

Detecting Concealed Explosives with Gamma Rays

FEATURE

by Joseph J. Sredniawski

Gamma resonance absorption can be used to detect concealed explosives in loaded cargo containers

In the wake of the destruction of Pan Am Flight 103 over Lockerbie, Scotland, U.S. airport security suddenly looked dismayingly vulnerable. After all, airport security systems were designed to detect hijackers carrying concealed guns or knives. Flight 103, however, was probably destroyed by the detonation of less than a pound of plastic explosive.

In response to the Aviation Security Act of 1990, drafted after the Lockerbie tragedy, the Federal Aviation Administration (FAA) has funded at least 85 projects to develop new explosives-detection technologies. Of these 40 are currently active, and 19 of the 40 are dedicated to the development of prototype detection systems.

So far, the only system that has met the FAA's classified certification standard for explosives detection is the InVision CTX 5000, an X-ray machine that uses computerized axial tomography to create images of the contents of baggage. InVision Technologies (Foster City, CA) was recently awarded a \$52.2 million FAA contract to build and install 54 of these machines in 1997.

According to *Aviation Week & Space Technology*, "The FAA has been looking for a single machine that can automatically inspect bags with a high degree of detection and a low false-alarm rate," a so-called silver bullet. The agency is said to be under increasing pressure, however, to abandon the standard and to adopt a variety of technologies to meet all the security threats that airports face.

Among the most technologically demanding of these threats are explosives concealed in cargo containers. With the exception of passengers and carry-on baggage, everything that flies goes into the cargo hold. Currently, cargo containers are not screened for explosives before being loaded on an aircraft, in part because there is no practical means of doing so. The root of the difficulty is the sheer bulk of the container; whereas a typical carry-on suitcase has a volume of 2.27 cubic feet, an LD-3, a medium-sized cargo container, has a volume between 145 and 158 cubic feet.

For this reason the many technologies under development for screening loose baggage, such as dual-energy X-rays, X-rays with backscatter, thermal-neutron analysis, and quadrupole resonance, are not candidates for cargo screening. Experimental cargo-screening sys-

tems rely instead either on the ability to detect minute amounts of chemicals in air samples or on energetic particles, such as fast neutrons or gamma rays.

To solve the special problems posed by cargo inspection, the FAA is considering a technology called gamma resonance absorption (GRA), which relies on the preferential absorption of particular gamma rays to detect explosives. Northrop Grumman's Advanced Systems & Technology Group of Military Aircraft Systems Division (Bethpage, NY) is developing a proof-of-principle GRA system, with assistance from TRIUMF (Vancouver, BC) and Scientific Innovations (East Hampton, NY) and with funding from the Advanced Research Projects Agency. Although this system was originally intended primarily to detect drugs, analysis has shown that it might function more effectively as a bomb detector. The proof-of-principle system is expected to undergo testing early this year.

In addition to providing the penetrating power needed to inspect cargo, the GRA system has several features that give it a probability of detection superior to most explosives-detection systems now under development. It can discriminate between substances of equal density but different composition; it has the resolution needed to detect thin sheets of explosive; and it can create three-dimensional images of a container that would reveal explosives hidden behind other objects. Although GRA's greatest asset is its ability to inspect loaded cargo containers, it could also be used to examine smaller containers or loose baggage placed in a carousel for batch processing.

A needle in a haystack

Most plastic explosives, such as Semtex, military C4, and Detasheet, are dense materials that contain large amounts of nitrogen either in organic form or as nitrate salts. The GRA system distinguishes explosives from other materials on the basis of two characteristics: their total density, and their nitrogen or chlorine density. Total density alone is not sufficient to separate contraband from common materials or materials deliberately used for concealment; concrete, salt, and sugar, among other substances, have densities similar to those of explosives (see Figure 2).

Nor is nitrogen density alone sufficient; materials such as leather and nylon have nitrogen densities similar to those of explosives. But a high probability of detection



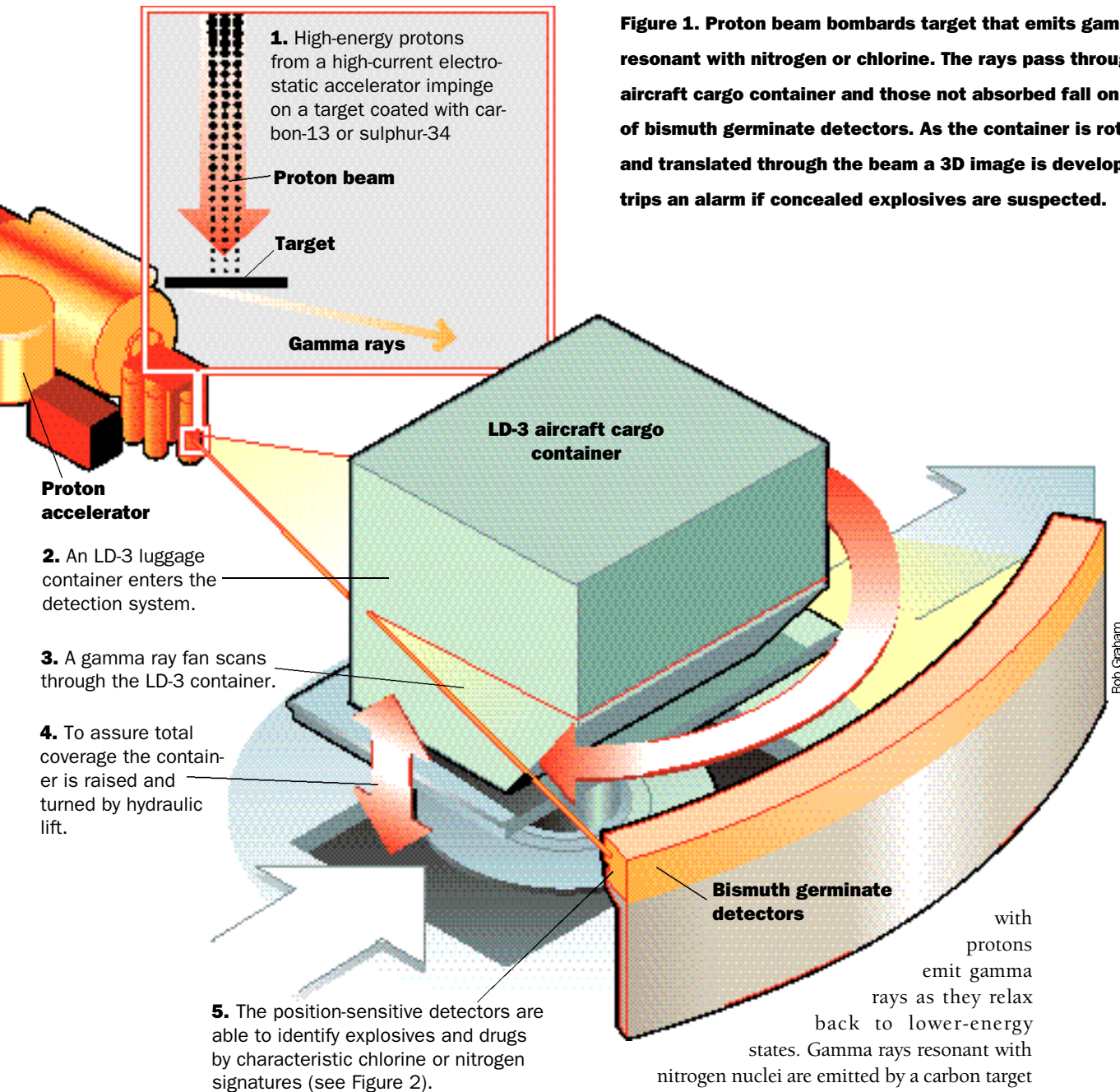


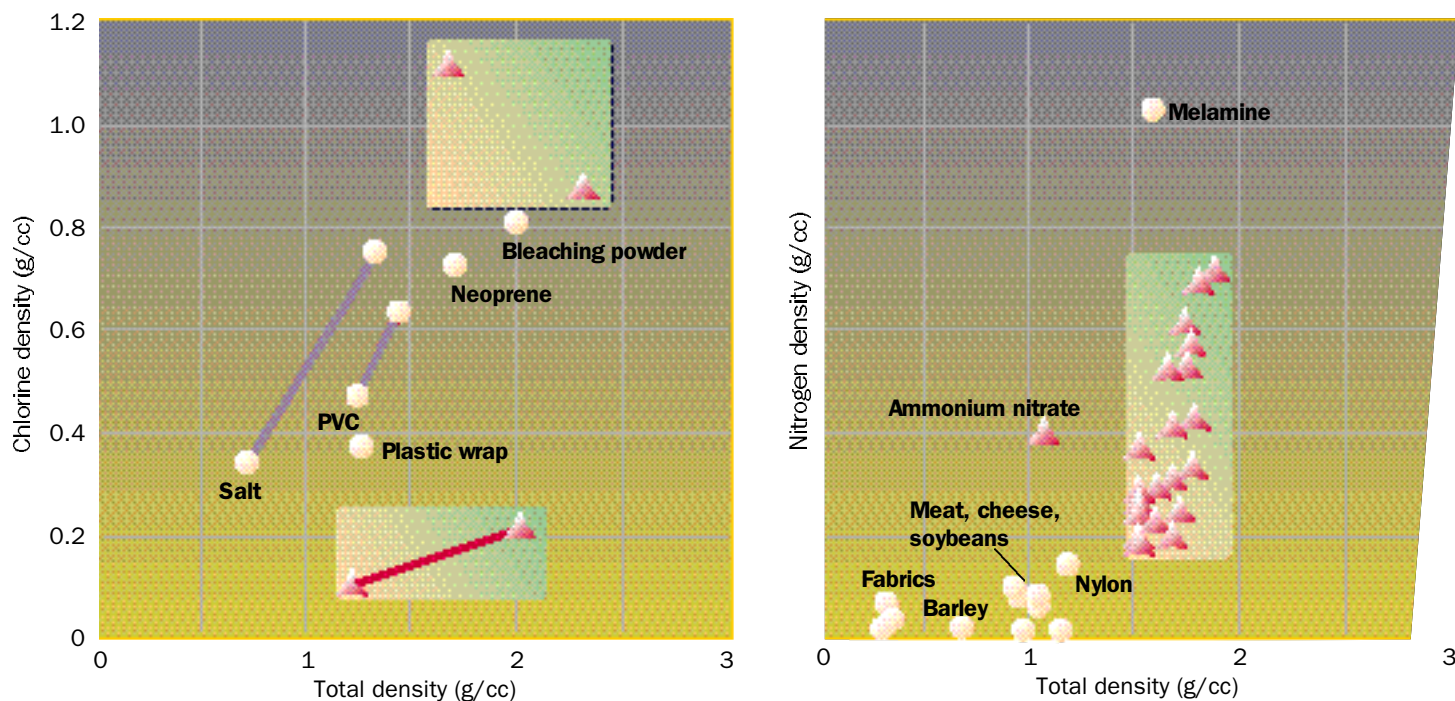
Figure 1. Proton beam bombards target that emits gamma rays resonant with nitrogen or chlorine. The rays pass through the aircraft cargo container and those not absorbed fall on an arc of bismuth germinate detectors. As the container is rotated and translated through the beam a 3D image is developed that trips an alarm if concealed explosives are suspected.



and low false-alarm rate can be achieved by examining both total density and nitrogen density and using tomography to produce three-dimensional maps of their distribution. Less common chlorine-rich explosives, such as HTH and N-trichloride, can be detected by examining chlorine density instead of nitrogen density.

In GRA, nitrogen or chlorine is detected by the preferential absorption of gamma rays: gamma radiation at 9.17 MeV is resonantly absorbed by nitrogen (^{14}N) nuclei, and 8.21 MeV gamma radiation is resonantly absorbed by chlorine (^{35}Cl) nuclei. The gamma rays are produced by nuclear reactions that occur when an appropriate target is bombarded with a proton beam of appropriate energy. Target nuclei excited by collisions

with protons emit gamma rays as they relax back to lower-energy states. Gamma rays resonant with nitrogen nuclei are emitted by a carbon target in a 360° cone at an angle of 80.7° to the proton beam. Gamma rays resonant with chlorine nuclei are emitted by a sulfur target in a similar cone at an angle of 82° to the proton beam. In both cases the resonant gamma cone is about 0.5° thick.

The gamma rays pass through the material under inspection, and those not absorbed there fall on an arc of bismuth germinate (BGO) detectors, the type of detector used in positron emission tomography. Because gamma rays resonant with nitrogen or chlorine are produced at similar angles to the proton beam, they can be detected with a common array. Bombardment of the target also produces a spray of gamma rays that are not resonant with any particular element. These are collected at off-resonant angles by the same detector array and used to obtain total-density data.



 Explosives
 Common materials
Figure 2. Explosives have a unique signature compared to common materials when chlorine density or nitrogen density is plotted against total density

The throughput problem

The goal in the design of any explosives-detection system is to achieve high throughput with a high probability of detection and a low false-alarm rate. Many of the engineering problems encountered in the design of the GRA system arise from the throughput requirement.

Under the best of circumstances, the probability that resonant gamma rays will be generated by collisions between protons and target nuclei is fairly low. To maximize the efficiency of gamma production, therefore, the proton beam must have a small energy spread. This dictates the choice of an electrostatic accelerator instead of, for example, a radio-frequency (rf) quadrupole accelerator, a component commonly used in the first stage of university or research accelerators. In an electrostatic accelerator, almost all of the protons exit at an energy equal to the potential of the high-voltage terminal. The particles exiting an rf quadrupole accelerator, on the other hand, have a much broader range of energies and produce resonant gammas less efficiently.

The need to minimize both power consumption and machine size dictated a novel, tandem accelerator design. A steady stream of negatively charged hydrogen ions generated by a special ion source is fed into the accelerator. The ions are accelerated toward a high-voltage terminal, where their electrons are stripped, converting them into protons. The protons are then accelerated to their final energy as they pass to ground potential. This tandem arrangement, where the particle charge is changed in midstream, gives twice the acceleration for a given power-supply potential as a single-ended design.

To obtain the gamma flux needed for reasonable baggage throughput, the proton beam current has to be at

least 10 mA, higher than a tandem electrostatic accelerator has ever achieved. Reaching such a high current required development of a stripper cell and a compact high-voltage power supply. Moreover, because the heat load on the gamma production target is roughly 17 kW/cm² at this beam current, advances in target design were also required.

Simulating performance

Were these innovations enough to put us over the FAA's specification of a baggage throughput of 450 bags per hour per machine? (This is the only specification in the classified explosives-detection standard that has been published.) To find out, we simulated the performance of the GRA system with a computer model.

In the model, the GRA system is assumed to be inspecting a cylindrical volume (the virtual cylinder swept out by the longest dimension of rectangular baggage) holding a mixture of 70% clothing, 25% dense objects, and 5% voids. The volume might contain either innocuous nitrogen-rich materials or nitrogen-based explosives. When the probability of detecting 450 g of explosive was set at 90%, the false-alarm rate was a function of the scan rate

The GRA system performs best in situations that exploit the penetrating power of gamma rays, such as cargo inspection. However, it can inspect small containers or loose baggage efficiently if the loose items are placed in a carousel sized to provide highest possible throughput at an acceptable false-alarm rate. The data provided by the simulation suggest that one such station could achieve a throughput of 300 to 500 bags per hour with a false-alarm rate lower than 4%. By comparison,

existing X-ray machines have a throughput of more than 1,000 bags per hour, but they experience a false-alarm rate of nearly 30%.


Size is an issue

An accelerator is a large piece of equipment and space is at a premium at airports, particularly older ones. Mundane as this consideration might seem, a practical system must address it. A tandem accelerator with a stripper cell is smaller than a single-ended electrostatic machine because a lower voltage is used to accelerate the particles. The clearance between the high-voltage terminal and the outside containment shell can be much smaller. Even so, a tandem accelerator is bigger than the average refrigerator.

In the end, the size problem may be solved in part by sharing the accelerator among targets or among detector arrays. One accelerator might supply several inspection stations on a time-share basis, or one accelerator and one target might supply as many as four detector arrays. The latter design, which would make use of the entire cone of resonant gamma rays, is made possible by a proprietary target that is virtually transparent to gamma radiation. We calculate that such a multiple-array sta-

tion could achieve a throughput approaching 2,000 bags per hour.

At a permanent GRA installation in a new airport, the accelerator would be located remotely, possibly in the basement of the building. The proton beam would be directed up through the floor to the target, which would be located between two opposite inspection stations. The two stations, handling loose baggage, would operate as a level-2 system—that is, employed to inspect baggage flagged as suspect by multiple level-1 X-ray systems.

Figure 1 shows a GRA system capable of interrogating LD-3 containers. Such a device might be shared by several air carriers and used to inspect selected cargo. A permanently installed GRA system sized for LD-3 containers might be able to inspect four containers simultaneously. The time needed to complete a full tomographic scan of an LD-3 is estimated to be between 10 and 20 minutes, and so the system might have a throughput as high as 24 containers per hour. 

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