# X-ray cargo screening systems: the technology behind image quality

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X-ray cargo screening for container security and contraband interdiction has emerged quickly and is fast becoming a common feature in ports throughout the world. While early systems were custom adaptations of industrial inspection equipment, today's x-ray inspection systems are specially tailored for the inspection of sea containers, trucks, and rail cars within small confined areas. The latest technology allows systems to rapidly produce high quality images (Figure 1) while minimising the disruption of commercial port activities. The question has changed from "whether to use x-ray inspection?" to "what to look for in current technology?" Clearly, image quality is the critical objective. Only with systems that can discriminate between subtle differences in density, shape, and outline, can a user effectively identify contraband materials.

Two primary components are responsible for determining the ultimate quality of the x-ray image a system produces. First, the x-ray source must have sufficient power and dose to fully penetrate the most densely loaded container, yet, not too much power, which would result in excessive cost, size, and operating area space requirements. Second, the detector array, which is the component that captures the x-rays that penetrate the container and converts them to electrical signals, must be highly sensitive and possess a wide dynamic range to provide data that accurately reflects the object being scanned.

## X-ray source technology

The first x-rays were produced with specially designed vacuum tubes, which are still used today for medical applications, industrial inspection, and airport baggage screening. While today's tubes offer much more sophisticated technology, they still are limited in energy output to about 450 KeV (kilo-electron-volts). This energy level limits the penetrating power to less than 100 mm of steel, making it inappropriate for container screening applications. A more effective solution is to generate the x-rays using linear accelerators (linacs), which are scaleable in energy output up to 9 MeV (mega-electron-volts), producing the ability to penetrate over 400 mm of steel.

The x-ray penetration of steel and water is often used to determine how much x-ray energy is needed for an application. The chart in Table 1 shows the maximum penetration in water and steel for x-rays at varying energies. Note that as energy changes, materials act differently in absorbing x-rays. This is reflected by a changing ratio of penetrating power. The ratios shown are the penetration through water divided by the penetration through steel for each energy range.

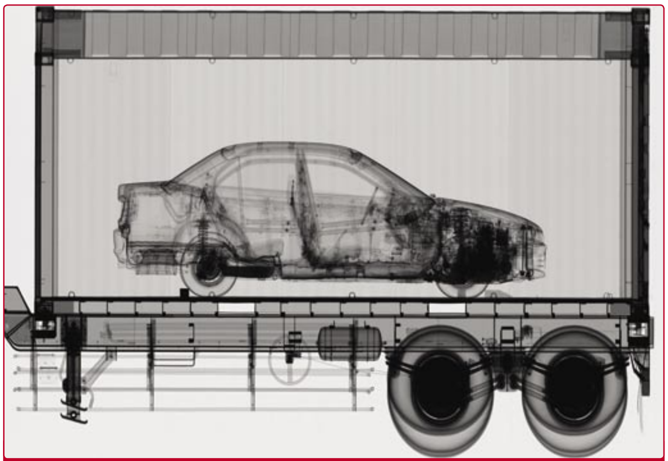

Figure 1. An actual cargo x-ray image.

While the optimal energy level for cargo screening is a function of the detector components and overall system design, many cargo screening system manufacturers have found that 3 MeV to 6 MeV linacs produce the best tradeoff for overall performance and cost. Below 2 MeV, x-ray penetration is not complete for heavily loaded containers. Conversely, energies significantly above 9 MeV require extensive shielding and produce neutrons as an unwanted by-product.

Linacs used for cargo screening have X-ray outputs that are pulsed rather than constant. Pulses are on the order of 4 microseconds long and have adjustable repetition rates of 50 to 500 pulses per second. While pulsed operation is a specific design technique to produce x-rays efficiently, it also allows smaller and more cost effective accelerators to be manufactured. Higher repetition rates do not affect the quality of the output and allow faster vehicle throughput. For example, at 500 pulses per second, cargo containers can be scanned as they move at speeds of nearly 10 kilometres per hour and still achieve a 5 mm horizontal resolution.

## X-ray detector technology

As high energy photons travel from the x-ray source through the container, some of the photons will be dissipated or trapped by the contents of the container and not be available for detection. However, those that make it all the way through ultimately strike the detector material, where they are converted into

TABLE 1: X-RAY ENERGY VS. PENETRATION

| Energy | 1.25 MeV | 2 MV | 3 MV | 4 MV | 6 MV | 9MV |
|---|---|---|---|---|---|---|
| Steel | 133 mm<br>5.2 inches | 205 mm<br>8.1 inches | 297 mm<br>11.7 inches | 352 mm<br>13.9 inches | 406 mm<br>16.0 inches | 430 mm<br>16.9 inches |
| Water | 88 cm<br>35 inches | 137 cm<br>54 inches | 205 cm<br>81 inches | 253 cm<br>100 inches | 316 cm<br>124 inches | 364 cm<br>143 inches |
| Ratio | 6.6 | 6.7 | 6.9 | 7.2 | 7.8 | 8.4 |

visible light (scintillation) and measured by very sensitive photo-detectors. While this basic technique has been used for some time, new advancements in detector technology have allowed several improvements in today's detector sub-systems. These improvements include the following features that users should consider when assessing detector technology.

## Modularity

Current designs offer individual detector channels (essentially 1 pixel per channel) that are grouped into modules (typically 32 channels per module) and then the modules are stacked to make a complete detector array. In this way, individual modules can be produced more economically and replaced in the field.

## Dynamic range

Image quality is dependent on the ability of detector systems to accurately measure the full range of x-ray signals striking the detector. Variations in the attenuation paths due to object densities, orientation, packaging, and the like can vary by as much as 100,000 to one. Thus, signal converters with at least 18 bits are needed to recover these widely variable signals.

## Sensitivity

Sensitivity is a detector's ability to measure small signals and small changes in signals. Because photons are converted to light and detected in an electrical circuit, the lowest level of signal that can be detected is theoretically set by the noise sources of the electrical components. Detector temperature and electrical component design are primary factors in determining this 'noise floor.' Because other non-electrical sources of noise such as channel cross-talk and scatter are present, the actual noise floor is higher than would be the case with just the electrical circuit noise. In addition, the detectable signal must be consistently stronger than the total noise level for the system to produce accurate measurements. It is also important to detect small changes in signals, which will represent shades of grey (or computer generated colour variations) in the final image. This sensitivity is dependent on the linearity of the detector transfer function. Good detectors will have electrical and mechanical components that compensate for nonlinear regions to allow accurate image reconstruction for the full range of possible signals.

## Scatter rejection

X-rays can be easily diverted when they strike electrons. When this occurs, the new paths are generally unpredictable, but will be non-colinear with the original path. Known as Compton scattering, this process is problematic for detector arrays because it results in new photon paths that sometimes strike adjacent detectors rather than the appropriate detector. These become false signals, which can interfere with or corrupt the intended measurement. Unlike noise, scatter has the potential to be much stronger and distort even moderate signals.

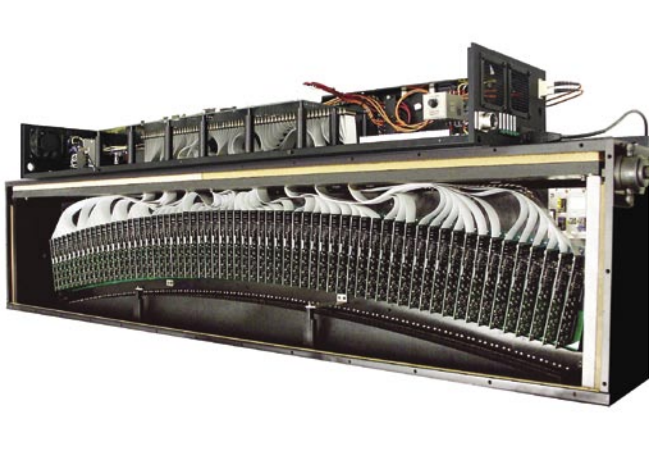

Figure 2. A current technology detector array with 20 bit resolution.

Scatter rejection through collimation and other techniques is an important overall system design characteristic but it is particularly important at the detectors themselves. Good detector design will include a careful physical orientation of the photo-electrical components in conjunction with layering of appropriate shielding materials. Much attention is given to the isolation of adjacent channels, which are more likely to be affected by scattering. Because these intricately designed components are expensive to produce, some low cost detector sub-systems lacking sufficient scatter reduction may exhibit substantially lower performance in terms of dynamic range and, thus, image quality.

## Element (pixel) size

The active area of each element in the detector and the spacing of detector elements (both typically in the 1 to 5 mm range) are a limiting factor in the raw data resolution available for computer image processing. Typical cargo scanning systems utilise linear arrays of detectors (see Figure 2) that are positioned vertically or in an 'L' shape, opposite the x-ray source, to provide a 'slice' of data for analysis. As the container is moved through this beam, an image is constructed by integrating all of the individual slices. Thus, the horizontal resolution is determined by a combination of the x-ray pulse repetition rate and the velocity of travel through the beam.

## Summary

Excellent image quality is the core requirement for an effective cargo screening system. It begins with the careful selection of an appropriate x-ray source and a matching detector sub-system that addresses the technical factors described in this article. With these elements in place, software developers and systems providers are continuously providing new features and capabilities to further enhance effective screening systems.


### ABOUT THE AUTHOR

**Dr. William A. Reed** is the Product Manager for New Products at Varian Medical Systems' Security and Inspection Products Group. He has held engineering and management positions for security equipment design firms for over 25 years and holds both US and International patents for security products.


### ABOUT THE COMPANY

**Varian Medical Systems, Inc., Security & Inspection Products**, is the market leader for industrial CT systems, high energy x-ray linear accelerators, and matching detector arrays. With over 35 years of experience in manufacturing industrial products, Varian has produced over 500 linear accelerators for the security and inspection market and maintains sales and support offices worldwide.


### ENQUIRIES

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