeling and simulation techniques for complex solid mechanics, the team could develop design optimization methods that effectively navigate the complex and nonintuitive design landscape of AM. Robust simulations were developed and used to link the shapes and materials of components to their unique responses under different conditions, and results were published in top journals, shared at conferences and at an invited lecture at the University of Texas at Austin.

Through various examples, Sandia showed it is possible to include complex behaviors in design optimization by carefully choosing design parameters and formulating problems effectively. This research is helping to advance the field of AM and set the stage for the next generation of engineered components. **(PI: Ryan Alberdi)**

LEVERAGING NEW TALENT > Contributions from postdoc Lucas Gallup and intern Dylan Joralmon further advanced the techniques in this project.



Light intensity distributions (left) are optimized to control local mechanical properties, guided by nonlinear simulations (center) of buckling and self-contact, resulting in observed responses (right).

PIONEERING NEW APPROACHES TO PREDICT MATERIAL FAILURE IN ENGINEERING APPLICATIONS

Understanding how materials can get damaged or fail is vital for ensuring the safety and reliability of structures. Sandia researchers aimed to improve understanding of how damage initiates and to move beyond traditional statistical methods. They focused on how materials deform and develop defects around particles and small voids, creating a detailed model that can be used in large-scale simulations of material failure.

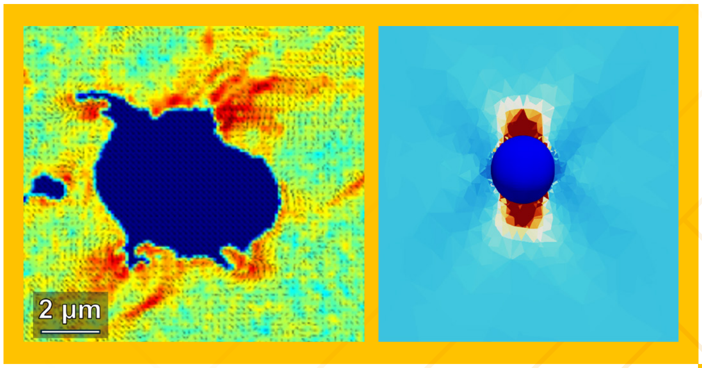
The team improved x-ray and electron microscopy techniques to study complex materials and their internal structures and used advanced methods to gather detailed information about the stress levels within the materials. This deeper understanding helped them create better computational models to predict when materials might fail.

Additionally, the team developed software tools for tasks like image processing, computational geometry, and optimization. These tools are now available for other researchers, benefiting the wider scientific community. Their findings were published in respected journals and presented at conferences, highlighting the teamwork among Sandia staff, postdoctoral researchers, interns, and academic partners from various universities. **(PI: Coleman Alleman)**

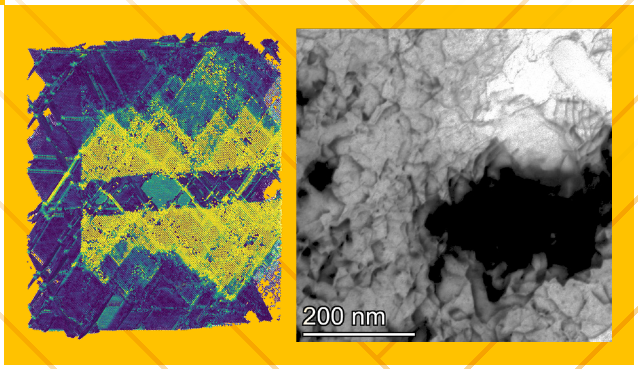
LEVERAGING NEW TALENT > This project leveraged the talents of PhD student Sam Dunham and his advisor Curt Bronkhorst at the University of Wisconsin.

READ MORE > *International Journal of Plasticity*

COOL FACT > This research has important implications for nuclear safety and ensuring the integrity of vital components.



Integrating nanoscale simulations (left) and characterization (right) of dislocations enhances insights into the factors driving damage nucleation in materials.



Synthesis of microscale characterization (left) and simulations (right) of plasticity advances modeling of damage initiation at second-phase particles in aluminum.

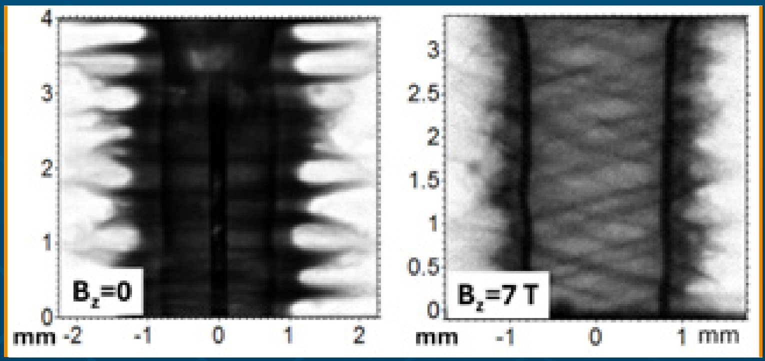
ADVANCING MAGNETIZED LINER INERTIAL FUSION PERFORMANCE BY UNDERSTANDING ELECTOTHERMAL INSTABILITY

The Z Facility generates extremely high electrical currents on the surface of cylindrical tubes filled with fusion fuel, causing these tubes, known as “liners,” to implode quickly. However, the electrothermal instability (ETI) causes uneven Ohmic heating and expansion of the liner’s outer surface, leading to an asymmetrical implosion and lower performance.

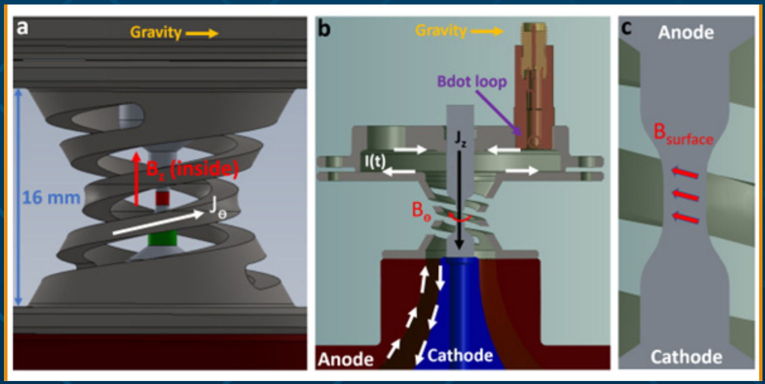
In Magnetized Liner Inertial Fusion (MagLIF) experiments, an additional magnetic field is applied, making it important to understand how ETI behaves in these conditions. To investigate this, Sandia researchers studied how heating occurs in z-pinch rods that had engineered defects—deliberately added tiny pits—on their surfaces. Experiments were conducted using two types of magnetic fields: a standard circular field and a helical field created by a special device that adds an axial component. The research found that the heating caused by ETI aligns with the surface magnetic field, resulting in elongated heating patterns that create ripples on the rod’s surface. These ETI-generated ripples lead to instability growth on imploding liners.

By gaining a clearer understanding of how ETI works, Sandia researchers can improve experimental methods to make liner implosions more stable and boost the performance of inertial confinement fusion systems, including MagLIF. **(PI: Thomas J. Awe)**

READ MORE > *Physical Review Letters*, *Physical Review E*, *Physics of Plasmas*



X-ray radiographs compare liner implosions—the left shows a purely azimuthal field, and the right demonstrates the influence of an axial magnetic field.



Experimental hardware including a helical return can which generates a helical magnetic field on the surface of a z-pinch rod.

DELIVERING EFFECTIVE MEDICAL COUNTERMEASURES USING mRNA TECHNOLOGY

Sandia researchers are tackling the urgent need for effective medical countermeasures (MCM) to combat infectious diseases and other health threats. Messenger RNA- (mRNA) based MCMs are promising alternatives to traditional protein-based therapies (e.g., peptides, antibodies). However, mRNA is effective only when successfully used by the body's cells to produce therapeutic proteins.

So far, evaluating how well mRNA can be used by cells has relied on slow and limited testing methods, which has slowed down the development of mRNA-based treatments. To overcome this challenge, Sandia researchers, in collaboration with Lawrence Livermore National Laboratory and Florida State University, developed a new approach that combines deep learning with high-throughput experimentation. This allows for accurate predictions and quick validation of how mRNA structures relate to their functions.

Using this innovative method, the team identified specific sequences in the 5′ untranslated region (5′-UTR) of mRNA that can either boost or reduce protein production. The knowledge and tools developed through this research will help further explore mRNA design principles, ultimately leading to the creation of more effective mRNA-based treatments and an improved response to health threats. (PI: Steve Branda)

COOL FACT > These new mRNA designs are now being used to create anti-viral medical countermeasures.

BOOSTING SOLAR ENERGY EFFICIENCY WITH ENHANCED OPTICAL MEASUREMENT SYSTEMS

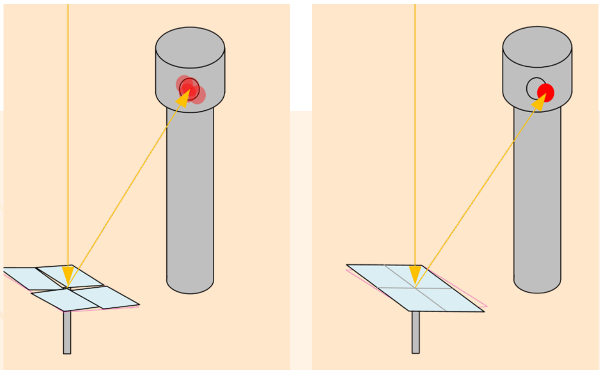
Improving the efficiency and accuracy of concentrating solar optics is imperative for harnessing solar energy. The Sandia researchers working on this project recognized that managing light collection is imperative for high solar power performance. Their initial experiments revealed that direct imaging of the sun could damage camera sensors, prompting them to explore various filters to safely capture solar images.

Through testing, the team found that simplifying the imaging system's aiming process improved data collection. By stabilizing mirror facets and leveraging Earth's rotation, they created a concentrated light beam that simplifies the camera setup.

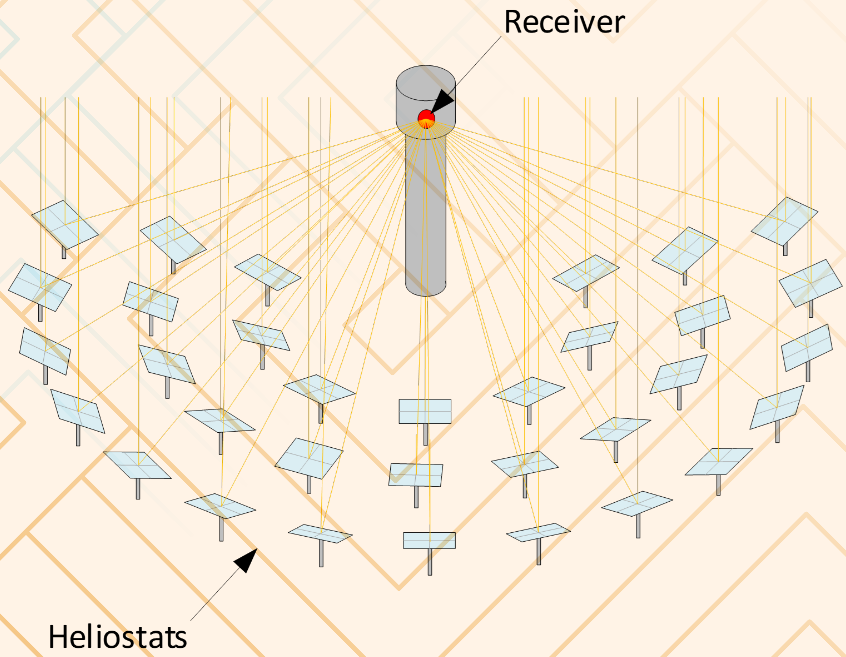
The project successfully demonstrated the ability to create high-resolution slope maps of mirrors without the need for large optical screens. This approach allows for faster calibration of heliostat fields, which are necessary for solar energy production. The research also has implications for national security applications and supports the development of new heliostat technologies.

Ultimately, this work aims to enhance the operational efficiency of solar energy systems, contributing to a more robust source of high-temperature heat with increased economic performance. **(PI: Randy Brost)**

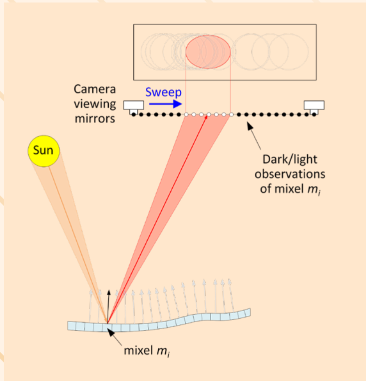
COOL FACT > Sandia filed for copyright to release their code and data through OpenCSP, promoting collaboration and knowledge sharing in the field.



Shape and aiming errors in heliostats can cause uneven light beams, reducing efficiency, increasing safety hazards, and potentially leading to damage or cautious operation.



In a perfect scenario, heliostats would create precise light beams, all directed accurately at the intended target for optimal energy collection.



Data collection. The camera sweeps across the reflected beam, collecting many images. Alternatively, the beam sweeps across the camera.

ASSESSING LOCALIZED STATES IMPACT ON NEXT-GEN MATERIALS FOR MOVING ENERGY AND INFORMATION

Localized states refer to specific configurations or conditions within a material where certain properties, such as energy or charge, are concentrated in a limited region rather than being spread out uniformly. An important route to both storing and transporting information and energy relies on creating localized states within a material, but traditional approaches for finding such localized phenomena are not applicable to a wide range of materials.

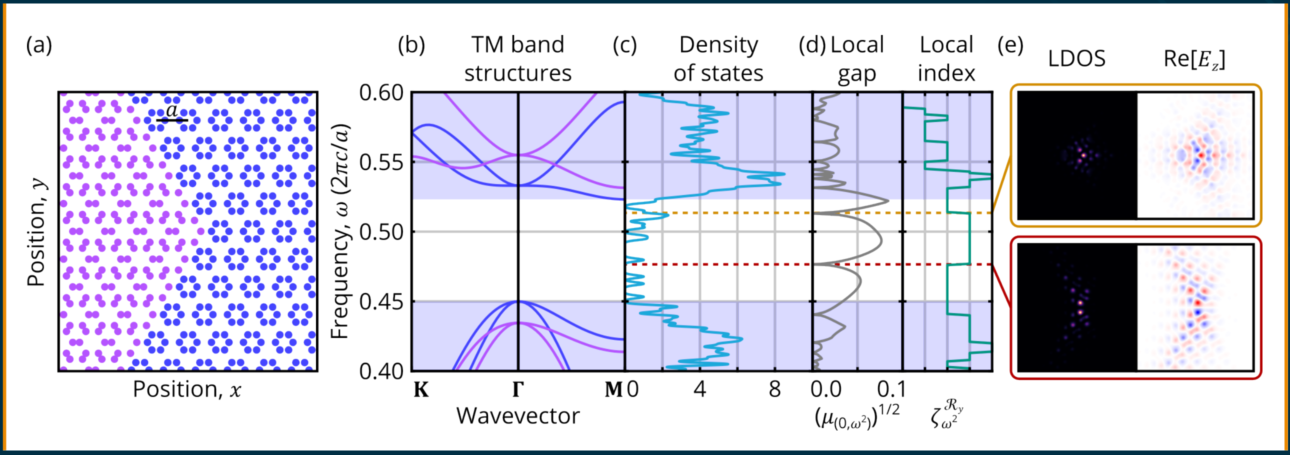
To open a new discovery space for finding and creating localized states, Sandia researchers developed and used a novel mathematical approach rooted in multi-operator pseudospectral methods. This innovative framework allows for a more efficient and flexible way to study localized phenomena across various materials.

Sandia researchers collaborated with University of New Mexico and Florida A&M University and benefitted from postdoc and intern contributions. Building on this project's successes, the team is applying these methods to better understand quantum materials and couple AI to their mathematical framework. This research could lead to major advancements in material science and technology. **(PI: Alexander Cerjan)**

LEVERAGING NEW TALENT > Postdocs Stephan Wong and Kahlil Dixon provided theoretical and numerical developments in applying these methods to nanophotonic and optoelectronic systems.

READ MORE > *Science Advances*, *Physical Review Letters* (*1*) (*2*) (*3*), *Nature Communications*, *Journal of Mathematical Physics*, *npj Nanophotonics*, *Journal of Mathematical Analysis and Applications* (*1*) (*2*), *APL Photonics*

COOL FACT > The research team was invited to give 16 invited talks and colloquia on their results, including at the Ettore Majorana Foundation and the Institute of Basic Science.



Pseudospectral methods enable the rapid identification of robust corner-localized states that are ideal for information or energy storage.

UNDERSTANDING HOW MATERIAL COMPOSITION AFFECTS RADIATION RESISTANCE IN FUSION MATERIALS

Materials used in future fusion reactors must endure extremely tough conditions, including intense exposure to plasma and neutrons. Researchers have found that multi-component alloys can better resist radiation damage, but the link between the composition of these alloys and how they respond to radiation is not fully understood.

To address this, the team used advanced computer modeling to identify which alloy compositions could improve resistance to damage from neutrons and helium bubbles. They discovered that increasing the amounts of tantalum or tungsten in the alloys helped reduce defects caused by neutron exposure, while adding more molybdenum slowed the growth of helium bubbles.

The researchers then created these optimized alloy compositions at Sandia and collaborated with the University of New Mexico and the University of Tennessee to test them. They also received time at the DIII-D National Fusion Facility to expose different alloy compositions to realistic fusion plasma conditions, allowing them to study how these materials erode under such environments.

The findings from this research will help in designing the next generation of materials that will face plasma in fusion energy systems. **(PI: Mary Alice Cusentino)**

LEVERAGING NEW TALENT > The project benefitted from the contributions of postdoc Elijah Davis and Guddi Suman and students Anna De Leon, Shane Evans, Katie Karl, Aspen Reyes, and Sadie Wicks.

UNDERSTANDING METHANE EMISSIONS FROM THAWING ARCTIC PERMAFROST

Global methane levels continue to rise as permafrost thaws in the Arctic. Sandia researchers are investigating the processes that lead to methane emissions from this change. This LDRD team employed a comprehensive approach that combines fieldwork, laboratory experiments, and numerical simulations to study the hydrological, thermal, and biogeochemical systems that influence methane production. By examining the role of microbial activity in decomposing organic matter under oxygen-limited conditions, Sandia researchers can assess how methane is transported from saturated wetland soils.

This research not only improves mechanistic Earth systems modeling but also highlights the importance of collaboration with institutions like the University of Texas at Austin and the University of Alaska, Fairbanks. Understanding methane dynamics in permafrost will help experts refine climate models and address these challenges.

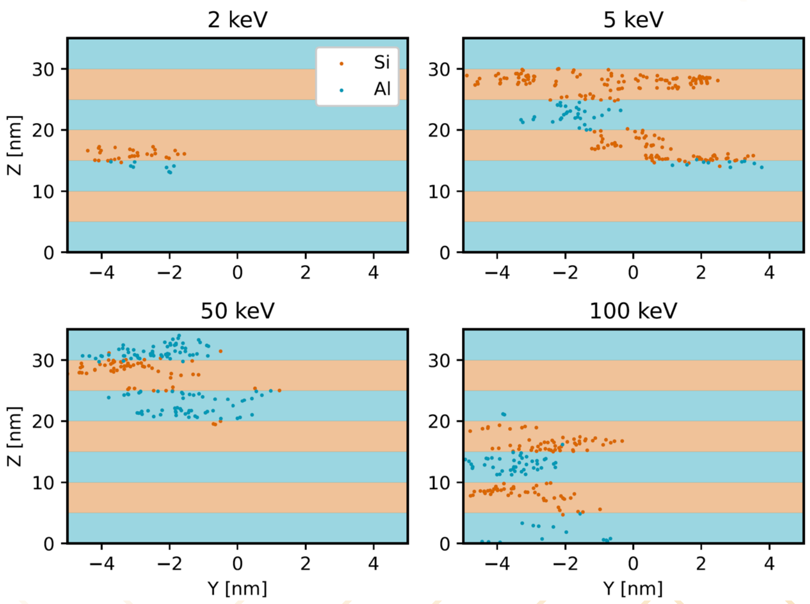
LEVERAGING NEW TALENT > Contributors, including Olin Carty, Lisa Bigler, and Tanner Mills, have advanced this work, which has been shared through publications and presentations at conferences like the AGU Fall Meeting.

AMPLIFYING UNDERSTANDING OF SEMICONDUCTOR RELIABILITY UNDER NEUTRON DAMAGE

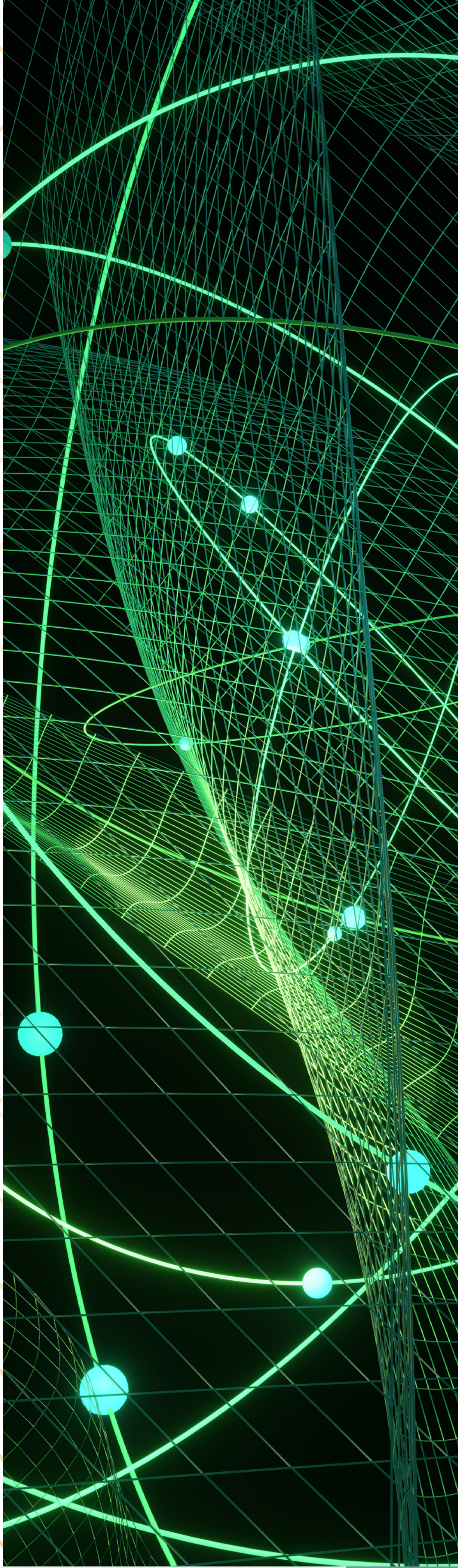
The choices made in physics models can greatly affect how researchers predict the damage caused by neutrons in semiconductor materials. Using specialized codes called MARLOWE and SRIM (Stopping and Range of Ions in Matter), the Sandia team found that model choices impact the predicted likelihood of defects and ionization, which are important for assessing the risk of failure in electronic devices.

By refining the MARLOWE model with detailed results from molecular dynamics simulations, the team was able to create a more accurate picture of how defects are produced in semiconductors. They discovered in a typical nanosheet finFET transistor that one out of every ten neutron strikes at an energy level of 1 MeV can damage multiple channels within the device. A single neutron strike in a small feature size device can cause a cascade which damages multiple sensitive regions.

This research enhances understanding of how neutrons interact with semiconductor materials, which is essential for developing more reliable electronic devices that can withstand radiation exposure. **(PI: Daniel M. Fletcher)**



Analysis of cascades revealing the final positions of interstitial atoms for varying primary knock-on atom energies.



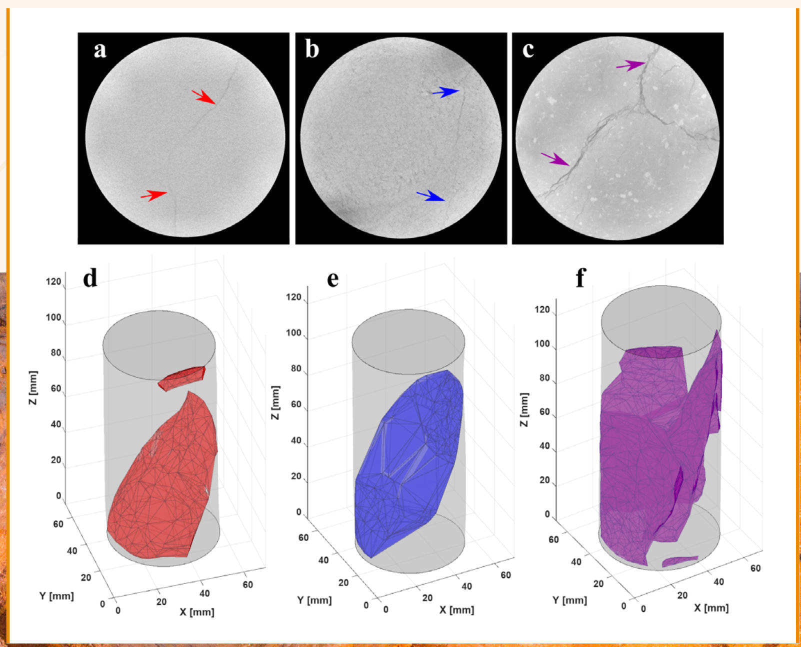
UNLOCKING DYNAMICS TO ADVANCE ENERGY INFRASTRUCTURE

Accurately detecting and characterizing fractures in geothermal reservoirs is pivotal when it comes to geothermal monitoring and improving understanding of subsurface dynamics. Traditional methods, such as seismic analysis and tracer studies, often misinterpret fracture characteristics, leading to increased risks and costs. A groundbreaking project at Sandia has introduced a novel approach to fracture detection that could revolutionize geothermal energy and beyond.

This research reveals that rocks—sandstone, limestone, and granite—release a strong, transient spike in dissolved ions, like silicon and sodium, during fractures. These "chemical transients" serve as vital signals for fracture creation and permeability changes, enabling better quantification of fracture surface areas and real-time diagnostics. This innovation enhances geothermal applications and extends to nuclear and hydrogen projects.

Collaboration has been key, with Ahmad Ghassemi from the University of Oklahoma shaping the experimental design alongside Sandia contributors, including William Kibikas and experts Jessica Kruichak-Duhigg, Brittney Seaburn, and Perry Barrow. The project has led to significant findings, with publications submitted to reputable journals and presentations at major conferences. **(PI: William Kibikas)**

COOL FACT > With new funding from ARPA-E ROCKS and proposals focused on critical minerals, this research not only strengthens energy infrastructure but also contributes to a sustainable future for the country.



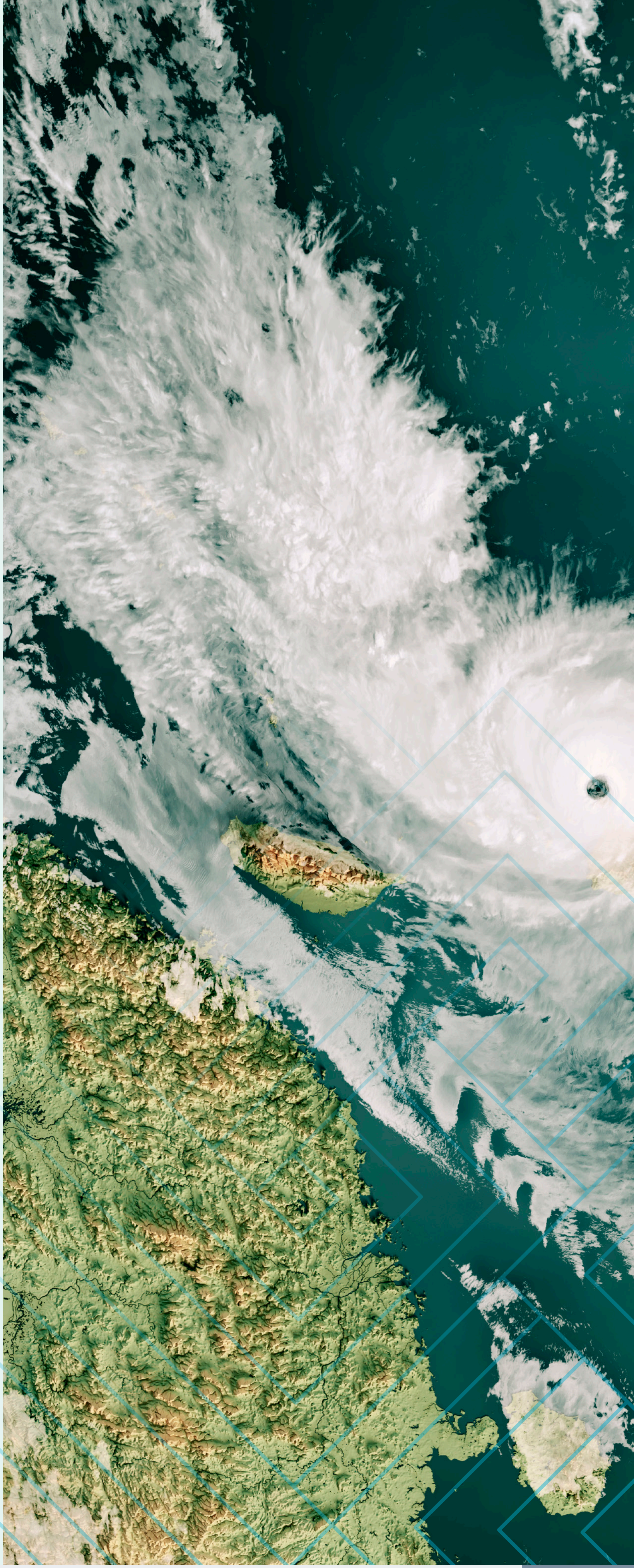
Total % increase in dissolved solids (mg) for each ion during the transient increase post-fracture.

STRENGTHENING CLIMATE SCIENCE USING ADVANCED MJO IDENTIFICATION TECHNIQUES

Understanding the Madden-Julian Oscillation (MJO) is key for predicting extreme weather events like tropical cyclones and droughts, which significantly impact global climate patterns. Sandia researchers aimed to improve the identification and characterization of the MJO using advanced techniques.

Traditional methods, such as principal component analysis, have limitations, including the assumption of orthogonality between components and inadequate consideration of variable importance. To address these challenges, the team employed a unique sequential canonical polyadic tensor decomposition approach. This method allowed Sandia researchers to identify six stable tropical weather modes, revealing that dynamic variables play a more important role than precipitation in MJO identification. Notably, the research uncovered a third component related to MJO variability, enhancing understanding of its dynamics.

The findings offer new opportunities for improved climate predictions and sub-seasonal forecasting, particularly in North America. This research, submitted for publication in the *American Meteorological Society's Monthly Weather Review*, represents a major advancement in climate science, providing a more robust framework for understanding the complex interactions within the climate system. It could lead to better preparedness for climate-related impacts worldwide. **(PI: Hemanth Kolla)**



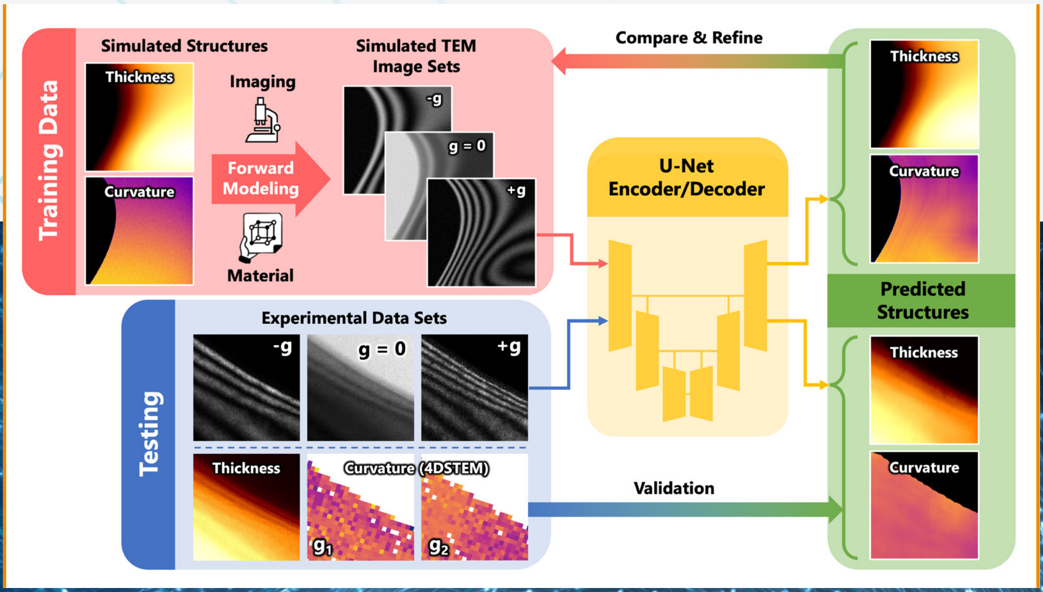
DECODING 3D NANOSCALE MATERIALS STRUCTURE IN ELECTRON MICROSCOPY IMAGES

Accurate 3D measurement of nanoscale structure and strain is essential for developing advanced materials and microelectronic systems. Transmission Electron Microscopy (TEM) images provide 2D projections of a sample and contain critical depth information about depth and structure, while existing methods struggle to decode information like local thickness and bending. Sandia researchers developed a supervised machine learning framework for decoding 3D structural information from conventional 2D TEM images.

The team generated a synthetic image library using realistic dynamical diffraction simulations of a wide range of geometries. A convolutional neural network trained on these data predicts local thickness and bending directly from 2D images. Validation on silicon samples demonstrated prediction accuracy comparable to established experimental techniques. The efficient, scalable approach accelerates quantitative 3D characterization and paves the way for detailed nanoscale strain mapping in crystalline materials. **(PI: Stephen D. House)**

LEVERAGING NEW TALENT > This project benefited from the contributions of Sandia postdoc researchers Daniel Vizoso and Andrew Baker, and PhD student Brenden Postma (Texas A&M University).

READ MORE > *Measurement*



Schematic of the workflow for generating simulated TEM image sets and training a neural network to extract the 3D sample geometries from such images.

ENHANCING ENERGY STORAGE AND FLEXIBLE ELECTRONICS BY UNDERSTANDING DEFORMATION IN LAYERED MATERIALS

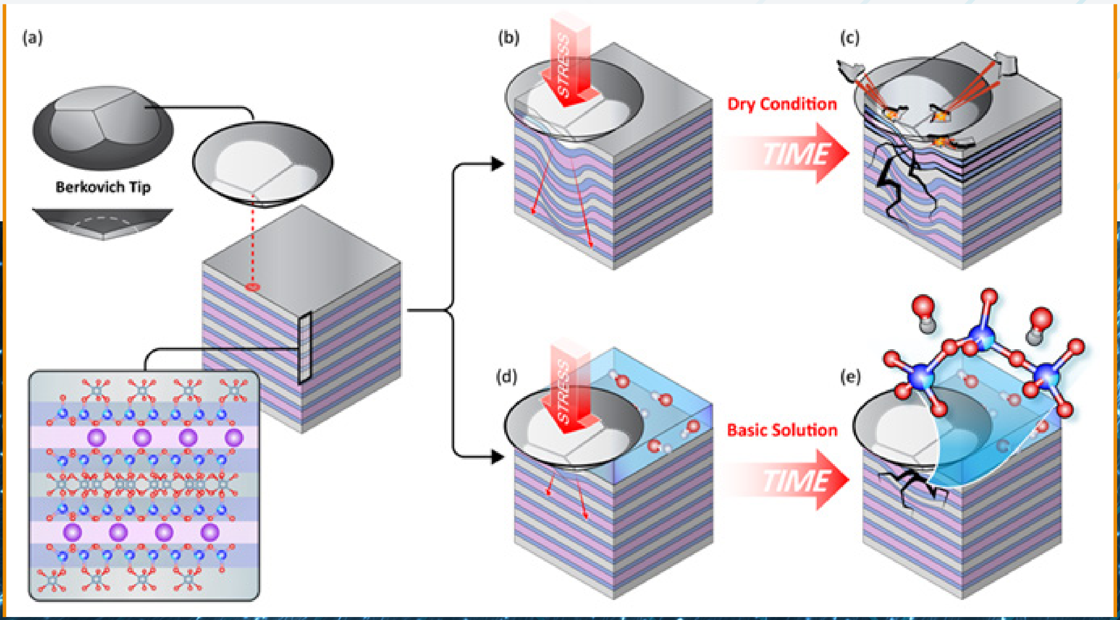
Understanding how layered materials, such as muscovite and shale rocks, respond to mechanical stress is fundamental for a range of applications, from energy storage to flexible electronics. Sandia researchers explored the deformation mechanisms in these materials at varying temperatures and in aqueous conditions, as this knowledge can enhance the design and performance of advanced technologies.

Using nanoindentation, the team investigated the behavior of muscovite and shale under stress. They discovered that small displacement bursts, or slips, are associated with plastic deformation, while larger slips indicate fracture events. These findings revealed that as temperature increases, or if aqueous solution is present, the load required for fracture decreases, suggesting that higher temperatures and aqueous solutions weaken the material.

Furthermore, the team's work extends beyond individual materials to larger-scale phenomena, such as microseismicity. By employing a micromechanical model, Sandia researchers can connect the slip behavior observed in nanoindentation experiments to the statistical patterns of microseismic events induced by fluid injection in geological formations. This innovative approach enables the extrapolation of laboratory findings to real-world scenarios, ultimately improving predictions of seismic activity associated with energy extraction and storage. **(PI: Anastasia G. Ilgen)**

READ MORE > *Nature Communications*, *University of Illinois Urbana-Champaign News*

Nanoindentation of muscovite mica in chemically reactive environments.



BRIDGING THE GAP: SCALING ALGAL RESEARCH FOR NATIONAL SECURITY AND SUSTAINABLE ENERGY

Scaling up laboratory experiments to real-world applications is a major challenge in bioscience, particularly in algal culture, where small-scale research often fails to translate to production-scale solutions. This issue impacts areas such as bioenergy and biodefense, both vital to national security.

Sandia researchers addressed this challenge by studying the green algae species Monoraphidium minutum during its scale-up to 1000-liter ponds, using multi-omics analysis to identify stress-specific signatures and uncover novel regulatory regions and transcriptional patterns. Collaborating with Cornell University, the team revealed key genes regulated by light and carbon dioxide, demonstrating that small-scale data can predict large-scale growth outcomes.

By integrating experimental methods with machine learning, Sandia researchers showed biological language model embeddings enhance predictive power, enabling accurate predictions across biological scales. This work reduces costs and improves efficiency in producing biofuels and biomaterials, while advancing secure bioeconomy efforts. This research supports AI, machine learning, and predictive biology, paving the way for solutions in national security and sustainable energy. **(PI: Raga Krishnakumar)**

A Sandia Labs employee evaluates a sample from an algal pond.

INTEGRATING CO2 CONVERSION IN BIOMANUFACTURING FOR ENERGY RESILIENCE

Microbial biomanufacturing is a promising avenue for biofuel and bioproduct production, but achieving economic viability for large-scale commodity chemicals is challenging. To reduce costs and unlock additional resources, Sandia researchers are working to harness a low-cost and abundant feedstock, carbon dioxide, for conversion into valuable products.

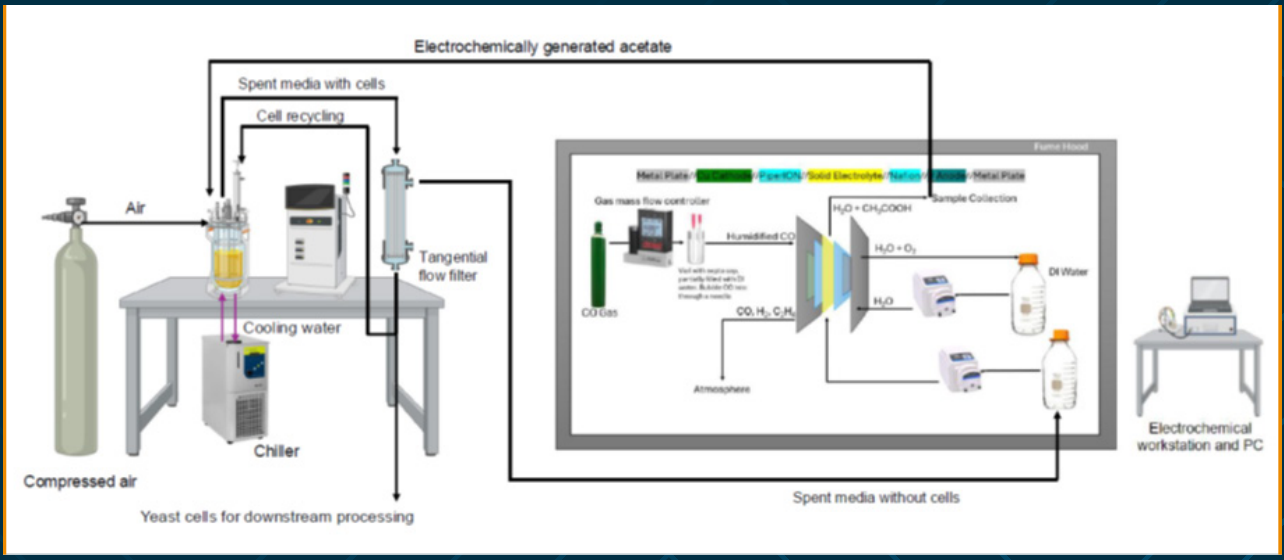
In collaboration with Haotian Wang's lab at Rice University, the team developed an integrated process that couples electrochemical reduction of carbon dioxide with biological upgrading to create aviation fuel precursors. This innovative approach uses a solid-state electrochemical system that works seamlessly with biological processes, enabling continuous upgrading.

The team optimized the electrochemical reduction of a CO2-derived intermediate to acetate and the subsequent conversion of acetate to lipids, the precursor to aviation fuel, in the oleaginous yeast Rhodosporidium toruloides. Significant advancements include enhanced yeast tolerance and conversion of acetate, improvements in lipid production and electrochemical cell stability, and technoeconomic analysis. The work has led to four publications (two pending), an Intellectual Property, and a postdoc-to-staff conversion at Sandia. **(PI: Di Liu)**

READ MORE > *Biotechnology for the Environment*, *Current Opinion in Biotechnology*

COOL FACT > This innovative research paves the way for utilizing low-cost feedstocks in bioconversion, ultimately boosting energy security and bolstering domestic supply chain resilience.

Integrated electrochemical-biological conversion system for CO/CO2 upgrading into aviation fuel precursors.



UNLOCKING MOLECULAR INSIGHTS TO SUPPORT MATERIAL DEVELOPMENT AND ENERGY EFFICIENCY

The ability to accurately predict molecular behavior can lead to the development of better materials and more efficient energy solutions, ultimately supporting advancements in technology and security efforts. Through this project, Sandia researchers focused on understanding molecular dynamics, particularly in situations where the behavior of molecules is influenced by complex interactions between their electrons and nuclei. Current methods often struggle to accurately capture these interactions, especially when it comes to geometric phase effects, which are important for understanding how molecules behave in real-world conditions.

The new approach developed by the team introduces a hybrid quantum-classical framework that provides a more accurate description of these dynamics. By separating the critical nuclear movements that need quantum treatment from those that can be treated classically, this method overcomes previous limitations that made it difficult to apply exact calculations to realistic systems. This allows researchers to study more complex molecular behaviors without the computational challenges that have held back progress in the past.

The impact of this work on the mission is significant. By providing a more accurate and practical way to model molecular dynamics, this framework can enhance understanding of chemical reactions and material properties and impact energy production, materials science, and national security. (PI: Laura M. McCaslin)

INCREASING ENERGY SECURITY THROUGH ADVANCED HYDROGEN STORAGE MODELING

There is a fundamental need for accurate modeling of hydrogen storage in geological formations. To capitalize on seasonal energy sources, effective hydrogen storage is required for consistent and reliable energy. Storage of hydrogen in geological formations, like conventional natural gas reservoirs, is one method of meeting this storage demand, however, conventional models fail to capture the unique transport behaviors of hydrogen due to its exceptionally small molecular size.

To overcome these challenges, researchers developed the Darcian Density-based Dusty Gas Model (D3G), a sophisticated simulator that accurately represents the complex interactions between hydrogen and other gases in porous geologic materials. This innovative model integrates Darcy's Law advection with both Stefan-Maxwell and Knudsen diffusion within a high-performance computing framework, enabling simulations at a geological scale. The D3G model has been rigorously validated against experimental data, demonstrating its ability to replicate essential phenomena such as reverse diffusion and diffusion barriers.
(PI: Matthew J. Paul)

COOL FACT > This breakthrough tool enhances the understanding of hydrogen transport and supports the identification of economically viable storage locations.

REVOLUTIONIZING X-RAY DETECTION BY ADVANCING QUANTUM SENSORS USING ATOMIC PRECISION ADVANCED MANUFACTURING

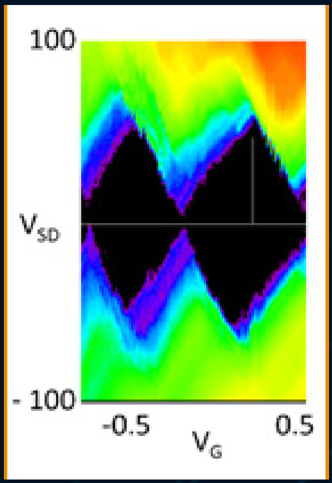
X-ray sensors based on conventional transistors suffer from an inability to distinguish energy. A more sensitive device could be made smaller and tiled into an array, where each element of the array incorporates different materials selected for their sensitivity to X-rays of different energies.

Sandia researchers saw an opportunity to develop a revolutionary tiled X-ray sensor by bringing a quantum device called a single electron transistor (SET) out of the realm of cryogenic environments into operating at room temperature. (This could be possible by using atomic precision advanced manufacturing (APAM) to design atomic clusters in silicon whose quantum nature withstands the thermal energy from room temperature, where that of either a single atom or a large ensemble does not.)

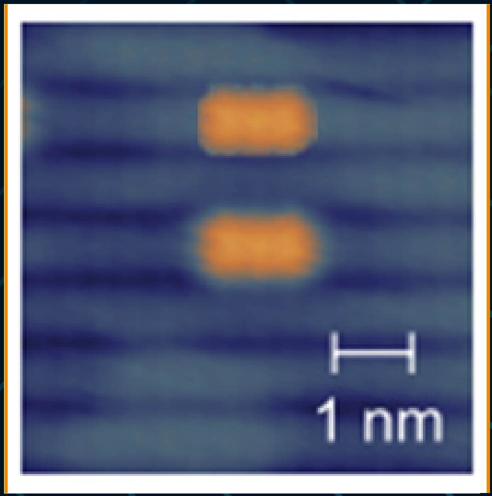
Key accomplishments included examination of different material stacks for X-ray absorption, a test platform for evaluating devices where even small amounts of current leakage is unacceptable, and understanding the chemical thermodynamics and kinetics involved with placing single atoms using APAM.

Results were presented in several venues, including a patent disclosure, conferences of the American Physical Society and the Materials Research Society, and an APAM-specific workshop. **(PI: Shashank Misra)**

READ MORE > *Journal of Applied Physics*, *The Journal of Physical Chemistry C*



A SET biased at the edge of one of the black diamonds can detect small changes in the background electric field.



Multi-atom clusters can be designed in silicon using single dimer spacing between three-dimer chains, the only structure to deterministically incorporate exactly one phosphorus dopant atom.

PHARMACEUTICAL AND ENERGY FIELDS BENEFIT FROM PREDICTING AND CONTROLLING CRYSTALLIZATION PROCESSES

Understanding how crystals form is important for various industries, from pharmaceuticals to energy production. Sandia researchers have explored the recrystallization of resveratrol, a therapeutic compound, using a groundbreaking approach that combines multiscale experiments, modeling, and simulations. This research aims to improve the ability to predict and control crystallization processes, which can lead to better products and manufacturing techniques.

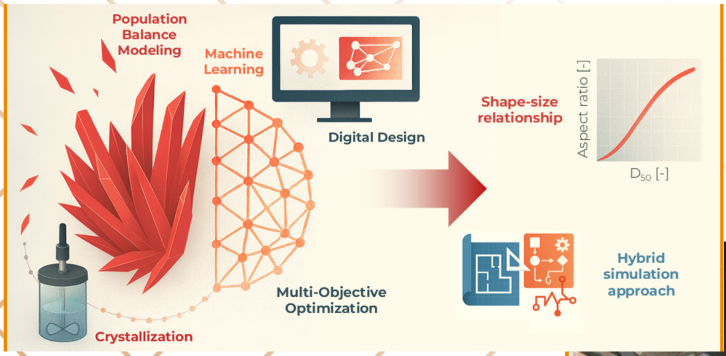
The team developed a kinetic Monte Carlo model for single crystal formation and a coupled computational fluid dynamics/population balance method for ensembles of crystals. These advancements enhance the understanding of how crystals grow and change shape.

A Purdue University collaboration led to the development of a method for automating crystallization processes and a new control strategy for “dialing in” the desired crystal size and shape. A Florida State University collaboration resulted in a publication and a submission. Overall, the team gave 24 conferences presentations and authored seven publications.

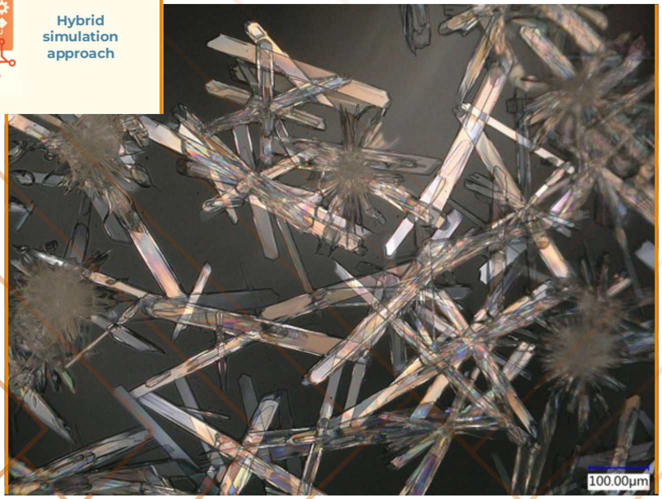
This work is particularly relevant for nuclear deterrence projects involving wet chemistry, contributing to new initiatives focused on manufacturing and metal precipitation. Overall, this research promises to enhance efficiency and effectiveness across multiple fields. **(PI: Rekha Rao)**

LEVERAGING NEW TALENT > Postdocs Helen Cleaves and Tesia Janicki worked on the project and transitioned to staff. Postdoc Tyler Kennelly was also indispensable to the effort.

READ MORE > *AICHE Journal* (journal cover)



Sandia's collaboration with Purdue led to an AICHE Journal cover focused on AI-enhanced modeling using digital crystal engineering.



Complex morphology of resveratrol crystals showing aggregation of needles to form snowflakes.

OPTIMIZING THERMAL EXPANSION IN POLYMERS FOR DIVERSE INDUSTRIAL APPLICATIONS

Managing thermal expansion mismatch is essential for ensuring the reliability, performance, and safety of polymer-based products across various industries. In this project, Sandia researchers focused on designing, synthesizing, and incorporating a negative coefficient of thermal expansion (CTE) molecule into polymer structures. The innovative method they developed allows polymers to better match the thermal expansion rates of metals, reducing failures caused by heating and cooling cycles.

The team's low coefficient of thermal expansion molecules enhance polymer durability, offering improved resistance to cracking and warping. By eliminating the need for fillers or compliant layers, Sandia's solution also reduces material weight, which is significant for industries where weight impacts performance, such as automotive and defense.

The demand for reliable polymers is high, particularly in applications like photovoltaic backsheets, where thermal expansion mismatch can lead to costly failures. Sandia's research has the potential to transform multiple sectors by providing a versatile solution that enhances performance and longevity. The project has garnered recognition, including an R&D 100 Award, Society of Women Engineers Ignite Award, a patent, and a publication, highlighting its innovative contributions to material science. **(PI: Erica Redline)**

COOL FACT > This advancement increases design flexibility, enabling tailored thermal behaviors in applications ranging from electronics to aerospace.

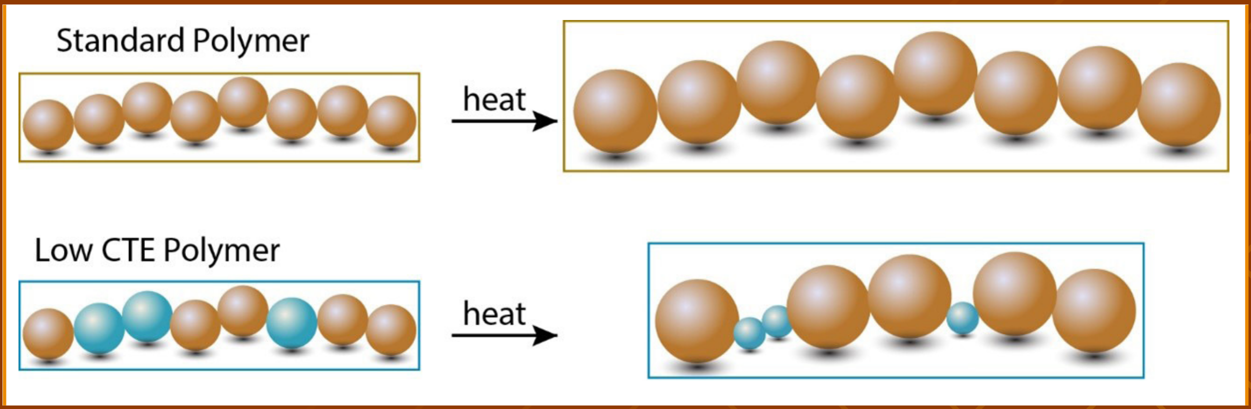


Illustration of the low CTE polymer behavior heating a standard polymer (top) versus a low CTE polymer (bottom) created using Sandia's technology. In this example, the orange spheres represent a typical polymer unit whereas the blue spheres represent the low CTE molecules.

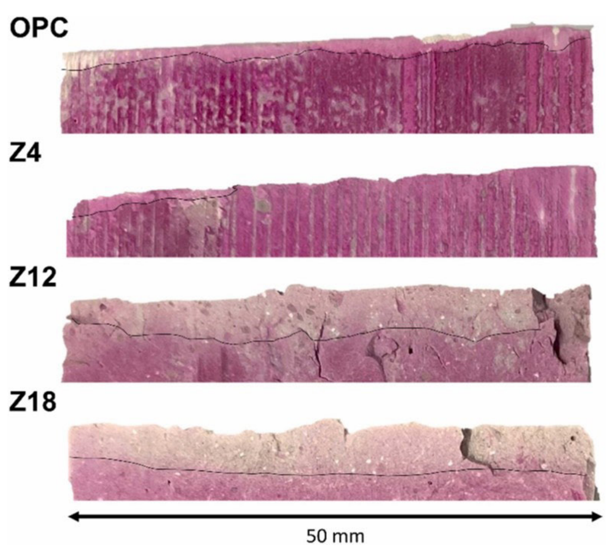
REVOLUTIONIZING CONSTRUCTION MATERIALS UTILIZING ZEOLITE MINERALS

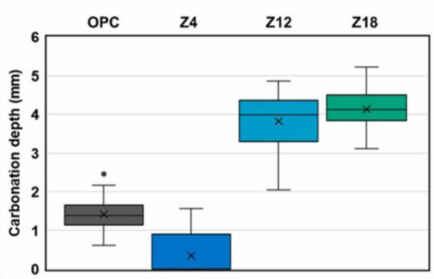
Concrete production is a major source of emissions, driven by both the chemical processes involved in making concrete and the high material demand. To tackle this challenge, Sandia is exploring innovative ways to incorporate zeolite, a natural aluminosilicate mineral, as a supplementary cementitious material. This approach aims to replace costly and energy-intensive cement clinker with locally sourced materials.

By incorporating synthetic zeolite Y, the LDRD team found that carbonation rates increase dramatically, improving the concrete's durability and potentially reducing emissions during the curing process. Sandia researchers conducted a techno-economic analysis and life cycle assessment, revealing that while zeolite-based concrete mixes have higher production costs, for thick concrete structures, zeolite-modified cement can offer advantages in decreasing overall emissions.

Technical findings have resulted in four intellectual property disclosures, four peer-reviewed publications, and fifteen conference presentations. By advancing the use of zeolite in concrete, Sandia is paving the way for innovative construction practices and highlighting the role of advanced materials in developing novel building solutions. **(PI: Jessica Rimsza)**

LEVERAGING NEW TALENT > The project team included postdoc Atolo Tuinukuafe and Jeffrey Bullard from Texas A&M University.





	OPC	Z4	Z12	Z18
Mean	1.41	0.35	3.82	4.13
SD	0.40	0.53	0.74	0.49
CoV	28%	153%	19%	12%

Results show (left) carbonation depth in zeolite-modified cement, with black lines marking the measured limits and a (right) box plot summarizing measurable carbonation depth as a function of zeolite concentration (Z4 = four weight percent zeolite).

TRANSFORMING GAS CAPTURE TECHNOLOGIES WITH INNOVATIVE POROUS LIQUIDS

The demand for efficient gas capture technologies is rising due to the need for cost-effective and energy-efficient solutions in industrial applications. Traditional methods are expensive and energy-intensive, prompting Sandia researchers to explore alternatives. This research focuses on porous liquids, innovative liquids with permanent internal porosity that capture gases more effectively with less energy than conventional liquids.

Sandia researchers investigated the use of porous organic cages within porous liquids to enhance gas capture capabilities. They found that these cages can expel captured gas molecules under high pressure, enabling low-energy regeneration. A new porous organic cage was developed, demonstrating a 2x increase in gas adsorption capacity due to improved interactions between the cage structure and gas molecules.

The findings underscore the transformative potential of porous liquids in gas separation technologies. By advancing the understanding of these materials, Sandia is developing innovative solutions that reduce energy consumption and enhance efficiency in gas capture processes. **(PI: Jessica Rimsza)**

COOL FACT > This project was recognized through an R&D 100 Award Finalist designation, a full patent application, two peer-reviewed publications, and four conference presentations.

STRENGTHENING ENERGY SECURITY BY DEVELOPING NOVEL HIGH-ENTROPY METAL-ORGANIC FRAMEWORKS

High-entropy materials (HEM) have emerged as promising catalysts due to their complex structures and compositions. However, traditional HEM catalysts are nonporous, and reactive sites are primarily limited to surface sites. To tackle these challenges, Sandia researchers developed the first porous high-entropy metal-organic frameworks (HEMOF) derived from polynuclear metal clusters. These innovative materials feature built-in Lewis acid sites, demonstrating exceptional activity for carbon dioxide fixation under mild conditions and short reaction times, surpassing existing heterogeneous catalysts.

The team utilized advanced computational tools, including density functional theory and AI/ML methods, to rationally design HEMOFs.

A U.S. patent application was filed, and follow-on projects have received funding from non-LDRD sponsors. PI Dorina Sava Gallis recently received two national awards for her leadership and contributions to the scientific community. **(PI: Dorina F. Sava Gallis)**

LEVERAGING NEW TALENT > The project leveraged contributions from postdoc researchers and undergraduate students, some of whom have transitioned to staff positions or advanced their studies. These include former postdoc Calen Leverant, who recently converted to Sandia staff; and Raphael Reyes, Madeline Steinberg, and Caith McKeown.

READ MORE > *Advanced Materials*, *Journal of the American Chemical Society*, *The Journal of Physical Chemistry C* (*1*) (*2*), *ACS Applied Nano Materials*

FORTIFYING SAFETY IN CONFINED SPACES THROUGH TAILORED METAL-ORGANIC FRAMEWORKS MATERIALS

The recovery of sulfur hexafluoride (SF6) is essential due to its potential to displace oxygen in confined spaces, creating significant safety hazards. Traditional recovery methods, such as energy-intensive cryogenic distillation, are not always effective, and detecting low concentrations remains difficult. To address these issues, Sandia researchers explored physisorption-based adsorption using advanced porous materials known as metal-organic frameworks (MOF).

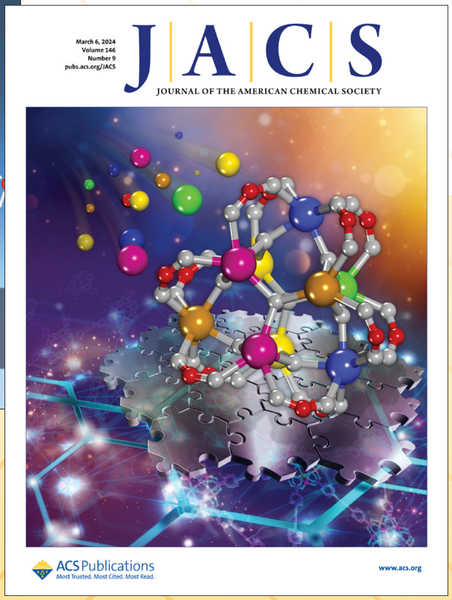
The team focused on developing a predictive capability for optimizing SF6 capture using MOFs. These materials, with their high surface areas and customizable pore environments, are promising candidates for gas capture and remediation. By integrating predictive computational tools with experimental validation, Sandia researchers identified several promising MOF candidates.

This research not only advances the understanding of engineered pore environments for improved gas adsorption but also paves the way for developing tailored MOF materials for effective gas capture in various industries. **(PI: Dorina F. Sava Gallis)**

READ MORE > *Journal of Materials Chemistry A*, *Chemical Communications*

COOL FACT > These advancements promote safer practices and enhance operational efficiency in sectors that utilize SF6, contributing to environmental safety and sustainability.

High-entropy metal-organic frameworks derived from polynuclear metal clusters containing as many as 15 unique metals were realized for the first time.



Heterometallic metal-organic frameworks represent an ideal platform to advance the development of next-generation, programmable materials.

UNDERSTANDING KEY STEPS IN THE ATMOSPHERIC SULFUR CYCLE TO BENEFIT ATMOSPHERIC SCIENCE AND CHEMISTRY

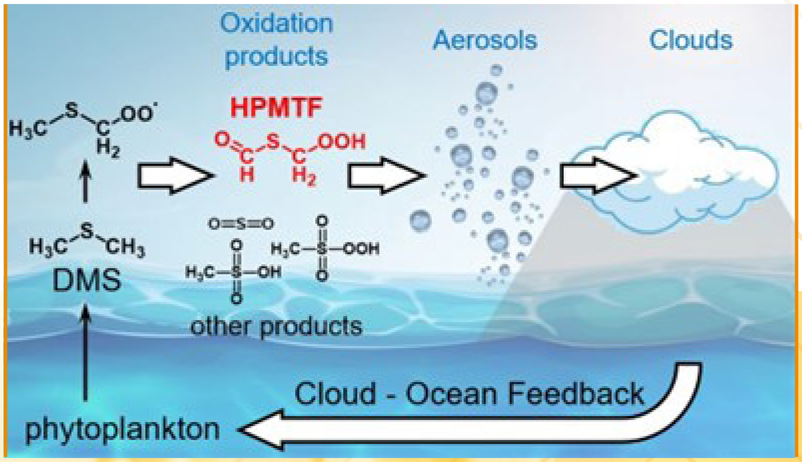
Understanding the oxidation of dimethyl sulfide (DMS)—the most abundant biogenic sulfur molecule released into the atmosphere—is fundamental for accurately modeling the global sulfur cycle. Yet, much of DMS oxidation chemistry is uncertain due to the challenges in detecting chemical intermediates, as traditional analytical methods often fail to capture short-lived reactive species.

Sandia researchers unraveled the complex network of DMS oxidation reactions, focusing on a key intermediate, hydroperoxymethyl thioformate (HPMTF), which has been invoked as a significant atmospheric sulfur reservoir. The team used novel time-resolved photoionization mass spectrometry methods to detect and characterize HPMTF and develop an "on-the-fly" source of HPTMF for further study. These advances allowed measurements of its formation rate and uptake on liquid droplets—critical quantities for assessing the impact of DMS on the Earth's atmosphere and radiative balance.

This work sheds light on DMS oxidation and provides a foundation for future investigations of other elusive chemical intermediates. The findings, shared at prominent scientific conferences, highlight Sandia's capabilities for advancing fundamental understanding of complex chemical reactions. **(PI: Leonid Sheps)**

LEVERAGING NEW TALENT > Postdoc Alexander Kjaersgaard was integral to the project's success.

READ MORE > *The Journal of Physical Chemistry A*



Dimethyl Sulfide (DMS) oxidation and the chemical intermediate Hydroperoxymethyl Thioformate (HPMTF) play major roles in the oceanic Chemistry – Aerosol – Cloud feedback cycle.

BOOSTING THE GOOD BACTERIA IN OUR MICROBIOME WITH VIRUS ASSISTANCE

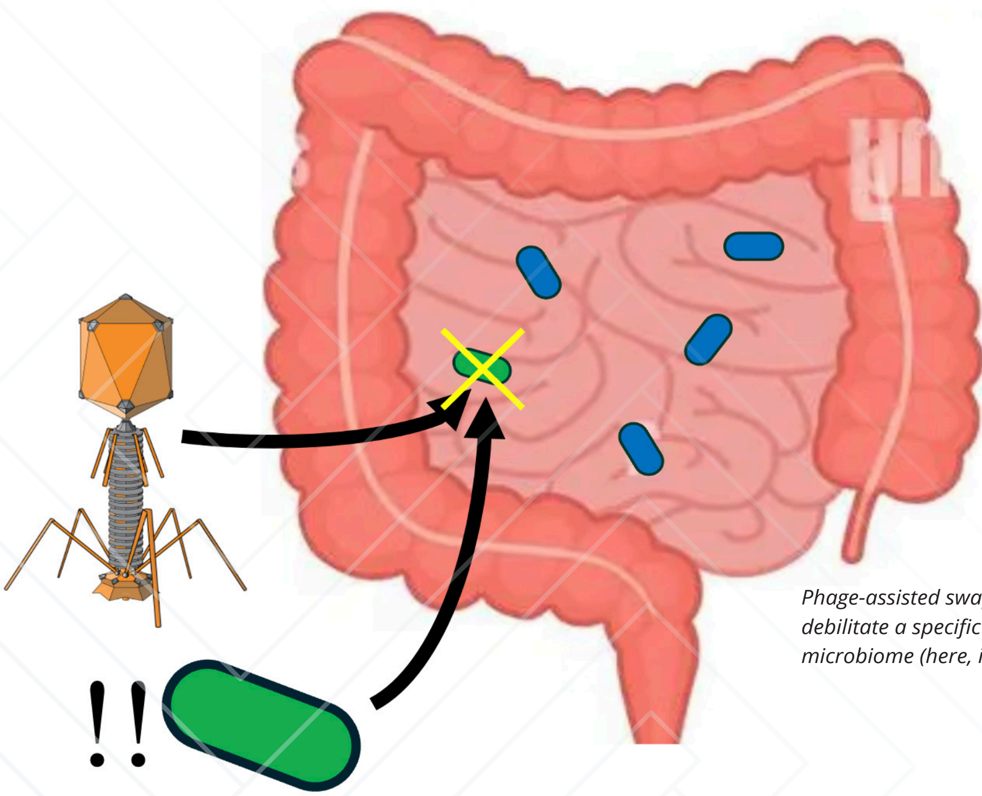
The ability to manipulate microbiomes is key for addressing health and energy challenges. Sandia researchers are exploring how to effectively achieve this goal. Initially, the team aimed to directly alter bacterial genomes in their natural environments but shifted to replacing existing microbiome members with enhanced lab strains. This innovative approach uses phages—viruses infecting bacteria—to ease bacterial replacement in a microbiome.

To support this work, Sandia enhanced its bioinformatics tools to identify phages that can integrate into bacterial genomes. The team successfully isolated phages that target human gut bacteria, particularly Bacteroides.

The researchers then developed a new idea called phage-assisted swapping, which uses phages to weaken established wild-type bacteria, allowing phage-resistant engineered variants to take their place. Initial experiments showed promise, as phage treatment reduced an existing Bacteroides population in the mouse gut, enabling the resistant variant to colonize. However, further improvement is needed, as the original population re-emerged after one week due to manageable growth challenges.

This research, which led to a follow-on external project, paves the way for advancements in microbiome engineering. **(PI: Kelly Porter Williams)**

READ MORE > *NAR Genomics and Bioinformatics*, *Practice and Experience in Advanced Research Computing* (*1*) (*2*), *PLoS ONE*, *2024 IEEE International Conference on Electro Information Technology*, *ASM Journals* (*1*) (*2*)



Phage-assisted swapping. A phage is employed to debilitate a specific bacterial population within the microbiome (here, in the gut).

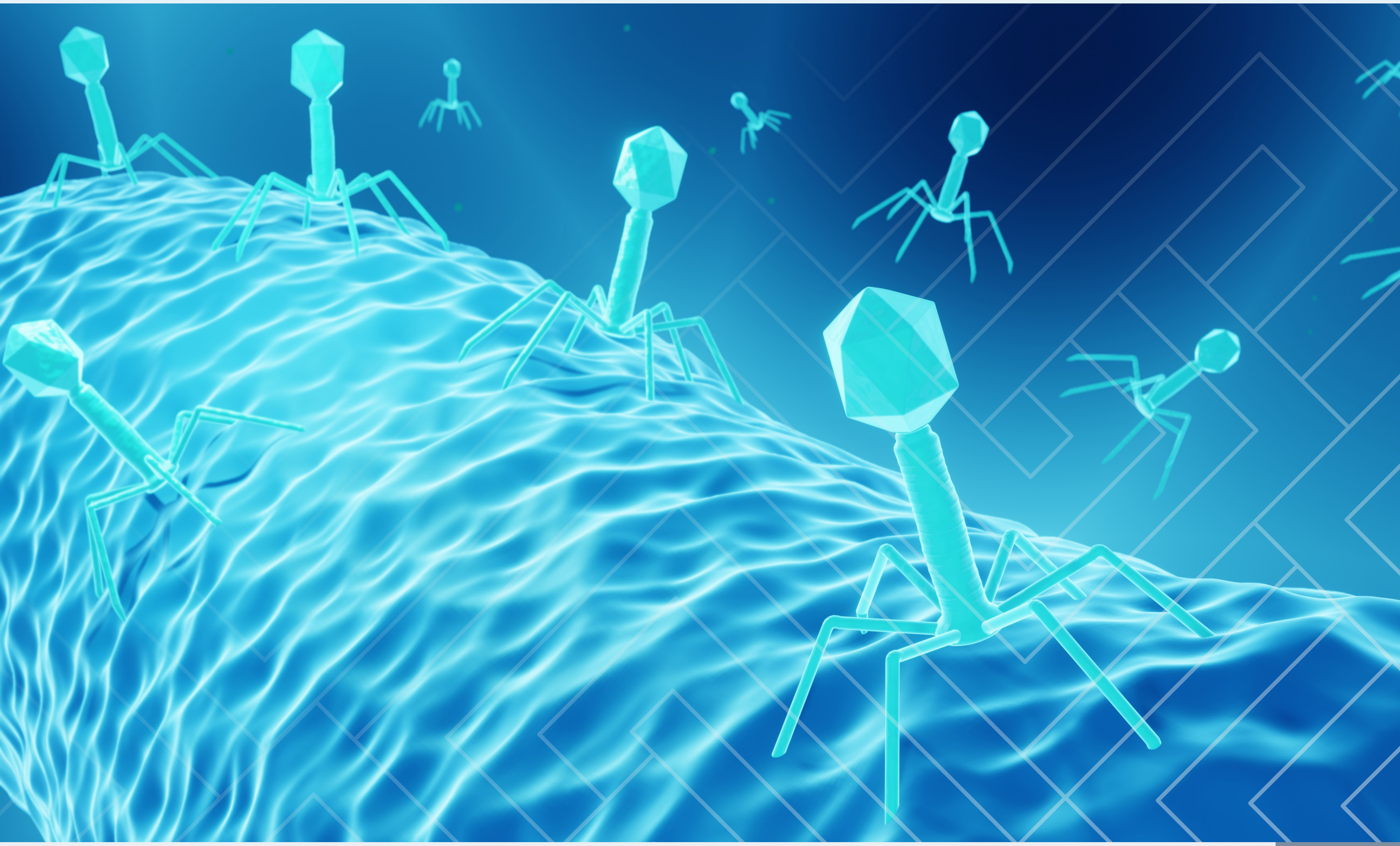
UTILIZING ENGINEERED PHAGES TO PROTECT ALGAE FROM HARMFUL MICROBES

Sandia researchers are addressing an important challenge in algae bioproduction that is crucial for creating sustainable biomaterials and bioenergy. Algae are often grown in open-air environments making them vulnerable to harmful bacteria and fungi that can hinder their growth and productivity. Current treatments to combat these infections are expensive and can disrupt the beneficial microorganisms that support algal health.

To tackle this issue, the team has explored the innovative use of bacteriophages—viruses that specifically target bacteria. By integrating the genome of a bacteriophage into the algae's own DNA, this team has created an artificial immune system. This allows the algae to produce bacteriophages, which can be released when the algae are threatened by infections or predation, effectively combating harmful infections.

The researchers successfully demonstrated this concept by integrating the MS2 RNA phage genome into a type of halotolerant green microalgae. This advancement paves the way for further optimization to enhance the resilience of algal production systems and more efficient and sustainable biomaterials and bioenergy. **(PI: Joshua David Podlevsky)**

COOL FACT > This is the first time that a eukaryotic system has produced harmful viruses that infect bacteria.



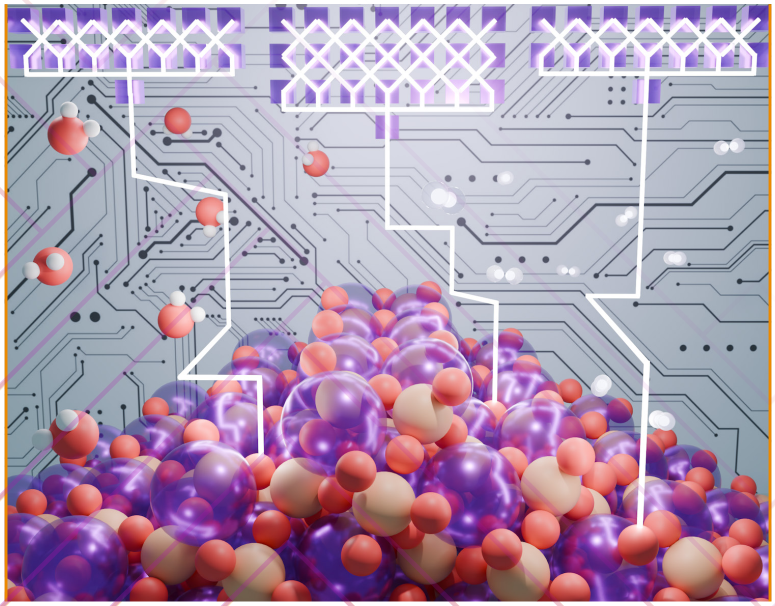
ACCELERATING DEFECT-OPTIMIZED MATERIALS DISCOVERY USING MACHINE LEARNING

Understanding and improving materials' defect properties is essential for advancing technology in areas like energy production and electronics. Sandia researchers conducted an LDRD project to explore how atomistic defects—tiny imperfections in materials—affect their performance. Traditional methods for computationally studying these defects, such as density functional theory, are often too slow and costly for large-scale materials discovery. To overcome this challenge, the team developed innovative machine learning techniques that can predict the thermodynamics and kinetics of defect formation and migration more efficiently.

By leveraging data from first-principles calculations, Sandia researchers trained models, including defect graph neural networks, that can accurately predict defect properties and quickly screen and identify promising candidates. Ultimately, Sandia's work aims to make materials discovery faster and more accessible, driving innovation in vital technological fields. **(PI: Matthew D. Witman)**

READ MORE > *Nature Computational Science* (*1*) (*2*), *Digital Discovery*, *Chemistry of Materials*

COOL FACT > This research accelerates the discovery of new materials and enhances understanding of existing ones, paving the way for breakthroughs in clean energy and advanced electronics.



An artistic rendition of a neural network predicting defect properties of a crystalline material.

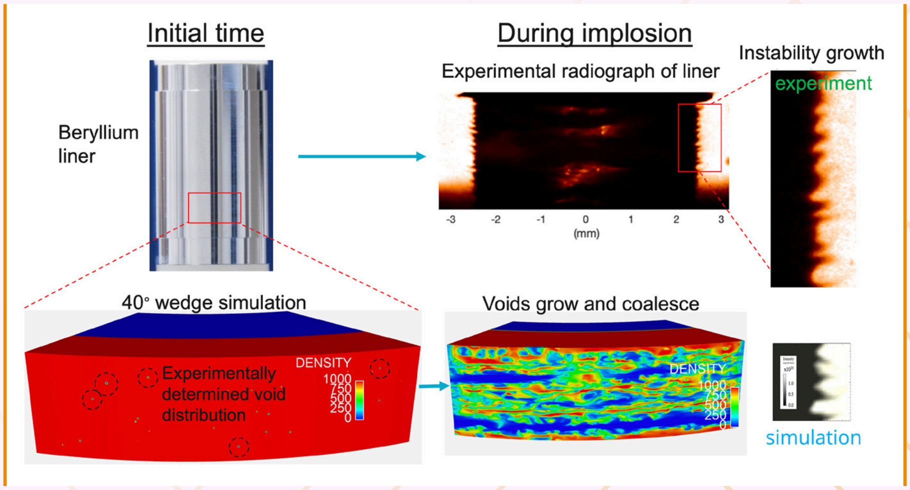
IMPROVING THE PREDICTIVE CAPABILITY FOR MODELING METALLIC LINERS USED IN FUSION RESEARCH

The pursuit of nuclear fusion energy is crucial for developing sustainable, clean energy sources. As part of this effort, researchers at Sandia's Z machine drive intense electrical current through metal shells (known as liners) filled with fusion fuel. The current compresses the liner, causing the fuel to heat and undergo fusion reactions. However, a challenge arises from the magneto Rayleigh-Taylor instability, which causes the liner to break apart during implosion, compromising fuel confinement.

In this LDRD, researchers examined the impact of native defects, specifically small voids in the metal, on this instability. These voids, averaging 10 microns in diameter, were previously overlooked in computational models. Through 3D simulations and theoretical analysis, the team discovered that these tiny voids significantly disrupt the electrical current, leading to their rapid expansion and merging into bands that promote instability growth.

The team achieved promising results by conducting high-resolution simulations that accurately reflected the distribution of voids observed in experiments, without the need for commonly used tuning parameters. **(PI: Edmund Yu)**

COOL FACT > This breakthrough emphasizes the importance of including voids in models and paves the way for improved predictive capabilities in modeling liners, ultimately advancing the field of nuclear fusion energy.



Simulations modeling internal voids in metallic liners show promising agreement with observed instabilities in experiment.

OPTIMIZING FLUID SIMULATIONS FOR BETTER PREDICTIONS

Developing new methods for simulating fluids ensures that the overall simulations accurately reflect the fundamental laws of physics. If these properties are ignored, the simulations can produce unrealistic results, which can lead to incorrect predictions.

To meet this need, the Sandia research team created a new approach called discrete exterior calculus (DEC) that successfully preserves all these important properties at the same time, something that previous methods struggled to do. These offer the possibility of enhanced robustness, reduced dissipation, and also could improve the coupling of hydrodynamics and electrodynamics in charged fluid models compared to existing approaches.

This work will lead to transformative increase in simulation capabilities for a range of DOE and Sandia missions, including plasma, compressible flow, geophysical fluid dynamics, aerodynamics, and combustion. **(PI: Chris Eldred)**

COOL FACT > Other researchers can now experiment with these new methods easily because of an open-source software library created by the Sandia LDRD team called *DecLib*.

ENHANCING FORECASTING ACCURACY FOR CARBON, WATER, AND ENERGY MANAGEMENT

Understanding the flow of carbon, water, and energy is imperative for maintaining weather and climate stability, enhancing agricultural productivity, and improving responses to extreme events. However, current forecasting methods lack the necessary data-driven capabilities, leading to significant variability and errors in predictions. Sandia researchers are employing self-supervised methods, akin to those used in advanced AI models, to enhance earth system modeling.

This innovative research aims to improve the accuracy of forecasting biogenic fluxes by developing specialized models that incorporate satellite data, weather patterns, vegetation types, and historical norms. By breaking down model uncertainty into its components, the team will create a more transparent and engaging workflow for predicting earth system behaviors.

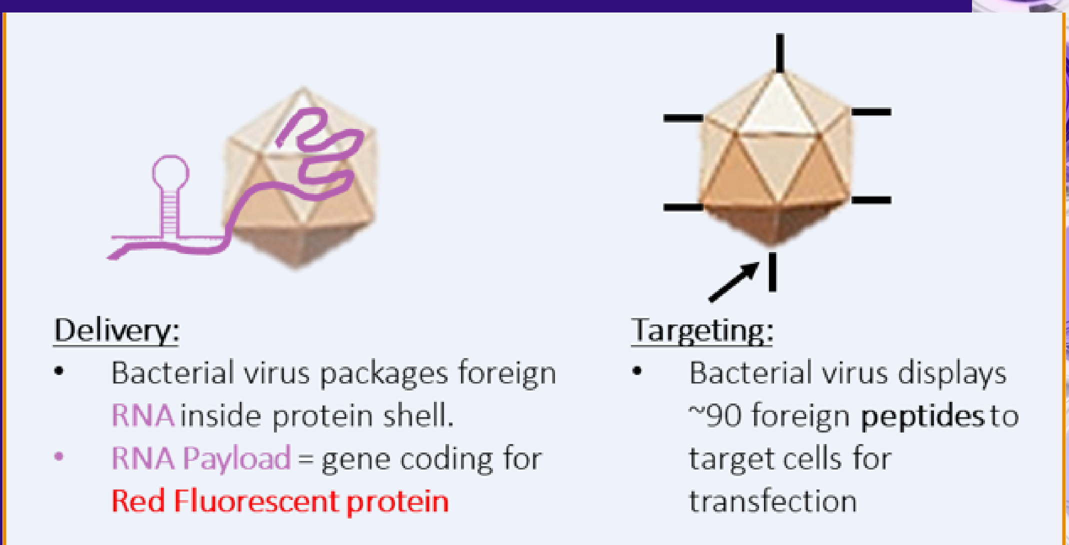
The goal is to establish a foundational model that accurately predicts ground-atmosphere fluxes of carbon, water, and energy. Sandia researchers will benchmark these models against other data-driven methods to ensure they meet or exceed current standards. The research outcomes will advance state-of-the-art earth system modeling capabilities, support the Energy Exascale Earth System Model, and inform decision-making related to environmental management. This work represents an important step forward in understanding and managing our planet's vital resources. **(PI: Daniel Krofcheck)**

ENGINEERING VIRUSES FOR TARGETED VACCINES AND COST-EFFECTIVE MEDICAL RESPONSES

The need for scalable, safer, and more precise RNA delivery technologies is imperative when it comes to tackling emerging health threats and enhancing biotechnology. Current RNA delivery systems, such as lipid nanoparticles and viral vectors, often encounter challenges like complex manufacturing processes, unwanted immune responses, and ineffective targeting of specific cells. To overcome these limitations, Sandia researchers designed a bacterial virus, specifically phage MS2, to selectively deliver RNA into mammalian cells.

This innovative RNA delivery platform has shown the ability to target specific cell types effectively. The implications of this technology are major, as it allows for the rapid and cost-effective production of novel tissue-specific vaccines, gene therapies, and countermeasures, even in resource-limited environments. The team's groundbreaking work has attracted funding from the Defense Threat Reduction Agency and received a Center for Integrated Nanotechnologies award, further inspiring a three-year LDRD initiative for FY2026. In addition, as subrecipients of the USDA Highly Pathogenic Avian Influenza Poultry Innovation Grand Challenge, they are collaborating with Barry Lutz (lead) from the University of Washington to utilize the technology developed in this project. **(PI: Jesse Cahill)**

COOL FACT > This research not only addresses current challenges in RNA delivery but also paves the way for advancements in medical treatments and public health responses.



A bacterial virus was engineered to be non-infectious and to deliver nucleic acid payload to cells.

CREATING SECURE QUANTUM COMMUNICATION CHANNELS WITH SILICON DEFECTS

Secure information transmission in the evolving landscape of quantum computing is imperative. LDRD researchers have developed a new method for building solid-state quantum networks using single photon-emitting defects in silicon to meet this need.

Quantum networks are essential for transmitting quantum information, typically through photons, between remote quantum processors. Sandia researchers have discovered that defects in silicon can serve as effective nodes for these networks. This is due to the abundance of known single photon emitters in silicon and the extensive investment in silicon fabrication technologies. The team utilized focused ion beam implantation to create these defects in silicon-on-insulator substrates. They also integrated the defects with established photonic integrated circuit architectures. By leveraging Sandia's expertise in silicon photonics and single ion implantation, the team established foundational techniques for precise defect implantation, entangling multiple emitters, and enhancing their properties to demonstrate quantum effects.

Sandia has refined its characterization capabilities and developed new defect formation methods. Initial quantum network devices have been tested, and the focus will now shift to integrating defects with silicon photonic devices and demonstrating single photon emission. This work has already led to crucial advancements, including the development of five new capabilities and three publications. Additionally, four postdoctoral researchers gained valuable experience, with two transitioning to staff positions. **(PI: Andy Mounce)**

DISCOVERING QUANTUM COMPUTING ERRORS USING INTERPRETABLE NEURAL NETWORKS

The pursuit of useful quantum computers requires learning and reducing errors and noise within these systems. As experimental quantum computing rapidly advances, the challenge intensifies; modern systems now feature hundreds of qubits, making traditional error characterization techniques harder to apply. Complex errors, such as crosstalk and non-Markovian effects, require thorough understanding, yet existing methods often fall short.

In response, Sandia researchers developed new kinds of neural networks that can characterize these complex errors in quantum computers at scale. The team proposed a novel approach where neural networks, equipped with interpretable parameters, identify the rates of different kinds of errors. This enables identification of errors in a system, facilitating the engineering of improved quantum computers.

Sandia demonstrated the effectiveness of these networks in learning coherent crosstalk and other complex errors in a simulated four-qubit system. The neural networks created in this project have the potential for further advancement, enabling modeling of large-scale quantum computing prototypes. The project has produced two papers that are being prepared for submission to journals and marks a significant advance in quantum computing research. **(PI: Timothy Proctor)**

COOL FACT > The created neural networks could help engineers better understand system limitations, design enhanced systems, and even automate their control.

PROJECT HIGHLIGHTS –

WORKFORCE DEVELOPMENT

Sandia's LDRD program enables principal investigators and research teams to collaborate with other national laboratories, academic institutions, and industry partners to revolutionize what is possible in science and engineering. This not only develops Sandia's workforce, but it also grows the nation's technical research capabilities overall, and even contributes to the economy. The highlights in this section are only a small subset of the impacts that have been made in 2025 through LDRD, but they give a glimpse of how significant the program is to the country and to the world.

PRESTIGIOUS FELLOWSHIPS, APPOINTMENTS AND MEMBERSHIPS

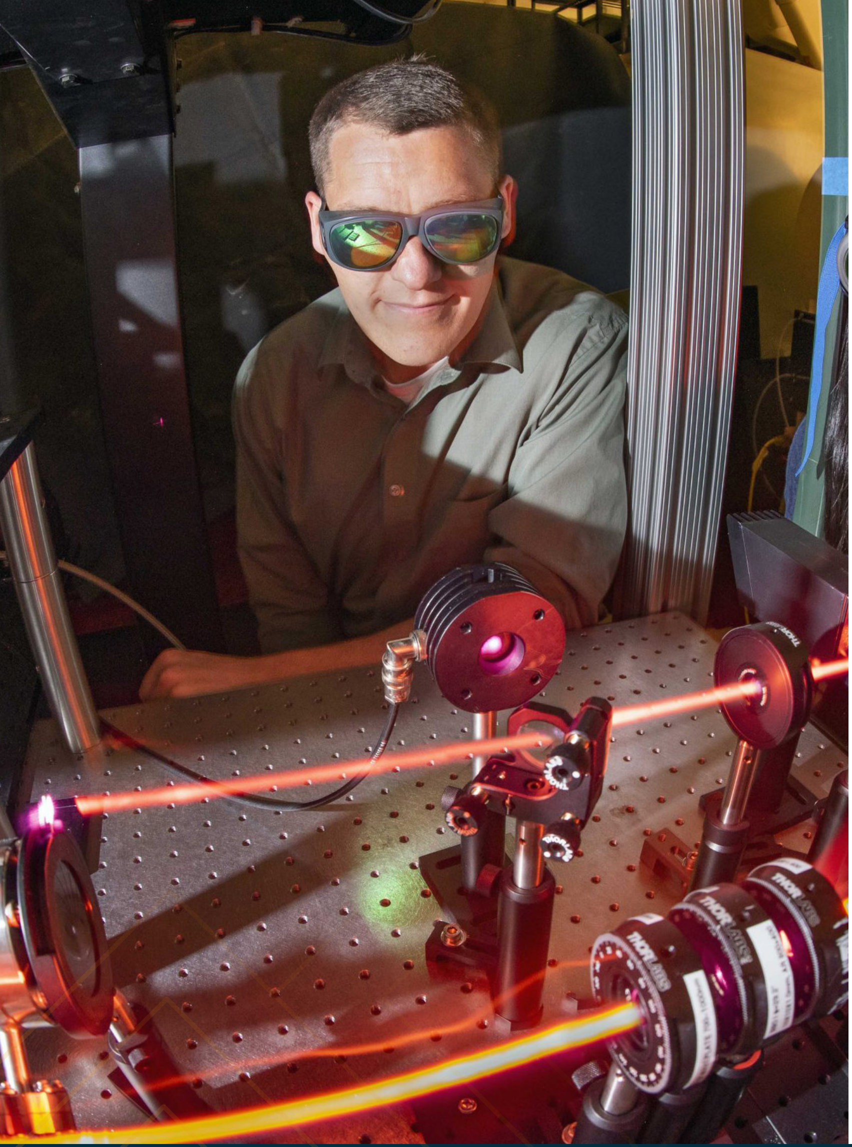
2025 R&D 100 RESEARCHER OF THE YEAR

Hongyou Fan hits the red carpet at the R&D 100 Awards in November 2025 before accepting his honor as Researcher of the Year. (Photo courtesy of Hongyou Fan)

Hongyou Fan was honored as the *R&D 100 Researcher of the Year* for 2025, a prestigious accolade that recognizes his leadership in R&D within scientific and innovative technologies. This award, often dubbed the "Oscars of Innovation," acknowledges significant advancements across various industries, with winners evaluated based on their previous achievements, mentorship, and outreach efforts. With over 25 years at Sandia, Fan has made substantial contributions in material science, chemical science, and nanoscience, particularly in sustainable energy solutions. He currently manages the Geomechanics and Geochemistry Department and oversees critical programs, including the establishment of Sandia's critical minerals program aimed at building a domestic supply chain for essential resources.

Fan's journey at Sandia began as a postdoctoral researcher in 1997, and his commitment has led to numerous accolades, including the Career Achievement Award from the Society of Asian Scientists and Engineers and his recent election as a Fellow by the National Academy of Inventors. His research focuses on the molecular behavior of materials under extreme conditions, contributing to breakthroughs in energy storage solutions and the recovery of critical minerals like lithium. Beyond his research, Fan is dedicated to mentoring young scientists, emphasizing the importance of persistence in scientific endeavors. His recognition as the R&D 100 Researcher of the Year not only highlights his personal achievements but also reflects Sandia's commitment to innovation and addressing pressing societal challenges.

Fan has acted as principal investigator on eight LDRD projects during his distinguished career at Sandia.



AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS

Daniel Richardson was elected as an Associate Fellow of the American Institute of Aeronautics and Astronautics. Richardson conducts applied research for nuclear deterrence and national security missions in the Experimental Thermal and Fluid Sciences Department at Sandia and is now counted among the distinguished group of professionals who have performed extraordinary work and advanced the state of science and technology in aeronautics and astronautics. His leadership on LDRD projects has contributed to cutting-edge work at Sandia that enhances the scientific basis for energy security and national security and defense applications.

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS

Edward I Cole, a Fellow at Sandia working on national security systems, has a distinguished history across the DOE Complex and has led Sandia LDRD projects going back to 2009. Cole has research interests in the development and improvement of non-destructive integrated circuit analysis tools, with emphasis on electron and optical beam techniques and has published frequently in the field of failure analysis. He holds 15 U.S. patents, has won two R&D 100 Awards, and was honored as IEEE Fellow for leadership in microelectronics defect localization equipment, science, and techniques.

SELECTED NEWLY PROMOTED SENIOR SCIENTIST HIGHLIGHTS

George Bachand is a pioneering bioengineer known for his innovative work at the intersection of bioscience and nanotechnology. His research at Sandia has primarily focused on understanding fundamental mechanisms of biomolecular processes, aiming to of translate these insights into practical solutions for contemporary engineering challenges. He has a broad publication record encompassing topics such as biomolecular and biotic/abiotic hybrid materials assembly, enzymatic "living materials," biosensing and detection, and microbial survival in extreme environments. Through his LDRD projects, Bachand's significant contributions have helped advance the fields of bioscience, materials science, and nanotechnology, while establishing new capabilities to address key national security challenges.

> *"LDRD plays an essential role at the Labs in advancing fundamental science and developing enabling technologies that address and anticipate national security needs. The program has enabled me to think creatively, cultivate innovative research ideas and approaches, and ultimately carry out cutting-edge research and development in support of Sandia's missions. Several of these projects began as seedling efforts that have since evolved into successful long-term initiatives, yielding impacts that have far exceeded our original expectations."*

Catherine (Cathy) Branda is a program manager at Sandia in Livermore, CA, overseeing the Chemical, Biological, Radiological, and Nuclear Deterrence (CBRN-D) portfolio, which is funded by various U.S. government departments.

Before her current role, she held several managerial positions at Sandia, including senior manager of the Radiation Signatures and Detection Science & Technology Group and the Applied Biosciences and Engineering Group, as well as manager of the Systems Biology Department. She has been instrumental in establishing Sandia's capabilities in genomics and bioinformatics and developing CBRN-D programs since joining the Labs in 2005. Initially, Branda focused on viral infection mechanisms and methodologies for virus detection.

"The Sandia LDRD program has been crucial to our success with U.S. government (USG) sponsors in CBRN-D. LDRD has allowed myself, and staff I've worked closely with, to pursue high risk but creative and potentially transformative research. In doing so, we have been able to, on multiple occasions, develop knowledge and early stage technologies that our USG sponsors are interested in advancing given the provided proof of principle data. Sandia is seen as a leader across the USG in several areas of CBRN-D, and this is a result of Sandia LDRD investment."

Peter Marleau has ~20 years of radiation and nuclear-detection experience. He earned a PhD in experimental high-energy particle physics from the University of California Davis in 2006, and has developed several fast-neutron detection, imaging, and spectroscopic systems for applications ranging from nuclear arms control treaty verification to nuclear-emergency response to homeland security and nuclear nonproliferation. He has led several nuclear-arms-control R&D projects and multinational working groups; most recently serving as the Science Integration Lead for the PROACTIVE arms control venture.

"LDRD support has been invaluable in the arc of my career here at Sandia. Several LDRD projects have seeded low-Technical Readiness Level R&D that became entire multi-year/decade research thrusts in Radiation and Nuclear Detection Systems. Early investment in aperture-based fast neutron imaging systems, for example, has led to many multi-million dollar projects in nuclear non-proliferation and nuclear arms control. Most recently, an LDRD to investigate neutron activation in nuclear disposition streams has led to a new project for FY26-FY28. Without LDRD, it is difficult to find support for the wild and risky ideas that often herald Sandia's leadership in innovative new fields."

EARLY CAREER AWARDS AND HONORS

Association of Materials Protection and Performance Early Career Excellence Award

Ryan Katona is a 2026 award recipient for the Early Career Excellence Award from the Association of Materials Protection and Performance. The award recognizes individuals that worked in academia, research, industry, or government and had excellent contributions and exceptional promise in materials protection and performance. The award acknowledges the creativity and innovation in developing or improving a method, process, apparatus, or equipment facilitating control of degradation or makes it less costly. Katona is currently leading the LDRD project, "LEMMs: Long-term, Electrochemical Materials Degradation Models."

National Lab Research SLAM Award

Michael Leveille, a postdoctoral researcher at Sandia, impressed the audience at the National Lab Research SLAM on March 5, 2025, where he competed against 16 other early-career researchers. In just three minutes and with a single slide, he presented his innovative work titled "Blend Green and Flow Clean: Hydrogen in Gas Pipelines," ultimately winning the *top spot in the Environment category*.

His research focuses on introducing hydrogen fuel into existing natural gas pipelines, which could help extend the U.S. domestic energy supply by utilizing hydrogen produced from water splitting. Leveille studies the material compatibility of gas lines to ensure their safe and reliable operation when hydrogen is introduced, examining the microscopic structure of plastic polymers exposed to hydrogen and natural gas blends, and so far, he has found no signs of damage. Leveille described the National Lab Research SLAM as an enjoyable event that highlights the diverse research conducted at national laboratories and encourages others interested in science communication to participate.

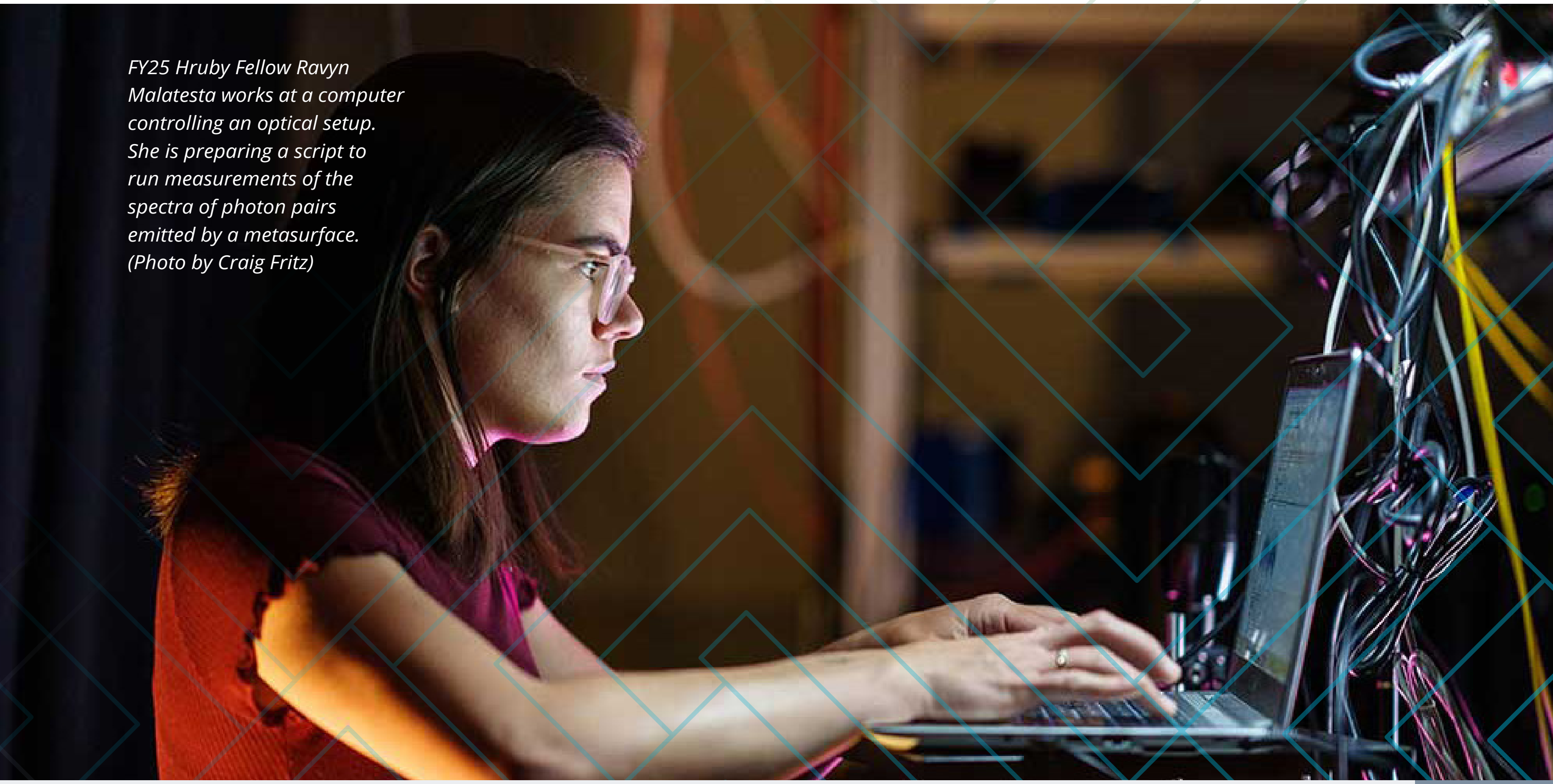
Michael Leveille's experience at the National Lab Research SLAM highlights the importance of pushing boundaries in science communication. (Photo by Blaise Douros)

FY25 HRUBY AND TRUMAN POSTDOCTORAL FELLOWSHIPS

Distinguished Level Fellowships are three-year appointments allowing outstanding researchers to advance Sandia's national security mission, conduct in-depth work at state-of-the-art facilities and learn from recognized engineers and scientists. The 2025 Hruby Fellows are **Ravyn Malatesta** and **Olivia Krohn**, and the 2025 Truman Fellows are **Dan Herman** and **Sam Peana**.

Ravyn Malatesta is a recipient of the Jill Hruby Postdoctoral Fellowship, which she was attracted to for its unique blend of intellectual freedom and the opportunity to cultivate essential leadership skills in a supportive research environment. Initially starting her academic journey in chemistry, Malatesta's interest in quantum mechanics led her to transition into physics, where she now focuses on the intricate relationship between light and matter. Her current research involves exploring how entanglement and other quantum properties of photons interact with materials, particularly using advanced metasurfaces to generate and control hyperentangled photon states. This work aims to enhance the information-carrying capacity of entangled photon signals, which could have significant implications for quantum communication and applications in low signal-to-noise environments.

In addition to her research, Malatesta is committed to improving science communication and has participated in leadership initiatives during her doctoral program to promote community building and effective communication in science. She believes that effective scientific communication is often overlooked in traditional scientific education and aims to advocate for improved standards in this area. As she embarks on her career through the Jill Hruby Fellowship, Malatesta exemplifies the potential of integrating scientific research with leadership, paving the way for advancements in both research and communication within the scientific community. She is currently the principal investigator of an LDRD project at Sandia.



FY25 Hruby Fellow Ravyn Malatesta works at a computer controlling an optical setup. She is preparing a script to run measurements of the spectra of photon pairs emitted by a metasurface. (Photo by Craig Fritz)

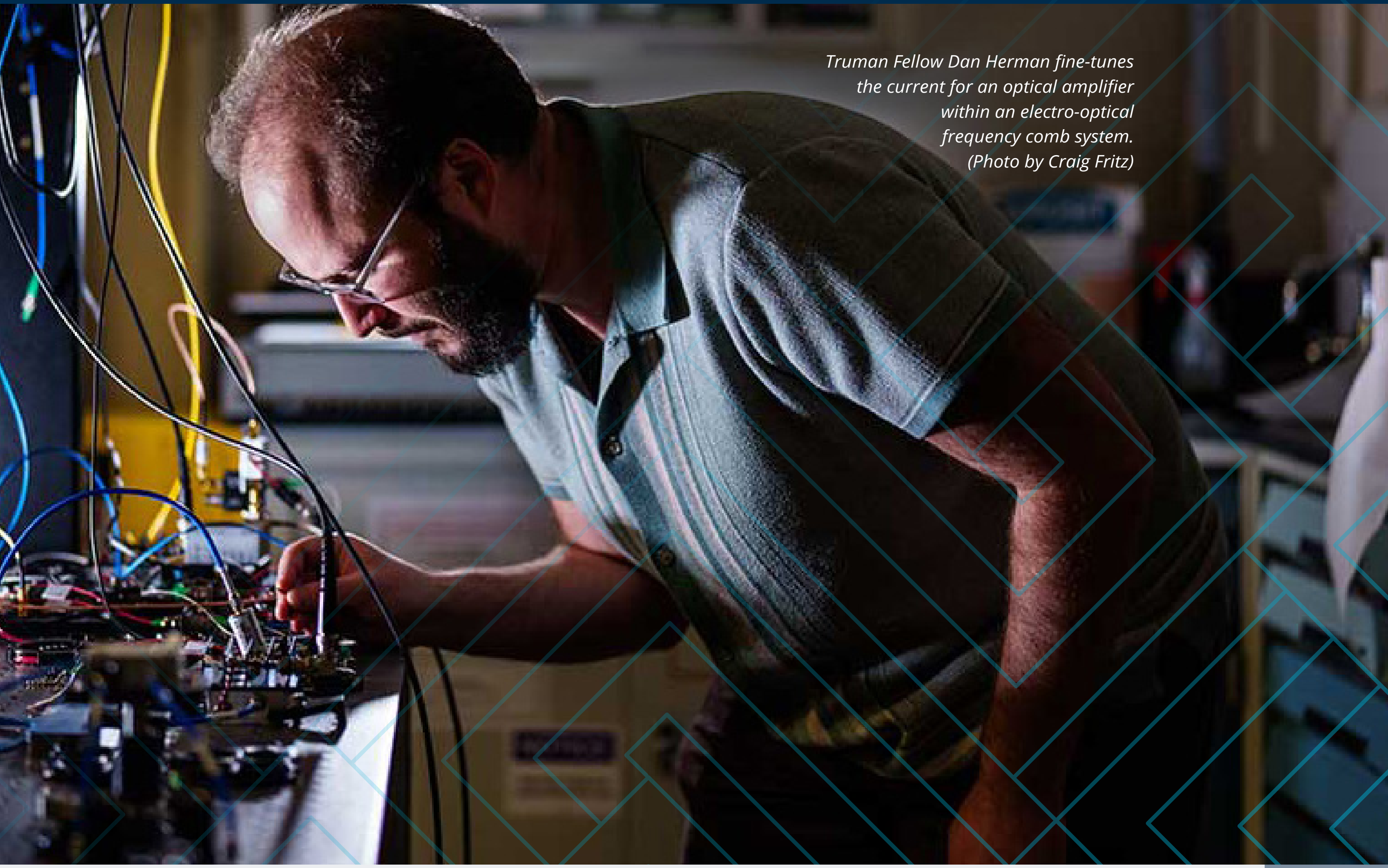
Hruby Fellow Olivia Krohn assembles a chamber suited for high vacuum to study quantum-state-controlled molecular collisions in an isolated, gas-phase environment. In the construction phase, she is using a wrench to assemble the steel vacuum chamber. (Photo by Randy Wong)

Olivia Krohn, a Jill Hruby Fellow, is conducting groundbreaking research on quantum-state-controlled molecular collisions in a high vacuum environment. Her work focuses on understanding molecular interactions at low energies, which is crucial for advancing scientific knowledge and developing innovative technologies. By studying how molecules collide and redistribute energy, Krohn aims to improve theoretical predictions about molecular behavior, particularly for larger or more energetic molecules. Her experimental approach utilizes advanced techniques, including lasers, to trace energy flow during chemical processes and assess the velocity of molecules post-collision. Krohn's team has developed a novel method to narrow velocity spreads using lasers, allowing for better control of molecular rotation and vibration, which enhances their collision studies.

Krohn was motivated to pursue the Jill Hruby Fellowship for its unique opportunity to engage in cutting-edge research within a collaborative community. She values the resources and mentorship provided by the fellowship, which aligns with her passion for exploring molecular interactions. The implications of her research extend beyond the laboratory, with potential applications in improving precision models for high-energy environments, interpreting light emissions in space, and enhancing energy efficiency in various processes. Ultimately, Krohn aims to deepen the understanding of molecular interactions to enable precise control over chemical reactions, paving the way for significant advancements in the field.

Dan Herman, a Truman Fellow, is focused on advancing the field of optical frequency combs—special lasers that emit a spectrum of colors in ultra-short optical pulses. These combs bridge high optical frequencies with lower radio frequencies and have applications in various areas, including trace gas sensing, optical communications, and quantum sensing. Herman's research aims to develop frequency combs into remote gas sensors to better understand ecological processes and enhance high-speed spectroscopy in laboratory settings. His previous work at the National Institute of Standards and Technology involved collaborating with agronomists to create a method for accurately measuring gas emissions from cattle farms, which has improved the understanding of methane and ammonia flux in agriculture.

Herman's motivation for pursuing the Truman Fellowship stems from his desire to connect advanced scientific research with real-world applications that benefit society. He believes that scientific advancements should prioritize public health and quality of life, and he feels fortunate to work in a field that allows him to explore the fundamental nature of matter and light while applying these insights for societal good. The fellowship provides him with a platform to collaborate with like-minded researchers, enabling him to tackle complex challenges and drive meaningful change in addressing pressing environmental and health issues. Through his work, Herman aims to amplify the impact of his research on ecological processes and public health, reinforcing his commitment to making a difference through science. He has led two LDRD projects while at Sandia with one ongoing.



Truman Fellow Dan Herman fine-tunes the current for an optical amplifier within an electro-optical frequency comb system. (Photo by Craig Fritz)

Truman Fellow Sam Peana constructs a laser enclosure for a confocal time-correlated single photon counting microscope. This microscope will be used to measure the quantum properties of single photon emitters that will be produced in the Microsystems Engineering, Science and Applications facility. (Photo by Craig Fritz)

Sam Peana, a Truman Fellow, is currently working in the field of quantum photonics, focusing on the construction of a laser enclosure for a confocal time-correlated single photon counting microscope. This microscope will be instrumental in measuring the quantum properties of single photon emitters produced at the Microsystems Engineering, Science and Applications facility. Peana's journey into technology began at a young age, sparked by his curiosity about computers and programming, which led him to explore various engineering projects, including a music synthesizer and a simple robot. His passion for science and engineering continues to guide his work today.

During his doctoral studies, Peana was part of a team that discovered a new type of single-photon emitter in silicon nitride-oxide, which has significant implications for quantum optical applications such as computing, networking, and sensing. He developed a method to produce these emitters at specific locations using standard semiconductor manufacturing techniques, paving the way for large-scale production of quantum optical devices akin to microchips. While many quantum devices have shown promise in lab settings, Peana emphasizes the importance of transitioning to large-scale manufacturing to make these technologies accessible to everyday users. He encourages aspiring scientists and engineers to embrace perseverance and audacity, advising them to take risks and not limit themselves in their pursuits. Peana has led two LDRD projects while at Sandia, and one of those projects is ongoing.

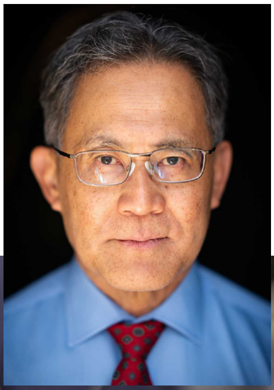
PROFESSIONAL SOCIETY AND CONFERENCE AWARDS

Society of Asian Scientists and Engineers Career Achievement Award

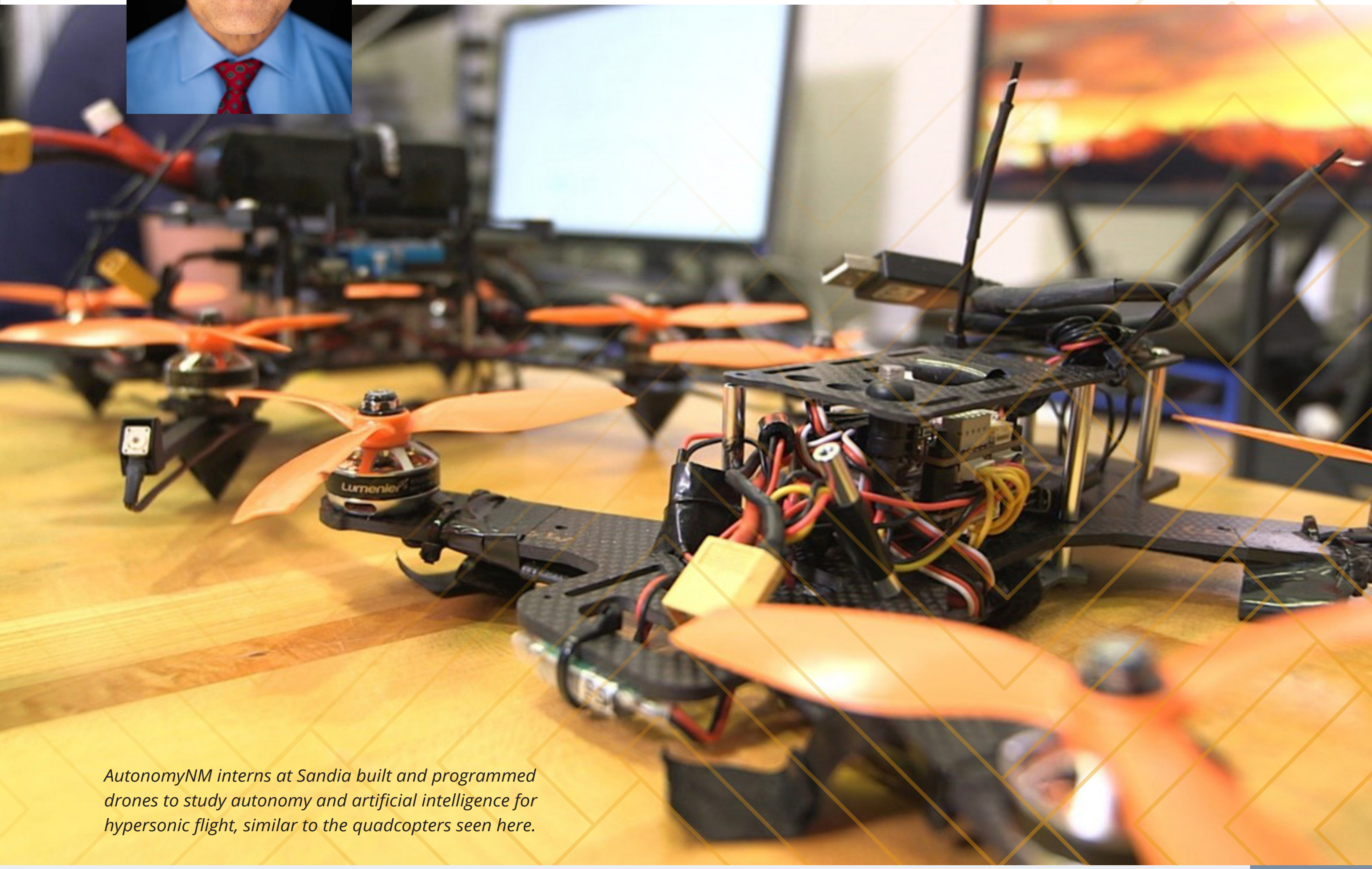
Anton Sumali, a mechanical engineer and manager at Sandia, received the *Society of Asian Scientists and Engineers Career Achievement Award*. He started his career in 1987 as a control systems engineer in Southeast Asia's petroleum industry after earning a Bachelor of Science in mechanical engineering from Indonesia's Bandung Institute of Technology and later obtaining advanced degrees in mechanical engineering from Virginia Tech.

His passion for learning led him to become an assistant professor at Purdue University. The September 11 attacks motivated him to seek opportunities at Sandia Labs, where he initially worked in structural dynamics before joining full-time in 2002, focusing on micro-electromechanical systems.

In the following decade, Sumali integrated his engineering and management expertise with his enthusiasm for teaching and mentoring, leading to the creation of the *AutonomyNM* Intern Institute at Sandia. This innovation hub supports advanced flight and space systems, emphasizing AI and reinforcement learning, while fostering new talent from top universities to apply AI in national security. Sumali has led two LDRD projects during his career at Sandia.

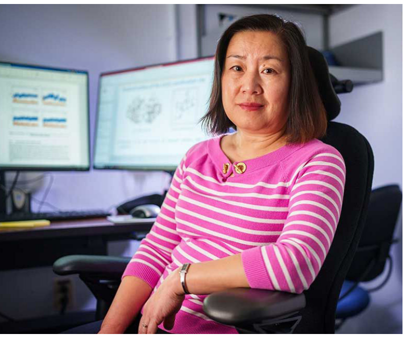


(Photo by Craig Fritz)



AutonomyNM interns at Sandia built and programmed drones to study autonomy and artificial intelligence for hypersonic flight, similar to the quadcopters seen here.

Society of Asian Scientists and Engineers Career Achievement Award



Sandia engineer Dongmei Ye was recently awarded the prestigious Society of Asian Scientists and Engineers Career Achievement Award, celebrating technical accomplishments and advancements in the fields of science, engineering and technology. (Photo by Craig Fritz)

Dongmei Ye has dedicated her 23-year career to enhancing public safety through her significant contributions to research and the nuclear security enterprise. Her work in supporting Sandia's nuclear weapons reliability mission has had a profound impact on maintaining the health of the stockpile and ensuring the effectiveness of the national nuclear deterrent. Recently, she was honored with the Society of Asian Scientists and Engineers (SASE) Career Achievement Award, which recognizes exemplary leadership and technical accomplishments in science, engineering, and technology, as well as volunteerism within the SASE community.

In addition to her role as a weapons reliability engineer, Ye has developed bioengineering capabilities and led research teams addressing challenges in biodefense and public health. Her notable achievements include creating a synthesis system for potential bioagents, developing countermeasures against nerve agents, and advancing therapeutics for Crohn's disease. During the COVID-19 pandemic, she played a crucial role in Sandia's diagnostic testing lab, facilitating thousands of tests to ensure the continuity of national security work. Ye is also a recipient of numerous awards, a prolific speaker, and actively involved in mentoring aspiring talents in various fields, including K-12 education and cultural outreach. She credits Sandia for providing an environment that fosters exploration and collaboration, enabling her and her colleagues to excel in their work. Ye has led three LDRD projects.

Federal Laboratory Consortium for Technology Transfer Outstanding Researcher

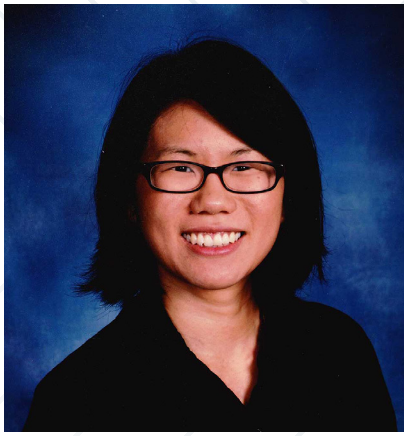
Scientist Hongyou Fan has been named Outstanding Researcher by the Federal Laboratory Consortium for his innovation and work in technology transfer. (Photo by Jennifer Plante)

Hongyou Fan was recognized for his innovative contributions and leadership in translating scientific discoveries into market-ready technologies by the Federal Laboratory Consortium for Technology Transfer. With a 25-year career at Sandia, Fan has been acknowledged as a "serial innovator" for his work in materials manufacturing, nanoelectronics, and critical materials supply chains.

One of Fan's notable achievements is the development of Disinfectant 2.0 during the COVID-19 pandemic, a long-lasting disinfectant that effectively kills viruses, bacteria, and fungi. This product is based on his research involving highly efficient porphyrin nanoparticle photosensitizers, which release substances that eliminate disease cells when triggered by light. Fan's efforts in technology transfer facilitated the commercialization of this product by Lunano LLC. He has received multiple awards for his contributions, including six Federal Laboratory Consortium awards and eight R&D 100 Awards, and he holds 21 patents with three pending.

Society of Asian Scientists and Engineers Promising Professional Achievement Award

Esther Woon Lyn John, a computer engineer at Sandia, was awarded the Society of *Asian Scientists and Engineers Promising Professional Achievement Award* for her impactful work in data science and analytics. Over the past decade, she has held significant roles at Cornell University, the World Bank, and Sandia Labs, where she has developed national security tools such as anomaly threat mapping for body scanners and logistics models for nuclear deterrence programs.



(Photo courtesy of Esther Woon Lyn John)

John's academic journey began with a focus on mathematics, leading to a PhD in transportation systems engineering with an emphasis on transport economics. Her interest in computer science was sparked during an undergraduate course, which directed her towards modeling and simulation. Throughout her career, she has leveraged her interdisciplinary background to tackle complex problems in transportation and security.

At Sandia, John creates simulation-based logistics models and data-driven analytics for various agencies, including the Transportation Security Administration and the DOE. She emphasizes the importance of tailored approaches for different projects and enjoys exploring real-world problems through modeling and simulation.

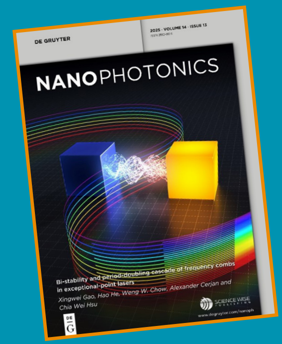
In addition to her professional achievements, John is dedicated to mentoring local middle and high school students, as well as Sandia interns and staff, highlighting her commitment to education and collaboration. The award recognizes her significant contributions to her field and her ongoing commitment to professional growth and advancement. John recently led an LDRD project.

Royal Society of Chemistry and American Chemical Society Fellow

Anastasia Ilgen was named as a Fellow of the Royal Society of Chemistry (RSC) in June 2025 and a Fellow of the American Chemical Society (ACS) in August 2025. Her RCS Fellowship is conferred on individuals who have demonstrated significant achievements in research, education, or professional practice, and who have made a notable impact on the advancement of chemical sciences both nationally and internationally. One of the highlighted accomplishments in the application was the research in chemo-mechanics, which is supported by her current LDRD, "Nano-Earth: Layered Materials as Nano-scale Analogs for Subsurface Systems."

Ilgen's ACS Fellowship is a society-wide recognition for her impactful research advancing molecular understanding of interfacial geochemistry in nanopores/fractures, enabling clean water, sustainable energy, and critical materials applications. She was also recognized for strong, inclusive leadership in the ACS Geochemistry Division, Committee on Environment and Sustainability, and outreach including the College-to-Career website.

Matthew Witman and his LDRD project team had their work highlighted on the cover of *Digital Discovery*. The work highlighted in "MatFold: Systematic Insights into Materials Discovery Models' Performance Through Standardized Cross-validation Protocols" was done in collaboration with Northeastern University. Witman has led two LDRD projects with one ongoing.



Alexander Cerjan and his team had their work highlighted on the cover of *Nanophotonics*. Their article, "Bi-stability and Period-doubling Cascade of Frequency Combs in Exceptional-point Lasers" was supported through an LDRD project. Cerjan has led six LDRDs at Sandia with one ongoing.

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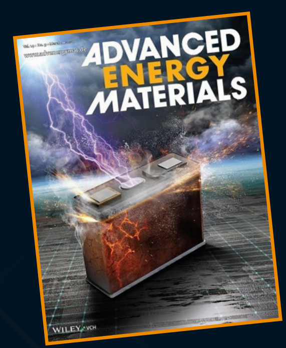
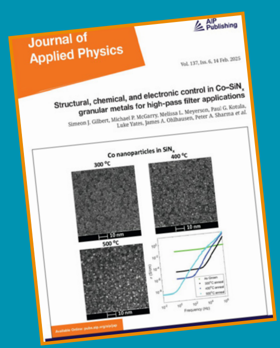
Adam Cook and his LDRD team were highlighted on the cover of *Advanced Engineering Materials* in association with their article "Monodomain Liquid-Crystal Elastomer Lattices for Broad Strain-Rate Mechanical Damping." Cook has led five LDRD projects at Sandia.



Remi Dingreville and his team had their LDRD article, "Harnessing Electrochemical-Mechanical Couplings to Improve the Reliability of Solid-State Batteries" on the cover of *Advanced Energy Materials*. Dingreville has led 10 LDRD projects while at Sandia.



Nicki Bennett and her team had their article, "Modeled Sensitivity of Multi-MA Accelerator Performance to Electrode Contaminant Inventory," recognized as an Editor's Pick as part of a Fusion Energy Collection. This work was supported through the Assured Survivability & Agility LDRD Mission Campaign. Bennett has acted as PI on six LDRDs.

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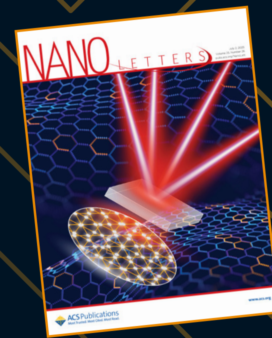
Dorina Sava Gallis and her team published an LDRD article on "High-Entropy Metal-Organic Frameworks (HEMOFs): A New Frontier in Materials Design for CO_2 Utilization" in *Advanced Materials*, and were highlighted on the cover of the journal.

Another project led by Sava Gallis resulted in a cover on *Chemical Communications* for their article, "Tuning the Pore Chemistry of Zr-MOFs for Efficient Metal Ion Capture from Complex Streams." Sava Gallis has led eight LDRD projects at Sandia.



Jeremy Wright and his team published "Lithography-Defined Semiconductor Moirés with Anomalous In-Gap Quantum Hall States" in *Nano Letters* and were highlighted on the journal cover. Wright has led five LDRD projects, including the ongoing Photonic Enabled Tera-scale InfraRed Imager LDRD Grand Challenge.

Laura Biedermann and her LDRD teams published the article "Structural, Chemical, and Electronic Control in Co-SiN$_x$ Granular Metals for High-pass Filter Applications," in *Journal of Applied Physics*, and it was highlighted on the cover. This publication was supported by discoveries from two LDRD projects. Biedermann has led 11 LDRDs at Sandia with one ongoing.

Amun Jarzembski and his LDRD team published "Wide-Field Bond Quality Evaluation Using Frequency Domain Thermoreflectance with Deep Neural Network Feature Reconstruction" in *Advanced Materials Interfaces* and landed on the cover. Jarzembski has acted as PI on three LDRD projects at Sandia.

Raktim Sarma and his LDRD team published "Imaging Photonic Resonances Within an All Dielectric Metasurface via Photoelectron Emission Microscopy" and were selected for the cover of *Advanced Photonics Research*. Sarma has led two LDRD projects with one ongoing.

Umakant Mishra received the 2025 Editor's Citation of Excellence Award from *Soil Science Society of America Journal*. Mishra is currently leading the project, "Machine Learning to Represent Environmental Feedback of Soil Microbial Community in Earth System Models to Investigate its Implication for Dryland Soil Carbon Dynamics." Mishra has led three LDRD projects for Sandia with one ongoing.