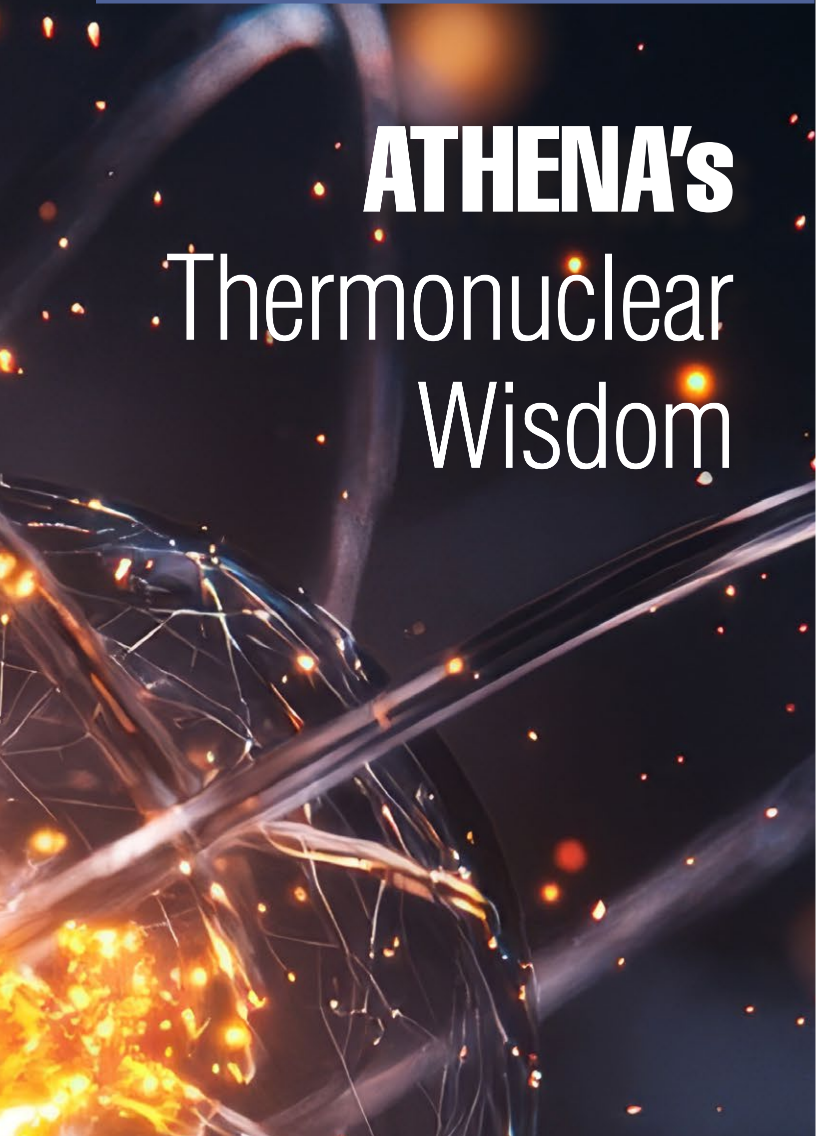
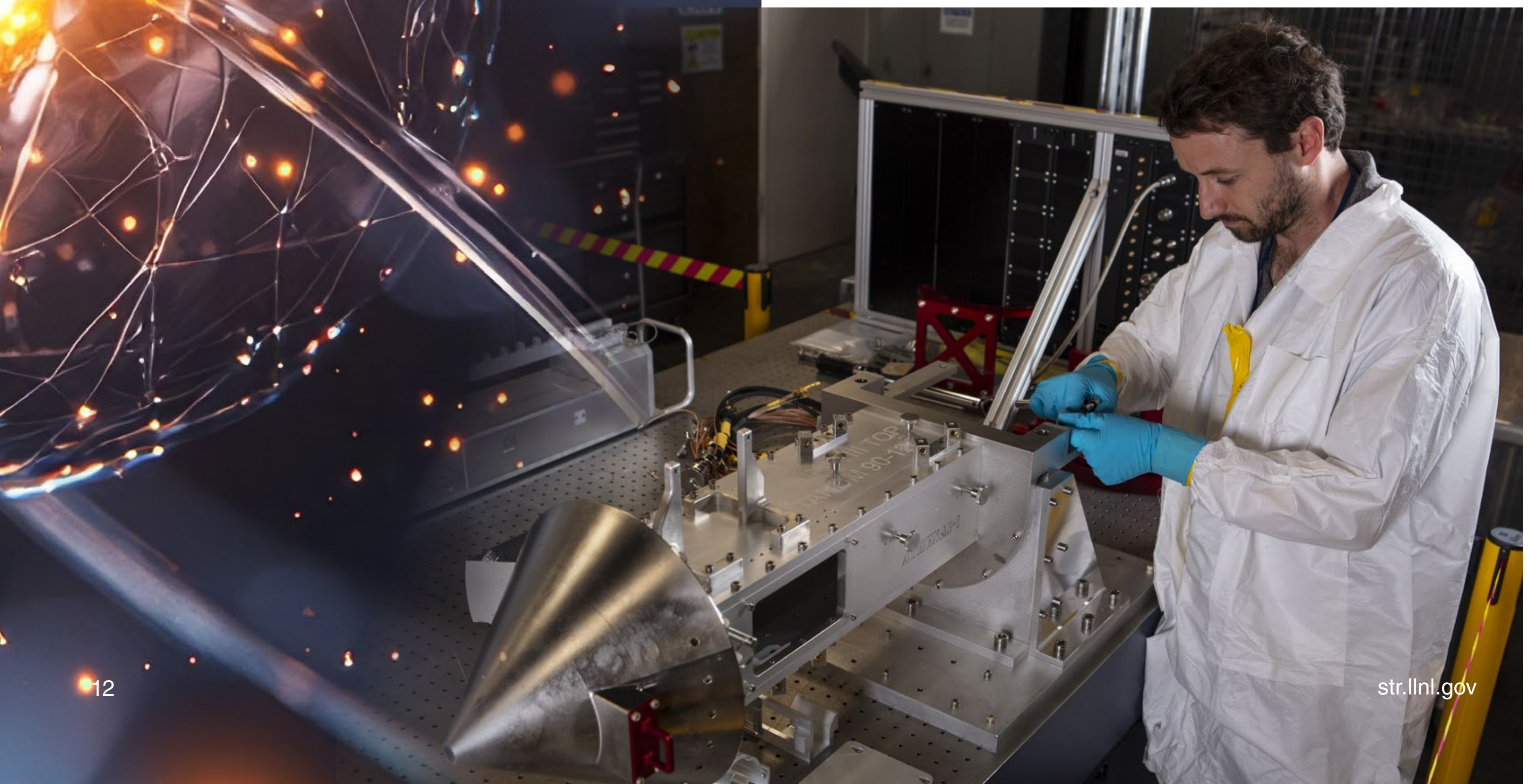


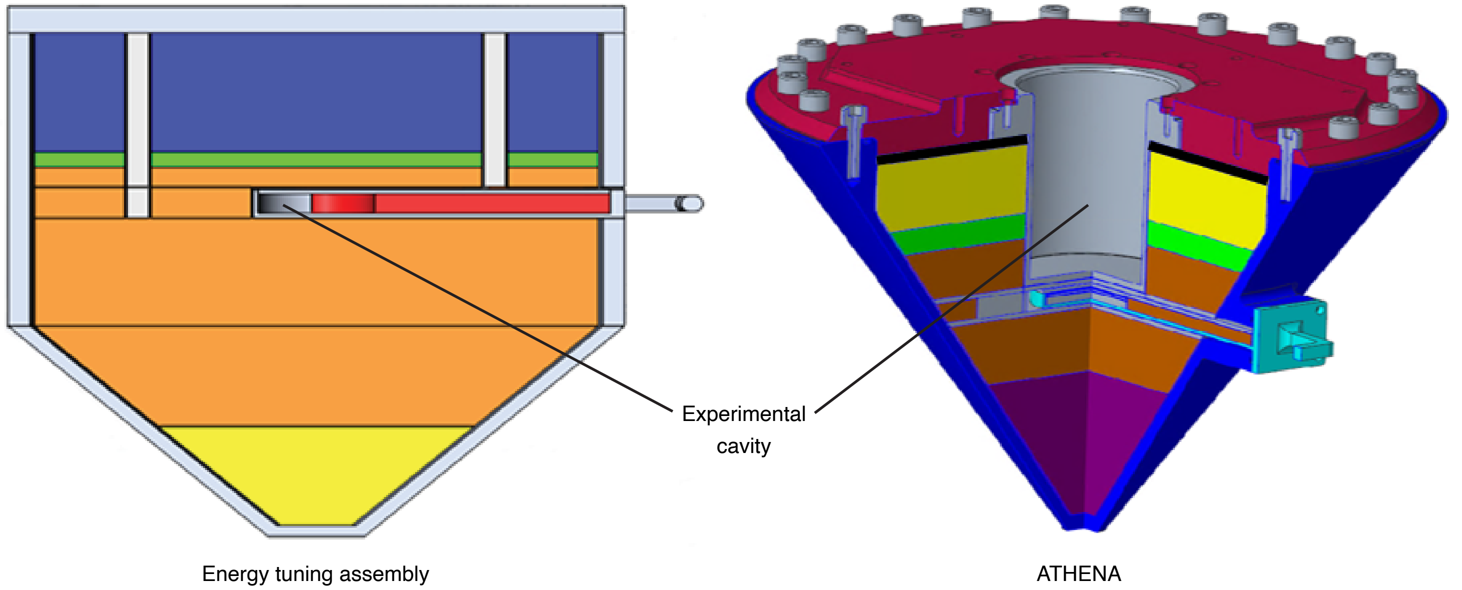
ATHENA's Thermonuclear Wisdom

Lawrence Livermore's research efforts over the last several decades have evolved in tandem with ever-changing national security threats and stockpile stewardship needs. When nuclear weapons testing ended in the 1990s, the nuclear forensic community had to find alternate ways to drive innovation in areas of materials science, radiation survivability, analytical measurements, and assessment methodologies, as well as test and improve operational capabilities, especially after the September 11, 2001, terrorist attack. With real-world postdetonation environments unavailable, researchers shifted focus to simulated postdetonation environments.

The National Ignition Facility (NIF) is the world's most powerful source of short-pulse neutrons, which it generates through the fusion of deuterium (D)—a stable isotope of hydrogen with one neutron in its nucleus—and tritium (T), a radioactive isotope of hydrogen with two neutrons. The neutrons resulting from this D–T fusion reaction produce a unique energy spectrum dominated by 14 megaelectronvolt (MeV) neutrons. The same fusion reaction occurs in a thermonuclear weapon detonation and results in 14 MeV neutrons. However, nuclear weapons also produce fission reactions with uranium and plutonium that result in fission spectrum neutrons (neutrons containing about 10 percent of the energy of NIF neutrons) that are distributed across a broad energy spectrum, not limited to 14 MeV.

Livermore researcher Eric Stern works with the ATHENA (Advanced Technology High-Energy NIF Array) moderator assembly in the laboratory. (Image by Jason Laurea.)





Researchers designed the energy tuning assembly (left) to generate a deuterium–tritium and fission neutron spectrum for irradiation of uranium in the small experimental cavity in the center. ATHENA (right) achieves the same spectra-generating capability but contains an extended experimental platform suitable for irradiating microelectronics. Different colored blocks in each platform represent different materials and do not correspond across the two platforms.

NIF, therefore, provides energy intensities well suited for simulating thermonuclear weapon detonations, but the neutrons NIF produces do not match the full spectrum of neutrons found in thermonuclear explosions. To address this discrepancy, the University of California, Berkeley (UCB), Lawrence Livermore, and the Air Force Institute of Technology (AFIT) launched a collaboration to develop a neutron energy moderator assembly that can downscatter NIF neutrons into a spectrum closer to that of a thermonuclear detonation and enable the production of more accurate irradiated materials samples. The collaboration began with an experimental system called an energy tuning assembly (ETA) and has since evolved into the new ATHENA (Advanced Technology High-Energy NIF Array) platform at Lawrence Livermore. "Our first design for ETA was based around the concept that if we could make the neutrons look more representative of a nuclear weapon environment, then we could automatically produce a complete representative fission product spectrum," says Lieutenant Colonel James Bevins, who developed the ETA as a doctorate student at UCB and now serves as an adjunct associate professor of Nuclear Engineering at AFIT. "At the time of ETA's development, NIF was pushing towards intensities that would allow us to produce meaningful quantities of important isotopes from the fission product distribution."

The ETA device, a cone-shaped metal moderator, is composed of an aluminum shell and includes lead, bismuth, tungsten, praseodymium, silicon, boron carbide, and a small central chamber that holds samples. As the NIF neutron impulse passes through ETA, the moderator assembly downscatters the neutrons to the desired spectrum and irradiates the samples within. Bevins characterized the initial ETA design with the help of Livermore staff physicist Darren Bleuel at Lawrence Berkeley National Laboratory's 88-Inch Cyclotron facility, where they exposed activation foils of zirconium, indium, aluminum, gold, and other elements to a neutron beam with and without the ETA to characterize the spectra generated under both conditions.

In comparing experimental test results measuring the irradiated activation foils to predictions of ETA's performance using the Monte Carlo Neutral-Particle code, the team found significant agreement. This outcome indicated that ETA was a viable tool to generate samples with the same properties as thermonuclear explosion debris. "ETA worked fantastically for its original application, which was to produce representative fission products from a highly enriched uranium sample that could be used for synthetic debris creation," says Bevins. ETA thus set the stage for neutron spectral tuning, a critical capability as needs evolved.

The Birth of ATHENA

As national security priorities shifted from terrorism to global power competition, the survivability of nuclear weapons—and the systems that must operate in nuclear weapons environments—became more important, expanding the need for a platform such as ETA beyond synthetic debris creation. Bevins and AFIT graduate student Major Nicholas Quartemont iterated on ETA to develop the next generation, suitable for testing systems in surrogate nuclear weapons environments: ATHENA.

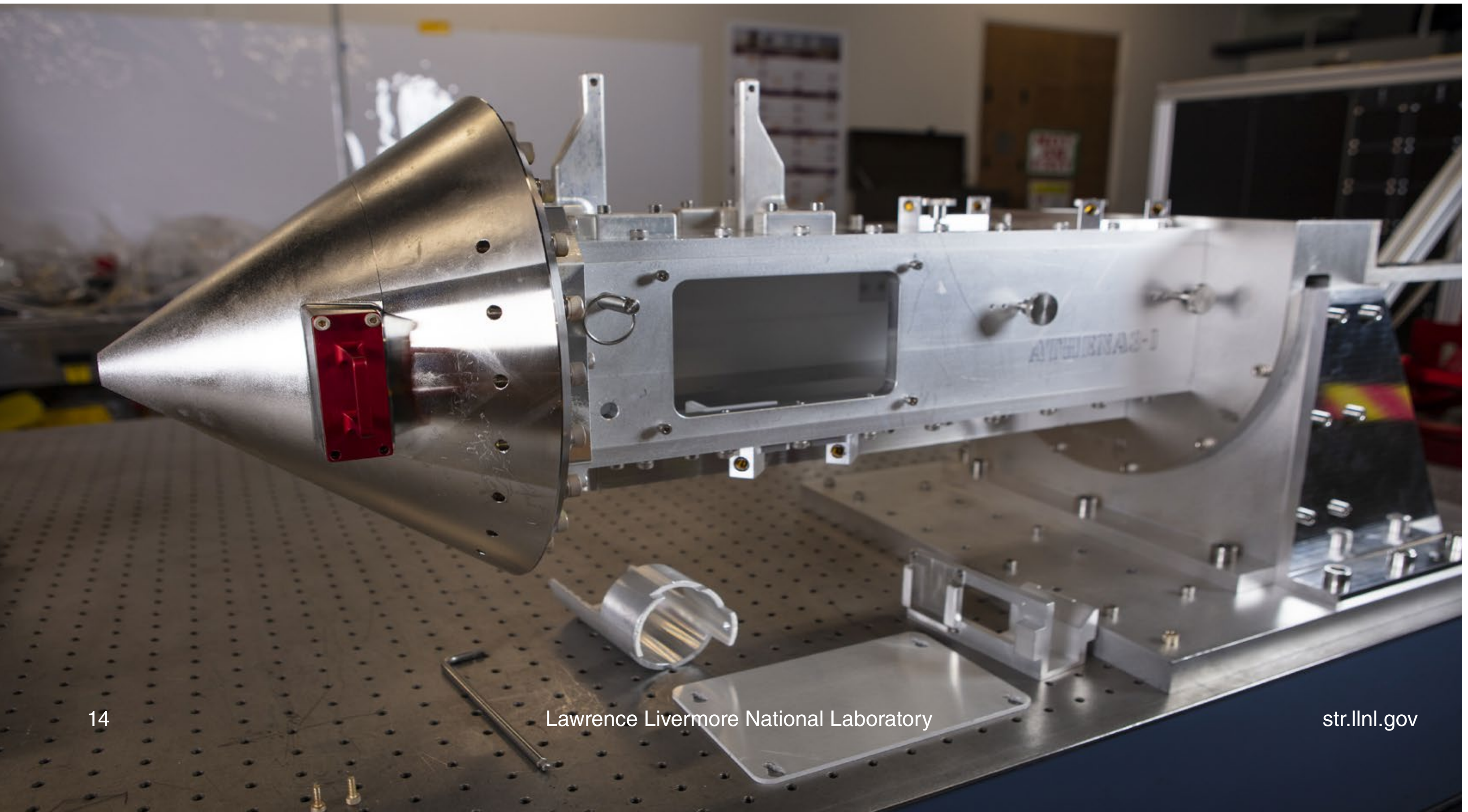
The primary purpose of ATHENA was to design a larger version of the ETA platform with an experimental cavity in the moderator assembly to irradiate and test microelectronics and examine their response to intense, prompt neutron environments. "Most understanding of how modern microelectronics respond in weapons-relevant environments is empirically based, and a similar capability to the ATHENA platform to test microelectronics since the days of underground testing hasn't existed," says Bevins. "With the advancement of microelectronics, we've sought to leverage the unique NIF environment to understand the importance of neutron spectrum and timing on device response." The team created two irradiation platforms, one in a pure fusion environment and the second in the moderated spectrum. This setup enabled the team to measure and compare differences in responses on the same system. Comparing the irradiation on two platforms reveals useful information about the electronics and other test facilities in the United States that generally produce either fission spectrum neutrons or 14-MeV neutrons, similar to NIF. By examining the differences between a representative spectrum with ATHENA and an ordinary NIF spectrum, researchers can better understand the limitations of those other facilities and identify where NIF experiments are best suited to address scientific gaps.

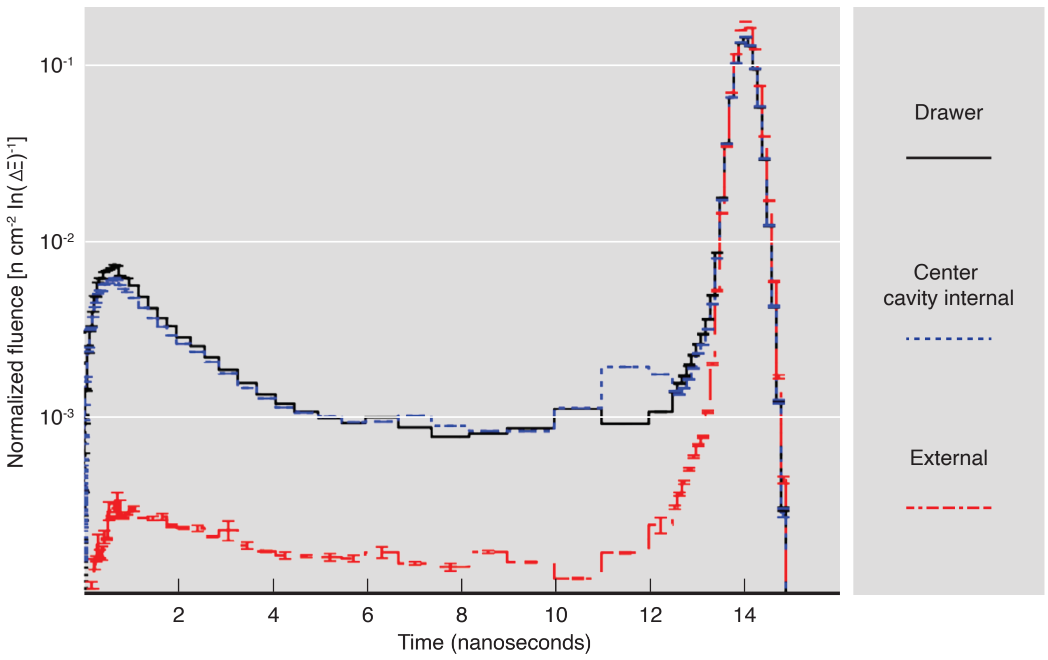
A NIF shot on ATHENA from beginning to end is different from other experiments at the facility, and much of the crucial science work for an ATHENA shot occurs after the laser is fired. "Typically, NIF experiments conclude as soon as the laser fires and the data goes up the wires. For an ATHENA experiment, we consider that stage the start," says Charles Yeamans, the NIF Materials and Radiation Effects scientific lead and NIF responsible individual for ATHENA shots. "Weeks or even months of chemistry and nuclear counting could take place before the data analysis part begins." NIF's capabilities enable the buildup of an instantaneous population of radioisotopes with a single burst, something other neutron sources cannot achieve. However, the isotopes' short half-lives limit how much time is available to count them once the sample has been irradiated. "Realizing the logistical challenge of these experiments is important," says Bleuel. "For instance, indium has a four-hour half-life. After the shot concludes, several steps follow for ATHENA retraction, sample retrieval, and transfer to the nuclear counting facility. If those steps take longer than four hours, we will lose half our data."

After retrieving samples from NIF, Livermore radiochemist Narek Gharibyan uses high-purity germanium detectors to directly measure samples, such as activation foils, and determine the quantities of radioactive products they contain. Uranium samples require more strenuous chemistry to separate the fission products before counting them individually to achieve the highest measurement sensitivity. Once the samples are counted, Bevins and the AFIT team process the data through a technique called unfolding, which reveals the true energy spectrum from the measurements. Comparison with simulated results has thus far revealed that the ATHENA neutron environment can be modeled with high accuracy.

Applications for ATHENA's effectiveness go beyond the initial goal for national security and microelectronic applications, also testing the nation's capabilities for sample analysis and identifying room for improvement. Gharibyan says, "From the debris production standpoint, we want the capability to make post-shot samples that mimic systems to validate our national capabilities for measuring and assessing that type of debris sample."

The red handle on the ATHENA platform allows access to the internal extended experimental cavity in which microelectronics and other samples can be placed for irradiation at the National Ignition Facility (NIF). (Image by Jason Laurea.)





This graph compares the neutron spectra NIF's beam generates with and without ATHENA neutron scattering. The external, red curve is representative of NIF's starting spectra before scattering, and blue and black represent the downscattered spectra both in the internal chamber of ATHENA used for microelectronic irradiation and in the drawer used to hold the diagnostic activation foils. The vertical axis indicates the number of neutrons (n) passing through each square centimeter (cm^{-2}) for each logarithmic interval of energy (ln(ΔE)$^{-1}$), providing a clear view of how the neutron distribution varies across different energy ranges. (Quartemont, Gharibyan, Moody, and Bevins 2021. *Applied Radiation and Isotopes* 173, open access. doi:10.1016/j.apradiso.2021.109711.)

A Fruitful Collaboration

Since its start with Bevins and Bleuel, the ATHENA collaboration between Livermore and AFIT has helped advance understanding of how thermonuclear weapons affect materials and has been highly effective in training personnel. "AFIT is commendable among our collaborators because it supports changes in personnel. AFIT's goal is to help students graduate and complete thesis work," says Yeamans. Adds Bevins, "Few folks have the opportunity to run experiments on or analyze the data from a national-level facility such as NIF. This collaboration exposes AFIT students to important national security applications and enables them to understand what Livermore and its facilities can offer the nuclear enterprise." Nine AFIT students have conducted graduate research on ATHENA in the last six years.

Despite its demonstrated success, work using ATHENA has only just begun. Though lower-fluence neutron outputs have thus far provided proof of concept for ATHENA, the team has generated some of the fission product indicators at quantities too low for practical applications. Nonetheless, ATHENA's unique environment has made it the preferred platform for future work by AFIT and others. With NIF's recent records in yield, the team now aims to field the platform on an ignition shot and expand its capabilities to generate different spectra. "Having that extra intensity—several orders of magnitude—will significantly help with the total yield of fission products," says Gharibyan. Adds Bevins, "The results would be more representative of what you would see in a weapon sample that experienced a much larger number of fissions. We want to move from proof of concept—demonstrating that we can create a relevant environment—to something usable for both the technical nuclear forensic and nuclear survivability communities."

—Lilly Ackerman

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