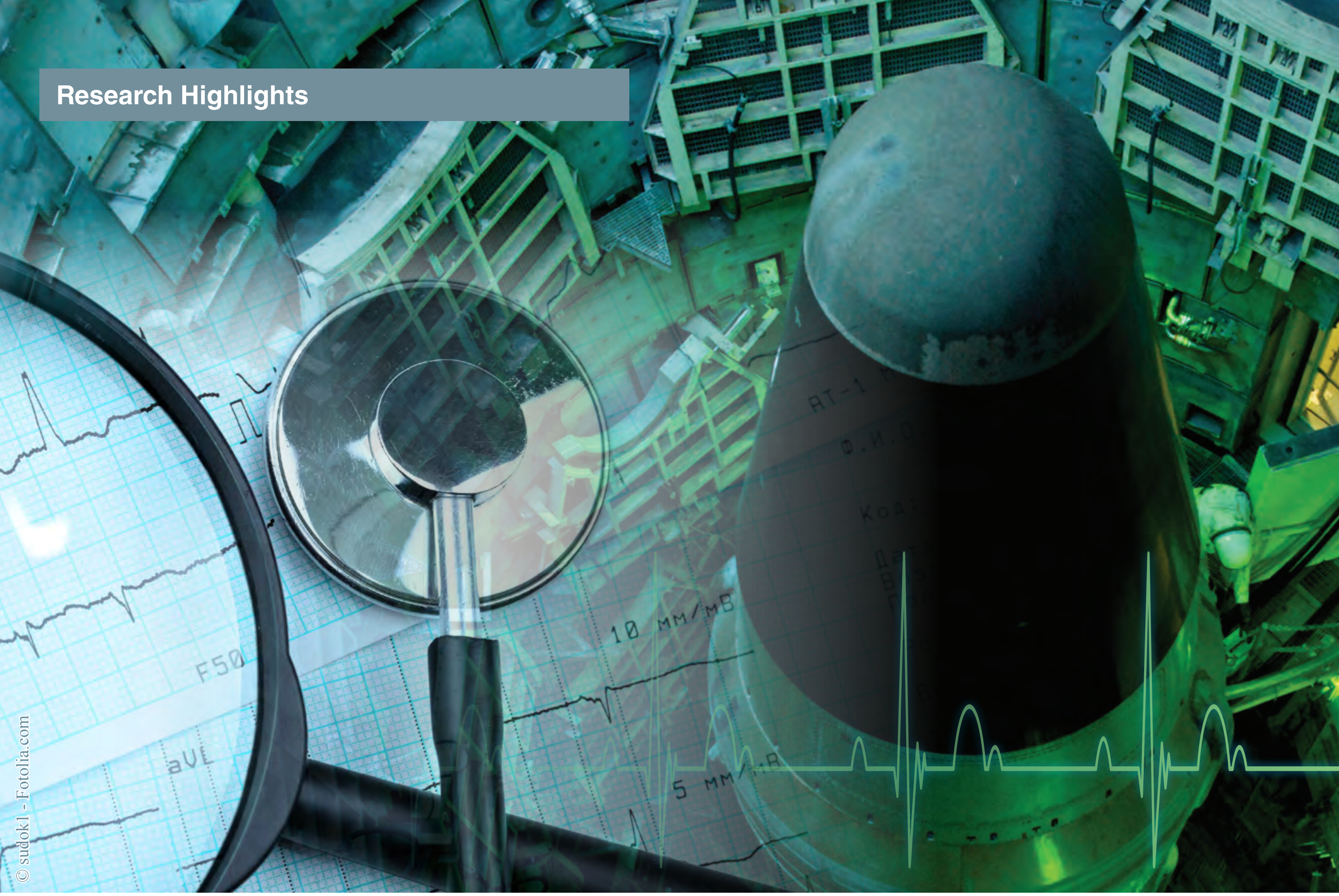

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Taking the Pulse of the Stockpile

SIMILAR to how a physician orders blood tests and uses a stethoscope to assess a patient's health, scientists apply diagnostic tools to weapons systems to interrogate what lies beneath their metallic "skin." Twenty-plus years ago, before the Department of Energy (DOE) established the Stockpile Stewardship and Management Program, the primary method of evaluating a nuclear weapon's health was to essentially destroy it—the weapon was dismantled and each component tested to ensure the system's functionality.

The cessation of nuclear testing and the implementation of stockpile stewardship in the 1990s significantly changed assessment strategies for nuclear weapons. (See the article beginning on p. 6.) The Enhanced Surveillance Campaign was instituted as part of the new stewardship program in recognition that existing weapons components need to stay in the stockpile as long as possible. Through this campaign, nondestructive diagnostic technologies have been developed that provide equivalent or better data than traditional destructive testing methods. Some of the technologies help scientists interrogate a weapon by retrieving small physical samples from the system's interior—analogous to a patient having their blood drawn. Other technologies, such as small embedded sensors, serve as a way to continuously monitor a weapon's overall health.

Nondestructive surveillance diagnostics are integrated into all aspects of the Stockpile Stewardship and Management Program. These technologies are combined with improved materials aging models to provide data and reduce uncertainty in predicting systems performance. They also supply essential input for determining new materials that can be used to refurbish weapons systems and extend weapons lifetimes for an additional 20 to 30 years. Thus, enhanced surveillance tools help to assure the future safety and reliability of the stockpile.

Sniffing Out Material Changes

Gas composition can provide information about chemical reactions occurring in weapons materials. Such reactions can occur between decomposition byproducts from polymers or high explosives with or without oxygen or water vapor that could leak into the sealed environment. Some of these reactions can be initiated or aggravated by the presence of ionizing radiation within the warhead.

Gaseous products such as water vapor, oxygen, and hydrogen are relatively easy to detect. Heavier organic gases are of special concern because they are less volatile yet can still diffuse throughout the system and interact with other materials. To extract gas samples from different compartments of a weapons system for analysis, scientists use a Livermore-developed microextraction technique. (See *S&TR*, July/August 2010, pp. 4–11). A narrow metal fiber coated with a polymer that adsorbs organic compounds is inserted into a weapon's headspace. The fiber is then retrieved and inserted into a gas chromatograph–mass spectrometer. The resultant spectra of the adsorbed volatile organic compounds provide a "snapshot" of a weapon's internal environment. With this technique, hundreds of compounds can be identified at concentrations down to a few parts per billion, providing insights into any changes in the weapon's polymers. When this technique was first developed in the late 1990s, sample collection was cumbersome and the samples themselves were short-lived. Improved sampling technologies have helped streamline the surveillance process and enabled long-term storage of samples for shipment to and analysis at other sites.

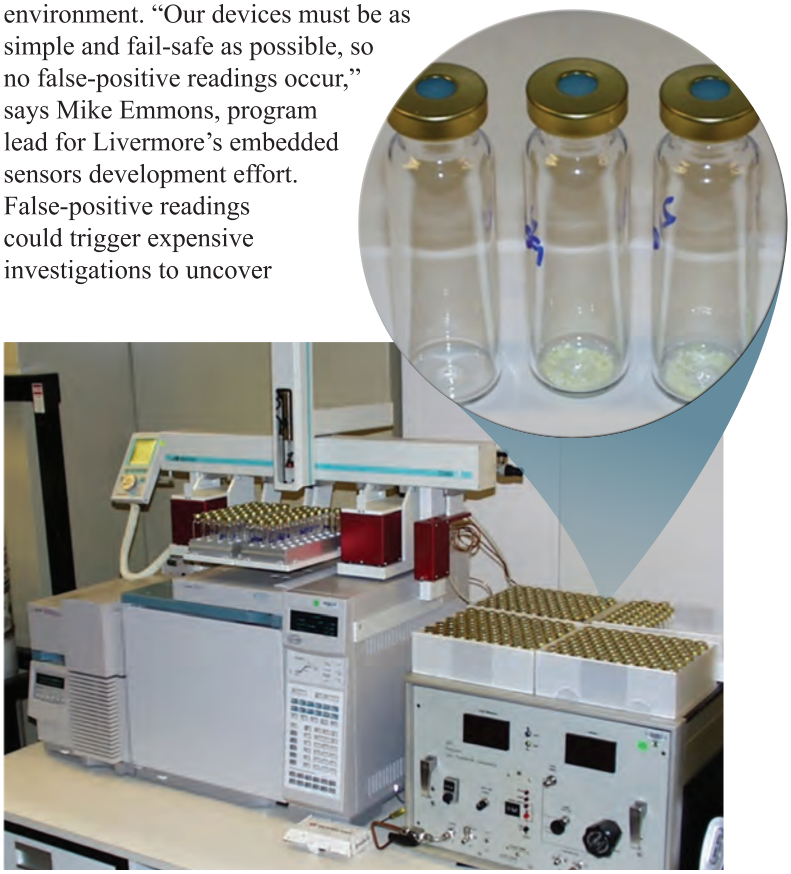
One of the current challenges with gas analysis is how best to analyze the resultant large spectral data sets from simple materials such as toluene to complex materials such as dodecamethylcyclohexa-siloxane. "We're turning to chemometrics to visualize these multidimensional databases and to look for correlations amongst thousands of spectra," explains Bill McLean, Livermore's Enhanced Surveillance Campaign manager. Laboratory scientists are collaborating with Professor Karl Booksh at the University of Delaware to develop chemometric visualization codes that will mine the vast chemical data sets and help scientists identify which spectral peaks are important. "Chemometric tools are very useful in extracting quantitative information and qualitative trends from complex and potentially noisy observational data. We can derive more knowledge by looking at the data in concert than by viewing changes in any single variable over time," says Booksh. With this information, researchers can determine chemical and degradation pathways and ultimately better understand the materials environment of a weapon.

Once these pathways are understood, researchers can conduct small-scale experiments in which finger-size sealed vials of materials, or a matrix of materials, are subjected to accelerated aging with heat, radiation, and desiccation, and then sampled periodically for outgassing. In the past, whole components or entire weapons were placed into enormous ovens and environmental chambers for accelerated aging and subsequent sampling. "In those tests," says McLean, "we did not necessarily know why something happened, or even which materials were to blame. Now, we can simultaneously test a vast array of material combinations in milligram amounts to pinpoint where problems originate. These techniques are smaller, faster, and cheaper than traditional methods."

Simple, Effective Devices

Embedded sensors provide persistent surveillance of the aging stockpile. These tiny and rugged sensors can be added into existing weapons and inserted into a system during a life-extension program. Once installed, the sensors provide continuous monitoring and nearly instantaneous detection of anomalies. (See *S&TR,* July/August 2008, pp. 12–19.)

Embedded sensors must be simple yet durable—remaining viable for thirty years within a high-radiation environment. "Our devices must be as simple and fail-safe as possible, so no false-positive readings occur," says Mike Emmons, program lead for Livermore's embedded sensors development effort. False-positive readings could trigger expensive investigations to uncover



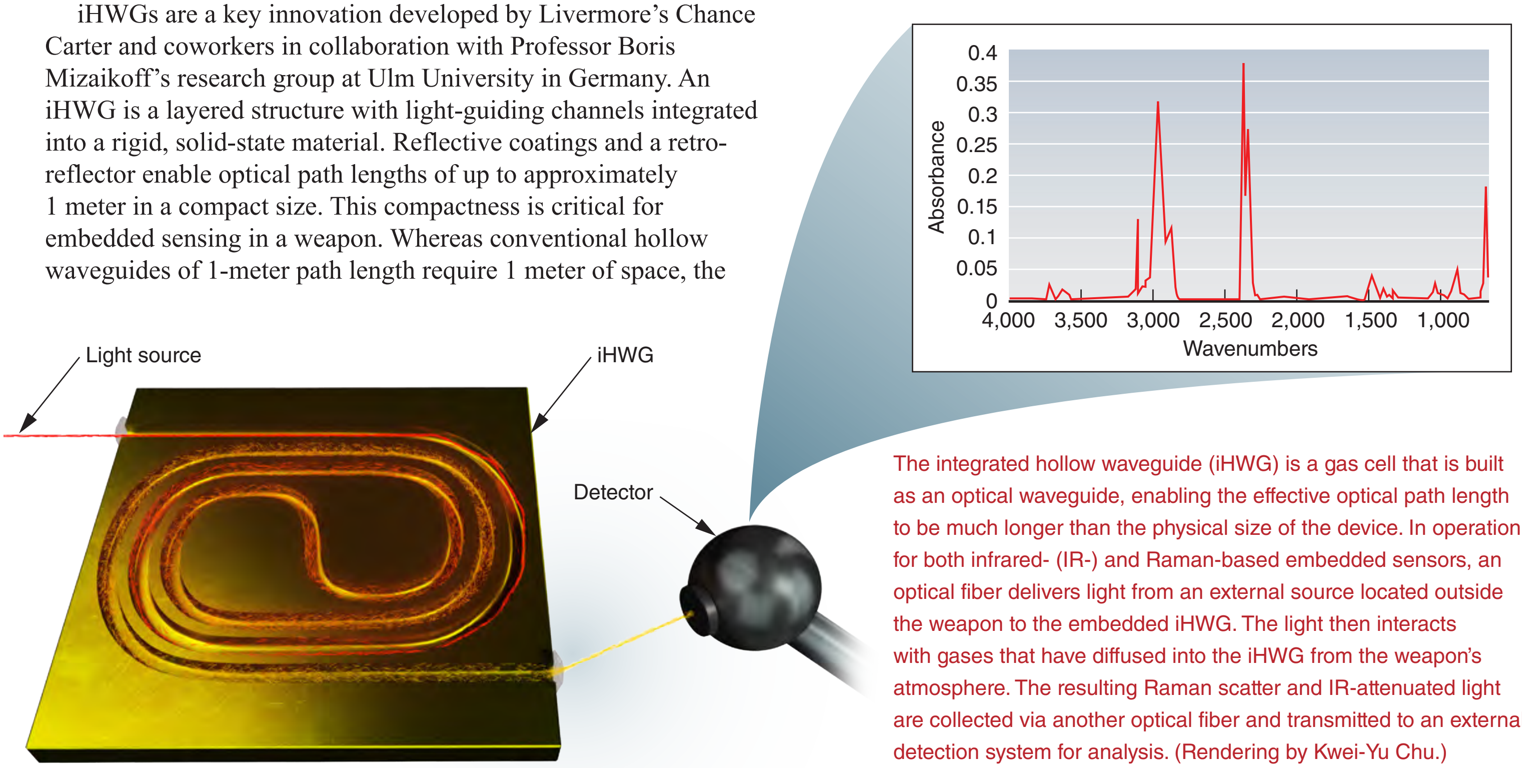
(top) Miniature sample vials are filled with combinations of potentially reactive gas compounds in small (milligram) amounts. (bottom) The vials are placed in heater blocks that are sampled periodically with a gas chromatograph–mass spectrometer equipped with an auto sampler for solid-phase microextraction.

nonexistent problems. “Whatever we do, we can’t impede the functionality of the weapon,” says Emmons. “Essentially, we are creating sensors that closely follow the ‘no mass, no volume’ dictum.” Much of the work on embedded sensors had its genesis in the Transformative Materials Initiative, an extensive three-year Laboratory Directed Research and Development project in the mid-2000s that focused on creating new multifunctional materials and sensors for long-term Laboratory mission needs.

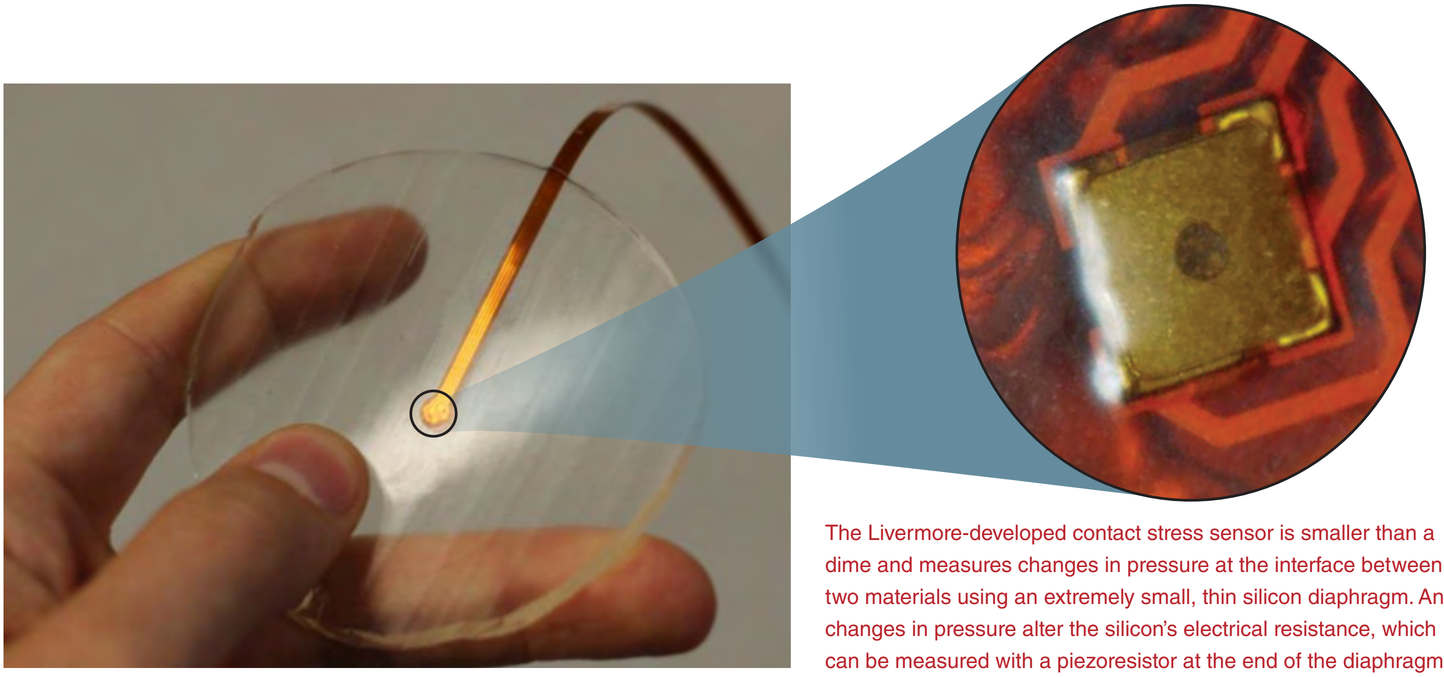
Embedded gas sensors provide data on the gas mixtures collecting in the spaces between components over time, and what chemical reactions and materials are involved. Livermore scientists are developing compact gas sensors based on Raman scattering and mid-infrared (MIR) absorption spectroscopy. In the former, laser light is transmitted via a solid-core optical fiber probe to an integrated hollow waveguide (iHWG). The laser excites gas molecules within the waveguide, producing Raman scattered light, which is transmitted via the same fiber bundle to a detection system. Similarly, MIR light from either a broadband or narrowband source is also transmitted via a solid-core optical fiber to an iHWG, where molecules absorb some of the light. The remaining unabsorbed light is transmitted back through the same fiber bundle to a detection system. Both Raman and MIR spectroscopies yield complementary spectral “fingerprints” of the gas encountered by the beams. Together, these techniques provide a broad in situ gas-sensing capability for detecting and quantifying all but the noble gases.

iHWGs are a key innovation developed by Livermore’s Chance Carter and coworkers in collaboration with Professor Boris Mizaikoff’s research group at Ulm University in Germany. An iHWG is a layered structure with light-guiding channels integrated into a rigid, solid-state material. Reflective coatings and a retroreflector enable optical path lengths of up to approximately 1 meter in a compact size. This compactness is critical for embedded sensing in a weapon. Whereas conventional hollow waveguides of 1-meter path length require 1 meter of space, the Livermore-developed iHWGs fit easily into the palm of a hand. “An iHWG essentially acts as an efficient, small-volume, miniaturized gas cell and reflective ‘light pipe’ for co-locating light with the gas,” explains Carter. “The iHWG concept represents a next-generation waveguide of unprecedented small size with customizable optical path lengths.” Another advantage of these gas sensors is that they are passive in nature. Emmons notes, “We don’t have to remove samples of solid or gaseous materials or disturb the weapons system in any way to collect the data.”

Knowing the mechanical state of a weapon provides assurance that the parts and pieces are in place and mechanically stable. Several different types of embedded sensors have been developed to collect such information. Mechanical impulse sensors use tiny accelerometers to determine whether a system has been jostled or shaken, pressure sensors use optical interferometry to detect materials aging or gas leakage, and stress sensors detect the movement of parts relative to each other. For example, Livermore has designed a contact stress sensor (CSS) that is smaller than a dime to measure contact stress—or the squeezing force—between two surfaces. Based on microelectromechanical systems, these devices are ideal for embedding because of their small dimensions, material properties, low power consumption, and mass



The integrated hollow waveguide (iHWG) is a gas cell that is built as an optical waveguide, enabling the effective optical path length to be much longer than the physical size of the device. In operation, for both infrared- (IR-) and Raman-based embedded sensors, an optical fiber delivers light from an external source located outside the weapon to the embedded iHWG. The light then interacts with gases that have diffused into the iHWG from the weapon’s atmosphere. The resulting Raman scatter and IR-attenuated light are collected via another optical fiber and transmitted to an external detection system for analysis. (Rendering by Kwei-Yu Chu.)



The Livermore-developed contact stress sensor is smaller than a dime and measures changes in pressure at the interface between two materials using an extremely small, thin silicon diaphragm. Any changes in pressure alter the silicon's electrical resistance, which can be measured with a piezoresistor at the end of the diaphragm.

manufacturability. CSS employs an extremely small, thin silicon diaphragm. Any changes in pressure alter the silicon's electrical resistance, which can be measured with a piezoresistor at the end of the diaphragm. Otherwise, the diaphragm is inert, springing back to its original shape when pressure is removed. "This sensor is so thin and small, it does not perturb the load we want to measure," says Emmons.

A spin-off device, the optical force probe, also uses a silicon-based pressure-sensitive diaphragm, but with an added twist. An optical fiber stretches across the diaphragm and is pressed down when the diaphragm bends under load. "By shining a light into the weapon, we can measure how much the fiber is stretched and correlate the measurement to the strain and interface loading in that area of the system," explains Emmons. A third mechanical sensor takes its cue from recent iButton technology. "We are working off the same concept, namely, a very small, battery-powered, durable sensor that can stick to something and later download recorded data," says Emmons. "In our case, we are designing a logger for monitoring shock and vibration." If jolted, a small accelerometer in the embedded logger would be triggered, recording the motion.

To extract data from embedded sensors, researchers have developed a portable diagnostics unit that can download sensor data and provide the necessary power sources, lasers, and data-acquisition hardware. Retrieving the data is as simple as attaching the diagnostics unit to a warhead.

Building a Foundation

An important part of sensor development is introducing these technologies to the weapons community early, so that scientists can see the devices' relevance and compatibility with their goals and efforts. Emmons says, "We try to incorporate various sensors into compatibility materials tests, hydrotests, engineering tests, and any other test in which they could be useful in gathering data. These tests provide a better foundation for their use in weapons systems."

Researchers are also investigating how to make the sensors more widely available outside the weapons complex. The CSS technology, for instance, has been licensed to MicroMetrics, Inc., which is using it to build sensors for personal devices, industrial products, and sporting goods. Sensors have also been installed into soldiers' helmets—if a blast occurs, the sensor data indicates to physicians how much pressure was created by the blast and, consequently, how badly a soldier might be injured.

Meanwhile, surveillance continues to be a vital part of assessing the state of the U.S. nuclear arsenal. Advanced nondestructive diagnostics developed through Livermore's Enhanced Surveillance Campaign are dramatically improving the nation's ability to conduct surveillance activities in ways that are robust, scientifically defensible, and cost effective. Moving forward, the search continues to find ever more sensitive tools and advanced technologies for assessing the health of the stockpile.

—Ann Parker

Key Words: chemometrics, contact stress sensor (CSS), embedded logger, embedded sensor, Enhanced Surveillance Campaign, integrated hollow waveguide (iHWG), nondestructive surveillance, nuclear stockpile, optical force probe, outgassing, Raman spectroscopy, Stockpile Stewardship and Management Program.

For further information contact Bill McLean (925) 423-0759 (mclean2@llnl.gov).