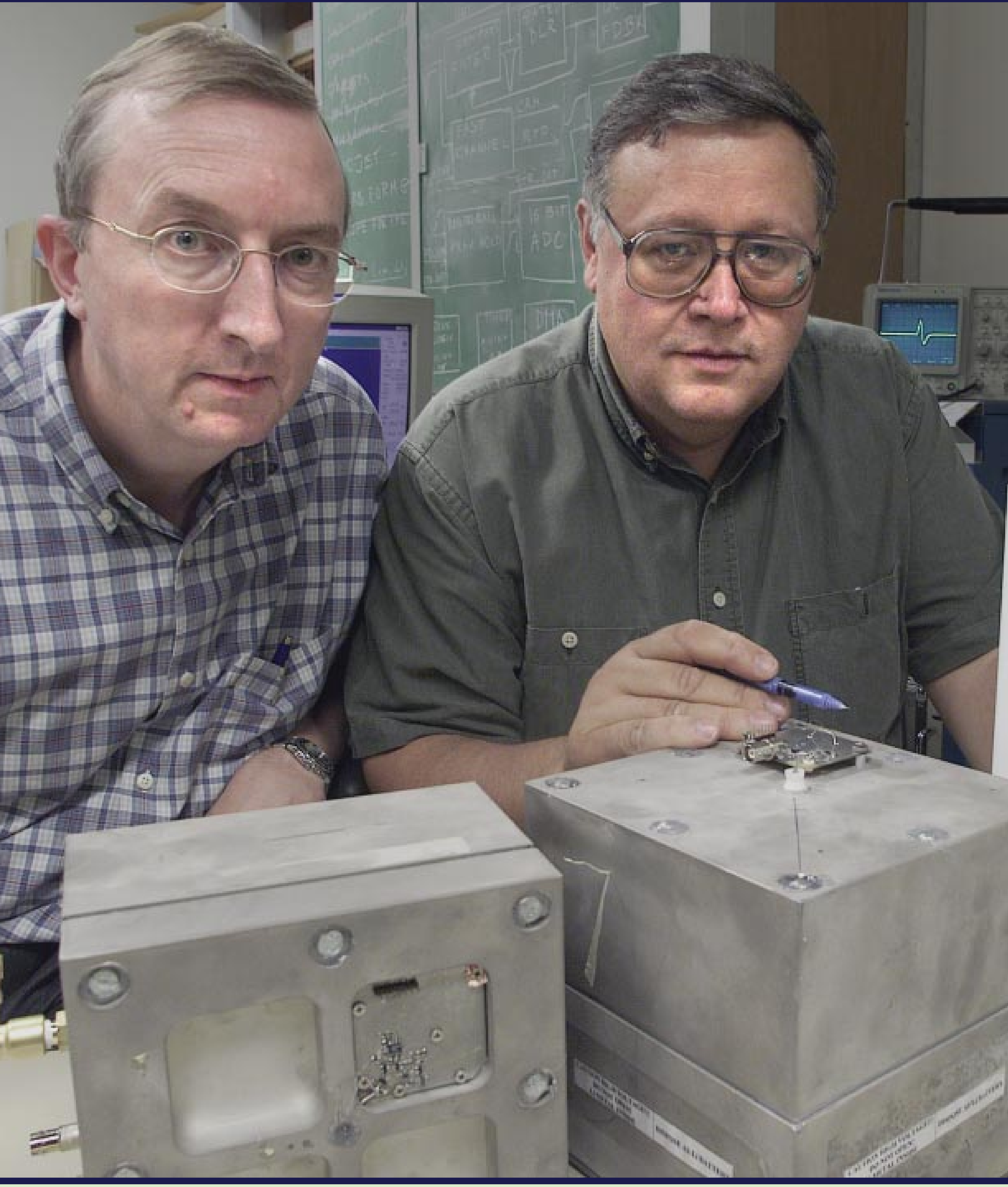


John Flower

Kiril Ianakiev (right) points to an electronics package on a single-cell prototype of his modular neutron detector. The detector is made of high-density polyethylene, a tough, durable plastic. Metal cladding on the exterior surfaces of the two single-cell prototypes shields their electronics from the electrical noise produced by power lines and other external sources. Measurements made with the prototypes have confirmed calculations of their neutron detection efficiency done by Martyn Swinhoe (left). The plastic detector body on the right will be used to build an eight-cell detector—the first fieldable version of the modular detector.

A Modular Neutron Detector

by Brian Fishbine

Lab scientists have developed a rugged, inexpensive neutron detector—made largely of plastic—that could be mass-produced to provide more-widespread border screening for nuclear contraband.

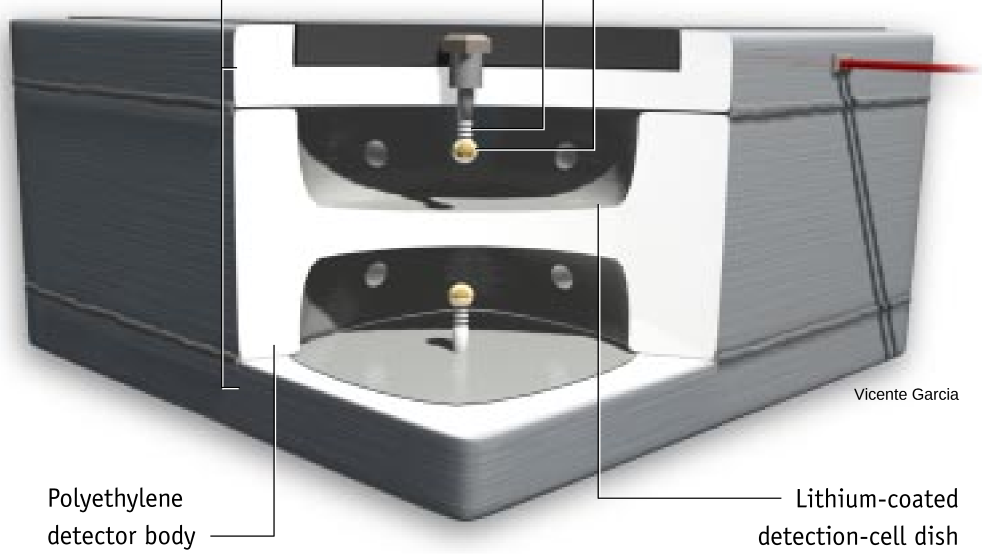
Government agencies are currently fielding neutron detectors at seaports, airports, rail yards, and border crossings to detect contraband plutonium from its neutron emissions. The aim is to foil terrorist attempts to smuggle a plutonium-fueled nuclear bomb or its plutonium parts into the country. Detonating a nuclear bomb in a city would be devastating.

But preventing such an attack is not easy because there are so many entry points to the United States. Each year, 7 million freight containers are unloaded at nearly 400 seaports; 800,000 commercial airline flights and 130,000 private flights land on U.S. soil; and 11 million trucks and 2 million railroad cars enter the country from Canada and Mexico. At each of the fifty or more vehicular border crossings, there are at least ten traffic lanes. To cover all these entry points would require several thousand neutron detectors, possibly tens of thousands.

The most commonly deployed neutron detector—a proportional counter—costs at least $30,000 for a model with a detection area of 1 square meter. Ten thousand of these detectors would cost at least $300 million.

Los Alamos scientist Kiril Ianakiev has developed an attractive alternative: a new breed of neutron detector. The detector's major parts include spark plugs, welding gas, and a briefcase-sized block of plastic that forms its body. The detector is rugged and inexpensive enough to be widely deployed—which is the whole idea.

Ianakiev's detector is also a good neutron detector: it detects 10 percent of the neutrons emitted by plutonium-240 that strike it. (Weapons-grade plutonium



A computer rendering of two argon-filled detection cells in an eight-cell detector. The high-energy neutrons emitted by plutonium are moderated to lower energies by the detector's polyethylene body so that they can be more readily absorbed by a cell's lithium coating. Nuclear reactions in the lithium produce tritons and alpha particles, about half of which penetrate the coating and ionize the cell's argon gas, producing electrons and positively charged ions. A radial electric field draws electrons to the spherical positive electrode and ions to the cell's negatively biased metal surfaces. The electron flow produces a current pulse, which is the detection signal.

typically contains about 5 percent plutonium-240.) By comparison, a proportional counter detects 15 percent of the neutrons. But a proportional counter is also nearly ten times more expensive. One of Ianakiev's detectors with a 1-square-meter detection area will cost about $4,000. Ten thousand detectors would cost only $40 million.

Leveraging the Microchip

To achieve this performance-to-cost breakthrough, Ianakiev has used modern electronics to redesign an old radiation detector. In 1908, scientists discovered that an energetic charged particle, an x-ray, or a gamma ray will produce a current pulse in gas that is subjected to an electric field. The radiation strips electrons from the gas atoms (ionizes them), and the electric field draws the resulting electrons and ions to the detector's positive and negative electrodes, respectively. The flow of electrons produces a tiny current pulse—the detection signal.

If the electric field is high enough, however, the electrons gain enough energy to ionize more gas atoms, a process that produces more electrons. The resulting "avalanche" of electron-ion pairs—called gas multiplication—amplifies the current pulse.

In the early days of radiation detectors, it was far easier to amplify the current pulses with gas multiplication than it was to amplify them with vacuum tubes, which had just been invented in 1906. Now, however, an inexpensive microchip can amplify the current pulses without gas multiplication, allowing Ianakiev to develop a detector that overcomes the limitations of early detector designs. (The sidebar on page 19 explains how gas-filled radiation detectors work.)

Detecting Neutrons

A gas-filled radiation detector cannot detect neutrons directly, however, because a neutron cannot ionize an atom. But several neutron-absorbing nuclear reactions produce energetic charged particles that do ionize atoms. These reactions include

neutron + ^{6}Li → triton + alpha particle,
neutron + ^{3}He → triton + proton, and
neutron + ^{10}B → ^{7}Li + alpha particle,

where Li is lithium, He is helium, B is boron, and the superscripts are isotopic numbers. A triton is the nucleus of a tritium atom (hydrogen-3); an alpha particle is the nucleus of a helium atom.

The reaction rates are significant only for neutrons with kinetic energies close to the thermal energy of their surroundings, about 0.025 electronvolt at room temperature. For the 1-million-electronvolt neutrons emitted by plutonium-240, the reaction rates are about one-thousandth those of thermal neutrons. To be detected, therefore, the plutonium neutrons must first lose energy in many glancing blows with a succession of nuclei, a process called moderation. Because light nuclei such as those from hydrogen atoms efficiently moderate neutrons, neutron detectors usually include a block or sheet of a hydrogenous moderator, such as paraffin or polyethylene.

Tough, Smart, and Modular

In Ianakiev's design, the detector's body is the moderator. The body of his current prototype is an 18×18×13-centimeter (7×7×5-inch) block of high-density polyethylene—a strong, durable plastic. The block contains a single rectangular detection cell filled with argon at atmospheric pressure. About 60 percent of the block is solid polyethylene. In addition to enhancing the detection efficiency, the mass of polyethylene makes the detector tough.

Embedded in the detector's body are electronic modules that condition and analyze the detection signal and monitor detector performance. An onboard microprocessor makes the detector easy for untrained operators to use and permits detectors to be networked.

The bottom of the detection cell looks like an oversized metal soap dish (see the drawing on page 20). Deposited on the cell's inner surface is a thin layer of lithium-6, which absorbs moderated neutrons and produces alpha particles and tritons. The layer is thick enough for a high reaction rate yet thin enough for about half of the tritons and alpha particles to penetrate the layer and

Gas-Filled Radiation Detectors

A gas-filled radiation detector is usually a glass tube that contains two concentric electrodes and a gas such as argon. The outer electrode is a metal tube; the inner electrode is a wire stretched between the ends of the tube along its axis. Energetic charged particles, x-rays, or gamma rays entering the detector strip electrons from the gas atoms to produce positively charged ions and negatively charged electrons. An electric field created by several hundred volts or more across the electrodes draws the ions to the negative electrode and the electrons to the positive electrode. The electron flow produces a current pulse, which is the detection signal. The charge produced by a 1-million-electronvolt charged particle coming to rest in the gas is about 5 femtocoulombs.

The magnitude of the electric field determines the detector's mode of operation. In order of increasing electric field, the detector operates as an ionization chamber, a proportional counter, or a Geiger-Müller tube. The modular neutron detector operates as an ionization chamber.

The field in an ionization chamber is high enough to prevent the electron-ion pairs produced by the radiation from recombining but too low for the electrons to produce additional electron-ion pairs in collisions with gas atoms. Because the current pulse produced by each radiation packet is proportional to the energy the packet ultimately deposits in the detection gas, the detector can measure the distribution of the deposited energies. This feature allows a neutron detector to discriminate between neutrons and background gamma rays, as shown in the figure on page 21. (Most of the background radiation comes from gamma-ray-emitting radioactive isotopes in the environment, such as potassium-40, uranium-238, and thorium.) However, the current pulse is so weak that it must be amplified electronically.

In a proportional counter, the field is high enough for the electrons to produce additional electron-ion pairs—an amplifying process called gas multiplication. A proportional counter requires only minimal electrical amplification. However, the field is still small enough to preserve the proportionality between the current pulse's amplitude and the energy deposited by the radiation packet. Thus, a proportional counter can also discriminate between neutrons and background gamma rays. The amplification factor of a proportional counter increases as the field increases.

At an even higher field, however, a gas-filled detector's proportionality is destroyed, and the amplitude of the detection signal is constant no matter what the deposited energy. A radiation detector operating in this mode is a Geiger-Müller tube, which needs little or no electrical amplification but cannot be used to measure the deposited energies. This tube is the heart of the Geiger counter.

Vicente Garcia

A computer rendering of a fieldable modular neutron detector, which will have eight detection cells and a detection area of 0.21 square meter. Most of the detector is high-density polyethylene. Electronics embedded in the detector's body amplify the detection signal, provide high voltage for the detection cells, and enable the detector to communicate with other detectors. Stacked on their sides, modular detectors could be used to build neutron-detection walls along highways, inspection arches at vehicle entry points, and distributed-detector networks encircling facilities or towns.

ionize the cell's gas. The optimal thickness for the layer was calculated by Los Alamos scientist Martyn Swinhoe.

Because lithium will not bond directly to polyethylene, the lithium is deposited on a metal substrate that does bond to the plastic. The substrate also prevents the gases emitted by polyethylene from entering the detection volume.

A flat polyethylene lid with a lithium undercoat covers the top of the cell and provides a flat surface for an O-ring gas seal. The lid is bolted to the detector's body. Filling the cell with argon at atmospheric pressure simplifies adding the gas during detector manufacture and eliminates the safety problems of pressurized vessels.

With the lid in place, the detection volume is completely enclosed by metal, which improves detection sensitivity by shielding the volume from the electrical noise produced by power lines and other external sources. The metal enclosure is also the detector's negative electrode. A thin aluminum sheet on the detector's exterior electrically shields the embedded electronic modules.

The cell's positive electrode is a metal ball screwed onto the end of a modified spark plug, which extends from the lid into the detection cell. In addition to providing an insulated connection to the positive electrode, the spark plug—built to withstand the harsh, percussive environment of an internal combustion engine—will not vibrate if the detector is bumped.

The shortest dimension of the detection cell—its depth—equals the longest distance a lithium-produced triton will travel in argon at atmospheric pressure before coming to rest. Because a lithium-produced alpha particle will travel an even shorter distance, both the tritons and the alpha particles ionize as much argon as possible, providing maximum detection sensitivity.

Head-to-Head with the Proportional Counter

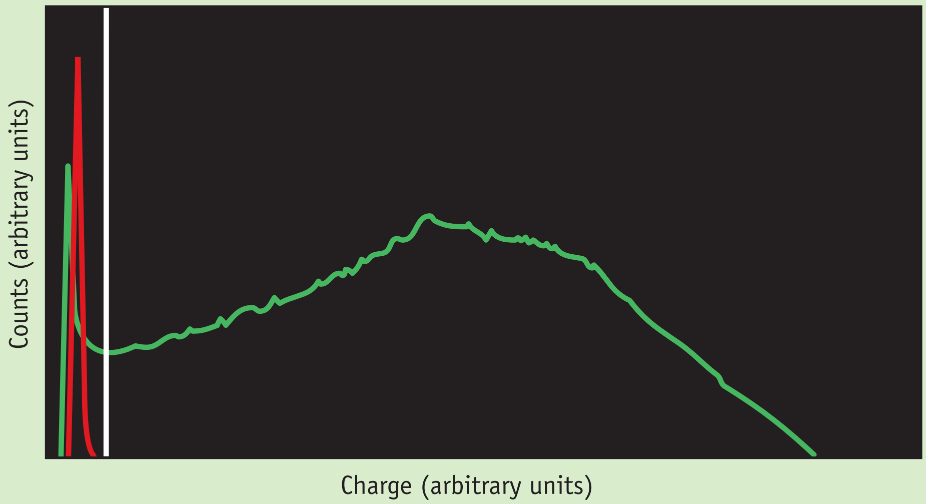
The neutron detectors now being deployed are proportional counters filled with either helium-3 or gas compounds made with boron-10. Proportional counters have been the workhorses of neutron detection for decades. A proportional counter with a detection area of 1 square meter requires about twenty 1-meter-long gas-filled tubes, each costing about $1,200.

Because a proportional counter uses gas multiplication, its detection signal is highly sensitive to gas impurities. Thus, the gas in a proportional-counter tube must be at least 99.999 percent pure. In fact, about half the cost of a helium-3 proportional-counter tube is in its high-purity gas. In contrast, Ianakiev's detector—which does not use gas multiplication—works even with inexpensive welding-grade argon, which has a purity of 99.5 percent. Furthermore, the small amounts of oxygen, water vapor, and carbon dioxide slowly emitted from the detector's interior surfaces will be absorbed by the lithium coating, so that outgassing will not affect detector performance for twenty years or more.

Finally, because the proportional counter's wire electrode can easily be made to vibrate—and thereby to produce spurious signals—the detectors are susceptible to shock and vibration. Supported by a robust spark plug, the relatively massive spherical electrode in Ianakiev's detector resists vibration.

Fieldable Detectors

Ianakiev's detector is rugged, reliable, and versatile—in addition to being a good neutron detector. To reduce the cost of his fieldable detectors, Ianakiev plans to use mass-production techniques and inexpensive materials. For example, he will form the detector's body from high-density polyethylene with injection molding, a common technique for making inexpensive plastic parts. He will use electroplating or sputtering techniques to lay down the detection cell's metal substrate. Finally, he will deposit the lithium layer over the substrate with techniques used to mass-produce lithium batteries. Such techniques should make it practical and economical to deploy neutron detectors wherever they are needed to counter terrorist nuclear threats. ■



Measurements made with a single-cell prototype of the modular neutron detector. Two isotopes were used for the tests: cesium-137 (red), which emits gamma rays, and californium-252 (green), which emits alpha particles, neutrons, and gamma rays. The horizontal axis is the charge produced in the detection cell by the radiation packets, which include gamma rays and the tritons and alpha particles emitted from neutron-absorbing reactions in the cell's lithium layer. (Californium-252's alpha particles are absorbed by the source's container before they reach the detector.) The vertical axis is the number of radiation packets that produce a given value of charge. The two sharp peaks on the left are produced by the sources' gamma rays. The remaining data is from neutrons. When the detection threshold is set at the white line, the detector responds only to neutron-emitting materials such as plutonium and rejects gamma-ray-emitting materials such as radioactive pharmaceuticals or radioactive elements in the environment. By discriminating between these two types of radioactive materials, the detector yields fewer false positives, increasing inspection efficiency.

The Researchers

Kiril Ianakiev has an M.S. in electrical engineering from the Technical University of Sofia, Bulgaria. Before joining Los Alamos as a technical staff member in 1996, he consulted at Los Alamos and for the International Atomic Energy Agency in Vienna on low-power, pulse-height analysis technology. He has six patents for nuclear instruments.

Martyn Swinhoe has a Ph.D. in nuclear physics from the University of Birmingham, United Kingdom. Before joining Los Alamos as a technical staff member in 2002, he worked at the Harwell Laboratory in the United Kingdom and as a Euratom safeguards inspector in Luxembourg.

John Flower