



Physicist Harry Martz checks a case used to acquire x-ray signature data on reference standards and explosives specimens after the case enters a baggage screening system maintained at Livermore's High Explosives Applications Facility (HEAF).

Understanding Homemade to Enhance

Researchers combine computer modeling and simulation, controlled experiments, and nondestructive evaluation to protect U.S. airline passengers from onboard explosives.

WITH more than 600 million passengers boarding U.S. airliners yearly, protecting the flying public from onboard explosives is a critical responsibility for the Department of Homeland Security (DHS) and its Transportation Security Administration (TSA). Keeping travelers safe requires that airport security quickly and accurately identify any credible threat posed by



Explosives Aviation Security

explosives hidden in checked and carry-on baggage or on passengers themselves. “We must be right every time,” says materials scientist Amy Waters, who leads the Explosives and Infrastructure Security Program in Livermore’s Global Security Principal Directorate.

Waters notes that U.S. air transportation has never been safer, but threats continue to evolve. Despite

the multiple layers of security at U.S. airports, terrorists still find aircraft tempting targets. “A plane going down is psychologically terrifying and would be a huge propaganda victory,” says Waters. She adds that any disruption to air transportation would be damaging to the U.S. economy.

Lawrence Livermore currently leads and participates in several efforts to

enhance aviation security, all centered around better understanding and detecting the threat from explosives carried aboard aircraft. This work builds on decades of nonnuclear explosives research—expertise the Laboratory has applied to address the needs of various government agencies, including the Departments of Energy, Defense, and Justice; the Federal Aviation Administration; DHS; and TSA.

About 35 Livermore chemists, engineers, structural analysts, physicists, and computer scientists contribute to these projects, which combine computer modeling and simulation, controlled experiments, and nondestructive evaluation. Ultimately, the goal of this coordinated effort is to develop a predictive capability to improve detection and mitigation of explosives threats.

From Military to Homemade

Historically, the explosives threat to aviation has been primarily limited to military and commercial devices, which are designed to be relatively safe to handle. Over the past decade, homemade explosives (HMEs) have become the material preferred by terrorists, a change in tactic that has challenged the capabilities of existing detection systems. As a result, providing increased knowledge about HMEs and developing advanced systems to detect them are increasingly important.

Livermore research efforts to enhance aviation security focus on three sets of questions regarding HMEs: First, what HMEs might terrorists use, how easy and safe are those materials to manufacture and transport, and what are their detonation and performance characteristics? Second, how destructive would a particular formulation be if detonated on a pressurized aircraft, what quantity would be required to bring down a jetliner, and to what extent could high-performance computing simulations replace experiments conducted on the ground? And finally, can the screening systems used at airports detect the growing list of HMEs so they never get on board?

Tapping the National Labs

In 2006, DHS established the National Explosives Engineering Sciences Security (NEXESS) Center to apply advanced science and engineering toward reducing the risks to aviation. The center relies on the expertise available at Lawrence Livermore, Los Alamos, and Sandia national laboratories to better

understand how HMEs are synthesized and formulated—critical information for deploying detection technologies that still meet the demands of the traveling public. Chemical engineer Jon Maienschein, former NEXESS leader and current director of Livermore's Energetic Materials Center, says, "In the past few decades, the use of so-called homemade or improvised explosives in attacks by terrorists has led to many questions, such as how these devices are made, what threat they pose to aircraft, how to handle them safely, and most importantly, how to detect them." (See *S&TR*, July/August 2012, pp. 4–11.)

NEXESS projects are focused on characterizing the performance of HMEs and understanding the vulnerability of aircraft to these threats. Researchers at NEXESS have provided an important science base for aviation security, for example, by evaluating various explosives formulations including HMEs and determining each one's detonability, method of initiation, detonation velocity, and impulse energy. NEXESS teams have combined sophisticated computer modeling with small- and large-scale experiments to assess the catastrophic damage threshold for aircraft as a function of the amount and location of the explosives and the flight conditions at the time of detonation. They also have evaluated the performance of emerging detection systems and their application at airport security checkpoints.

HMEs, which typically contain both a fuel and an oxidizer, can be dangerous to handle, and no surrogates are currently approved for experimental testing. "We are faced with applying a strict set of safety standards and practices to materials whose reaction chemistries and initiation mechanisms differ from those we have worked with more extensively," says Maienschein.

He adds that HMEs do not follow the standard detonation theories for military and commercial explosives. For example, HMEs often react much more slowly

than conventional explosives. While military explosives release energy in tens of microseconds, HMEs take hundreds to thousands of microseconds. Such "slow" chemical reactions may lead to incomplete detonations and a possible delayed energy release through a phenomenon called afterburn, which involves the combustion of unreacted ingredients with ambient air.

"Very slow energy releases are not well understood," says Maienschein. "Current theoretical and modeling approaches cannot accurately account for them. We must extend 50 years of experience with military and commercial formulations to this new class of explosives. As a result, the anticipated damage caused by detonating a specific amount of HME is less certain than, say, TNT [trinitrotoluene]."

Livermore chemists test formulations found in terrorist manuals on the Internet and those used in conflicts around the world. Although military explosives are manufactured to tight tolerances, terrorist



production methods are less stringent; a terrorist might resort to mixing an explosive in a bathtub, for example. As a result, the ratio of ingredients in HMEs may vary considerably. “We test and model fuels and oxidizers in different proportions to obtain a general understanding of HMEs,” says Maienschein. The goal is to deduce the characteristics of a family of related chemicals instead of determining the exact characteristics of every possible formula.

Robotics to Maximize Safety

Typically, HME ingredients are benign when handled individually, but mixed together, they become dangerous, particularly if they contain additives such as sulfur or aluminum. Explosive experts often turn to robotic and pneumatic systems to synthesize and test liquid and solid formulations that are too dangerous or unstable to mix or handle safely. At the Laboratory’s High Explosives Applications Facility (HEAF), personnel use the iRobot Packbot 510. Dubbed LEXI

(Livermore Explosives iRobot), the robot is manufactured by the same company that makes the Roomba vacuum-cleaning robot. “Before we acquired LEXI, we couldn’t study some of these explosives because of safety concerns,” says Livermore chemical engineer Sabrina DePiero.

DePiero prepares the materials by layering two or three ingredients including a fuel and oxidizer in a plastic cylinder. The ingredients are safe to handle at this stage because they have not been mixed. She then carries the cylinder to a walk-in HEAF firing tank and inserts it into an acoustic mixer called LabRam. After she leaves the area, the tank and secondary doors are closed and LabRam is started by remote control. LabRam mixes the materials using sound waves. When this step is finished, LEXI rolls to the mixer and removes the cylinder, which contains the now dangerous mixed explosive, and transports it to the tank’s firing table. LEXI rolls out the door, the door closes, and the explosive is detonated.

Data collected from experiments are added to the Laboratory’s online database of explosives, explosive properties, and potential materials from which terrorists could build a bomb. About 1,000 federal and state scientists, engineers, and emergency responders can access the database, which includes information on potential safety hazards involved in manufacturing and handling the different materials, the degree of difficulty a terrorist would face in attempting to destroy a plane with a particular device, and the energy output and power (how fast energy is released) from a detonation.

Test data also help scientists validate computer codes to ensure that calculations accurately simulate an HME’s destructive performance. In particular, explosives

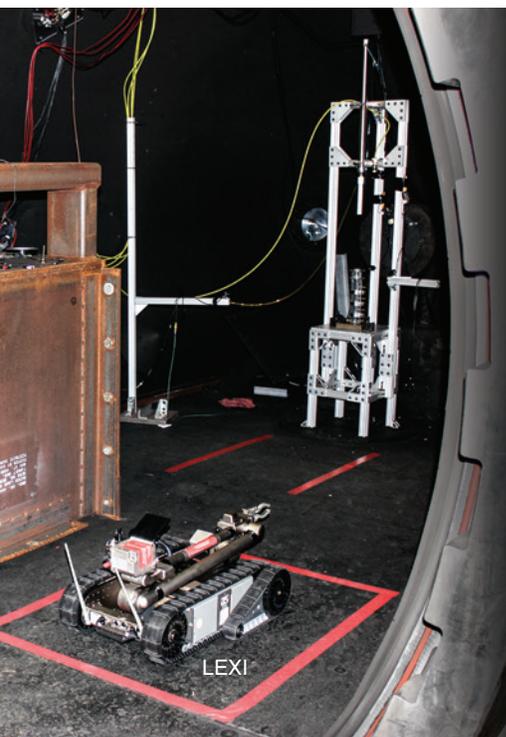
chemists rely on Livermore’s CHEETAH thermochemical code to predict detonation properties for any mixture, including its pressure, temperature, detonation energy, and rate of energy release.

Simulating Airborne Detonations

“Airplanes are more vulnerable to explosives than other structures such as subway tunnels because their frames are manufactured to be as light as possible,” says Maienschein. To analyze the susceptibility of airframes to HMEs, NEXESS experts combine computer analyses made with several Livermore codes and data from experiments on airframe components conducted by DHS at its Transportation Security Laboratory in Atlantic City, New Jersey.

The traditional method for determining the threshold mass of an explosive is subjecting retired aircraft to controlled internal explosions and monitoring the extent of damage. This approach has several limitations. Retired aircraft may have compromised physical structures, and their designs are not representative of newer planes in the commercial fleet. Also, because of costs, only a limited set of explosive parameters is tested. Moreover, a critical factor in the response of aircraft structural components is internal pressurization while a plane is in flight because it magnifies the effect of an onboard explosion. However, pressurized tests are more expensive than experiments at room pressure, and an aircraft can generally be used only once for such experiments.

DHS managers recognized that modern computational tools might overcome these limitations. If supercomputers could accurately illustrate how aircraft would respond to onboard explosions from HMEs, scientists would have a cost-effective tool to better understand and mitigate this threat to commercial aircraft. DHS thus sponsored a demonstration project at NEXESS laboratories aimed at applying the capabilities



Livermore Explosives iRobot (LEXI) works in a firing tank at HEAF. Shown to the left of LEXI is the metal container that houses the acoustic mixer called LabRam.

of high-performance simulation and modeling to explosions on aircraft.

For this project, the Laboratory’s simulation team, led by computational engineers Lee Glascoe and Steve Alves, developed a structural computer model of a

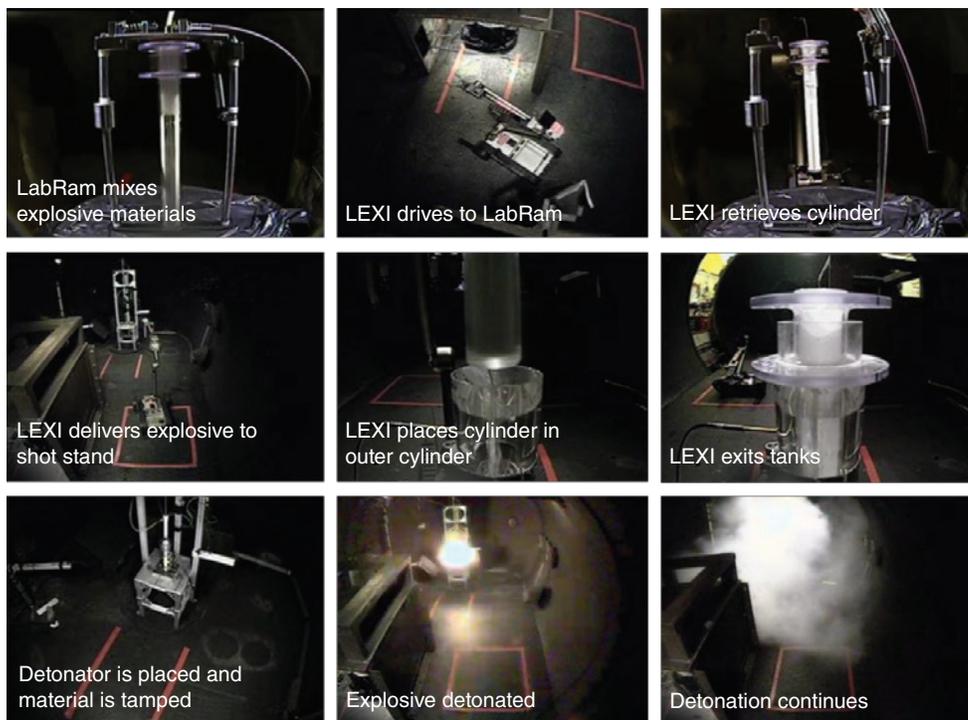
common commercial aircraft and subjected it to simulated explosive detonations.

Their goal was to determine the threshold amount of certain explosives that would catastrophically impact the plane. Many parameters are relevant to this complex

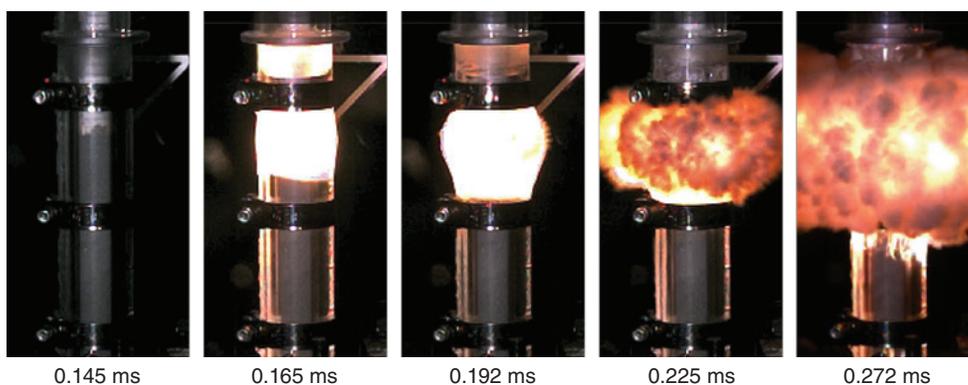
calculation, including the age and type of aircraft, its altitude at the time of detonation, and the shape of the explosive. The explosive’s location—for example, whether it is in an overhead compartment or bathroom or near a window—also affects the calculation because objects surrounding the charge may increase or decrease its destructiveness. This work leveraged modeling and simulation capabilities developed at Livermore to evaluate explosive threats to critical infrastructure, such as research led by Glascoe that examined ways to limit damage to underwater structures from destructive blasts.

At the start of the DHS project, NEXESS researchers developed a structural model of a commercial aircraft for which explosives test data were available. The simulations were “informed” by data generated by small- and large-scale experiments conducted by the Transportation Security Laboratory, Los Alamos, and Sandia. The team then applied these modeling approaches to another commercial aircraft for which no live-fire test data were available. The simulation tools calculated the threshold mass of an HME that would cause catastrophic failure in flight when placed at different locations inside the plane. The team also investigated multiple scenarios of varying quantities and formulations of explosives.

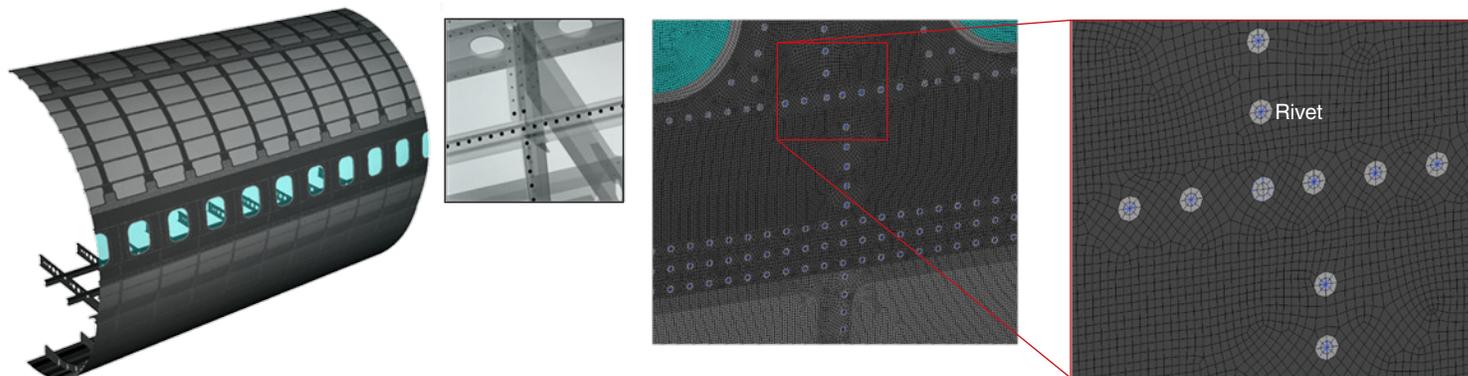
To simulate the high-pressure shock waves caused by detonating a selected HME, the researchers integrated the hydrodynamic code ALE3D and longtime workhorse code DYNA3D with thermochemistry data supplied by CHEETAH. ALE3D is a high-fidelity numerical simulation tool for analyzing the elastic, or plastic, response of materials under extreme conditions. CHEETAH results coupled with ALE3D predict the size and other characteristics of the blast. The time and spatially varying pressure from the blast were then mapped to determine damage to the aircraft’s frame on a fine three-dimensional (3D) grid.



These images show the sequence of operations (from left to right, top to bottom) performed by LEXI in testing homemade explosives (HMEs) in the HEAF gun tank.



After LEXI positions an explosive test assembly in the gun tank at HEAF, high-speed cameras record details of the explosion. This image sequence shows a detonability test of an aluminized explosive, where elapsed time is in milliseconds (ms).



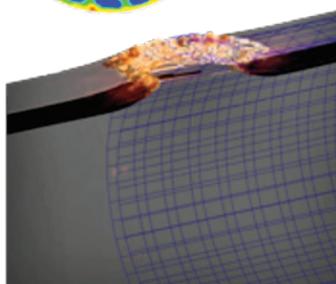
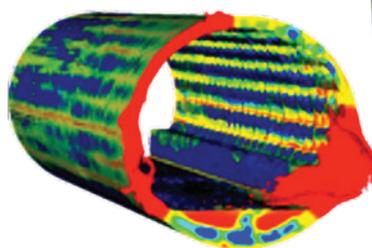
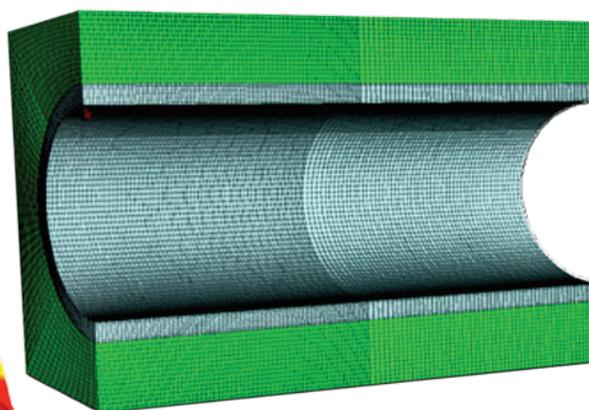
A finite-element model tested with the Laboratory’s DYNA3D and ALE3D codes revealed details of an airplane’s fuselage down to the stringers (horizontal elements) and rivets.

Simulations Validate Tests

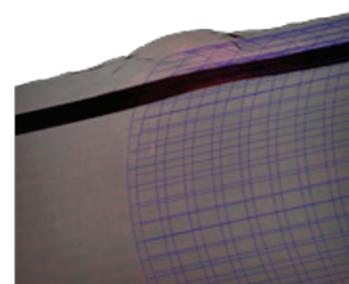
The simulations ran on a Livermore supercomputer with between 512 to 1,024 processors working in tandem. Simulating a detonation event that lasted a relatively long 40 milliseconds required about a day of computing time. The simulations revealed in three dimensions—and millisecond by millisecond—what is likely to take place when the selected HME is detonated inside an aircraft, in particular the blast’s effects on the aircraft’s aluminum skin and the degree to which the plane’s interior components and objects near the explosive mitigated the blast. Effects ranged from minor interior damage to cracks in the aluminum skin to sections of the fuselage blown out. “The numerical models were built to accommodate a large but necessary amount of structural detail about an aircraft,” says Glascoe. “Our simulations compare well with available experimental data at both the component and system level.”

Glascoe notes that data from physical experiments on aircraft components are particularly valuable because they provide “ground truth” for simulations. He compares the experiment–simulation linkage to the National Nuclear Security Administration’s Stockpile Stewardship Program, in which scientists ensure the safety and effectiveness of the nation’s nuclear weapons through simulations

Supercomputing models help scientists understand how enclosed structures made of complex materials such as steel-reinforced concrete will respond to an HME detonation.



Breach

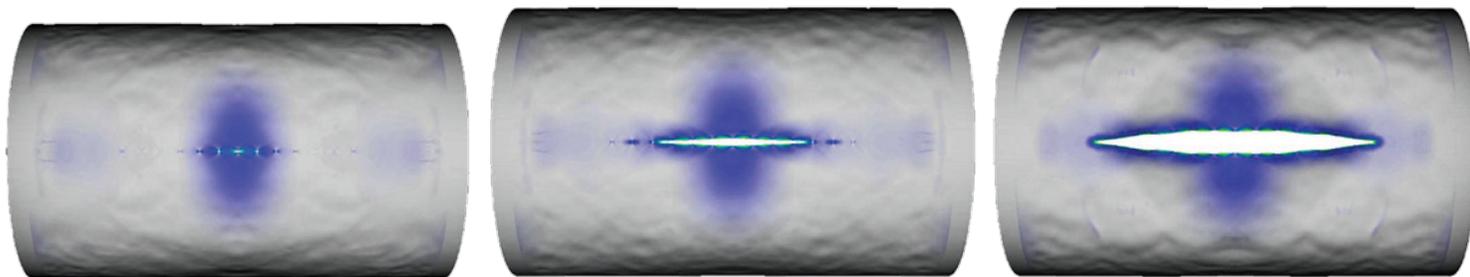


No breach

and physical component testing without resorting to underground nuclear tests. “Small-scale tests help determine how well our model works,” he says. “We learn details about how an aircraft might fail down to individual rivets.”

The project, which concluded in early 2013 with a final report to TSA,

demonstrated the utility of computer simulation. Says Maienschein, “We showed that our modeling and simulation tools can provide useful assessments of aircraft vulnerability and determine the threshold explosive masses for catastrophic damage at selected locations inside a specific aircraft.”



Snapshots from three simulations using ALE3D and DYNA3D show the damage caused by different quantities of HMEs detonated inside a small, thin-walled pressure vessel. Testing objects that are far less complicated than an airplane fuselage helps scientists validate the ability of larger computer models to capture important details.

3D Imaging at Every Airport

TSA has deployed a wide range of technologies to address known and emerging security threats to air transportation. X-ray computed tomography (CT) and radiography machines at every airport analyze the contents of all checked and carry-on baggage, searching for hidden explosives and other prohibited items. Additional layers of security include explosives detection canine units and techniques to screen baggage and passengers for traces of explosives. Scanners also examine bottled liquids at security checkpoints primarily to test medically exempt liquids, which may be transported in quantities greater than 100 milliliters (3.4 ounces).

Livermore experts have worked closely with government agencies and private industry to strengthen existing detection tools and commercialize new technologies. One example is a Livermore-developed device called ELITE, for Easy Livermore Inspection Test for Explosives. (See *S&TR*, October 2006, pp. 16–17.) This pocket-sized detector, which tests for a broad range of explosives, is now licensed to Field Forensics, Inc., and has been sold to law-enforcement agencies and the U.S. Army.

To meet TSA's screening requirements, physicist Harry Martz is leading a team of explosives and nondestructive evaluation experts to enhance the performance of

airport x-ray CT and radiography machines and to recommend improvements for future devices. Martz is head of the Laboratory's Center for Nondestructive Characterization, which has pioneered ways to use x rays and other forms of radiation for noninvasive imaging of everything from nuclear warhead components to bridge decks. (See *S&TR*, June 2011, pp. 19–21.) The goal of the Livermore Explosives Detection Program is to simultaneously enhance the machines' sensitivity to the expanding range of explosive threats without increasing the number of false alarms. Martz notes that any time an alarm is generated, security personnel must review the images or manually verify the bag's contents, which can slow airport operations.

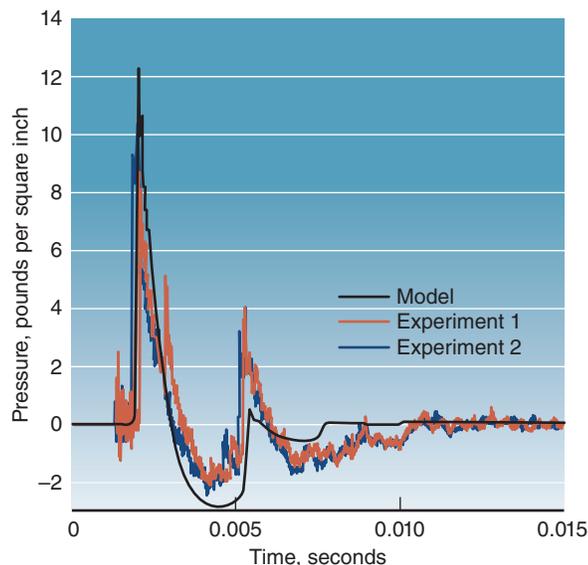
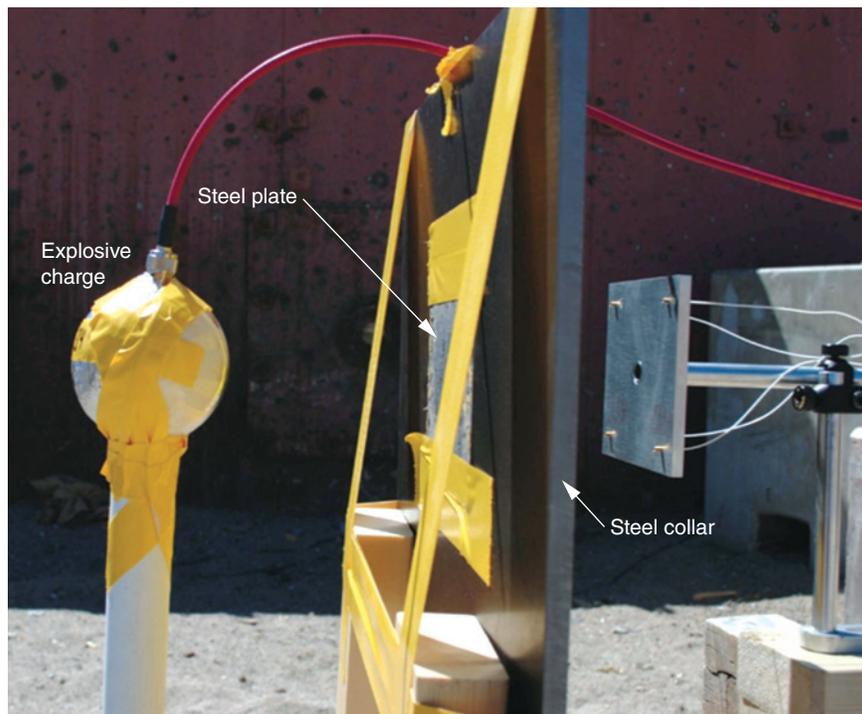
The Livermore team is enhancing two types of algorithms (data-processing strategies) that analyze the x-ray images produced by the machines. The first task is to improve the complex reconstruction algorithms that turn numerous two-dimensional x-ray projections into a detailed 3D representation of the items inside a piece of luggage. Says Martz, "Reconstructed 3D radiographic images provide a clearer picture of a bag's contents."

Martz's team is also improving threat-detection algorithms, which automatically interpret the 3D CT images produced by the first set of algorithms. Threat-detection algorithms extract relevant

characteristics such as a material's x-ray attenuation, density, atomic number, and mass and compare these data to values of known explosives, including HMEs. As baggage is scanned, the algorithms automatically classify each item inside as either a threat or a nonthreat. If an alarm signals a potential threat, TSA staff screen the item further. Computer simulations play an important role in improving signal accuracy. The Laboratory's HADES code, for example, can predict changes in radiographic signatures that are associated with explosives of different elemental content or density.

In a related effort, Livermore researchers are working on algorithms to advance dual-energy detection technology for use by TSA. With this technique, the detector measures the linear attenuation coefficients of materials at two energy spectra, one low and the other high. The measurements provide a stronger basis for interpreting an object's elemental composition and density. If dual-energy technology is adopted by TSA, it would enhance detection capabilities and overall efficiency.

The Livermore researchers have created a database with detailed information on the x-ray properties of explosives threats and nonthreats. These data help TSA and scanner manufacturers develop performance standards for screening checked and carry-on baggage. "We need an extremely high detection rate and a very



The photo shows the experimental setup used at Los Alamos National Laboratory to test the close-in effects of an explosive charge and to characterize the blast wave as it travels through air. The graph plots measurements from two Los Alamos experiments versus a Lawrence Livermore simulation of the same test.

low false-alarm rate to mitigate evolving threats,” says Martz. Another challenge is that some benign materials share similar characteristics with actual HME threats and thus could generate a false alarm.

Staying Ahead of the Next Threat

The team’s investigations to enhance the performance of existing or next-generation technologies should improve explosives detection systems, reduce false-alarm rates, and increase system operational efficiencies. “Advancing the technologies used at airports to screen for dangerous materials is a challenging task,” says Martz. “TSA and manufacturers are doing a good job, but we must continue to improve our capabilities.” The urgency of the task was underscored in July 2013 when TSA chief John Pistole discussed a next-generation device called Underwear 2—a successor

to the underwear bomb Umar Farouk Abdulmutallab attempted to detonate on a flight near Detroit on December 25, 2009. According to Pistole, the new and improved bomb, identified in May 2012, was designed to evade current TSA detection systems.

While counterterrorism officials are tracking down the latest generation of bomb makers, TSA and a small group of scientists and engineers are advancing their understanding of explosives and the methods to detect and mitigate these devices. Waters is optimistic. “For the first time, we’re developing a predictive capability to determine what a bad guy could do and how we could detect it,” she says. “This predictive understanding will enable us to help DHS stay ahead of the evolving threat to air travel.”

—Arnie Heller

Key Words: ALE3D code, aviation security, CHEETAH code, computed tomography (CT), DYNA3D code, Easy Livermore Inspection Test for Explosives (ELITE), Energetic Materials Center, HADES code, High Explosives Applications Facility (HEAF), homemade explosive (HME), LabRam, Livermore Explosives iRobot (LEXI), National Explosives Engineering Sciences Security (NEXESS) Center.

For further information contact Amy Waters (925) 423-2424 (waters4@llnl.gov).