Imaging Using Energy Discriminating Radiation Detector Array

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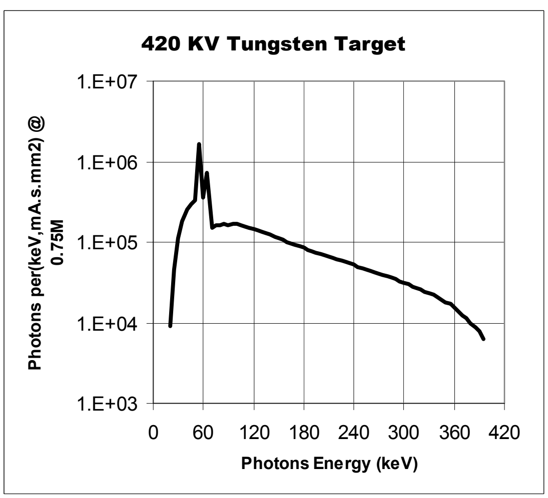
ABSTRACT

Industrial X-ray radiography is often done using a broad band energy source and always a broad band energy detector. There exist several major advantages in the use of narrow band sources and or detectors, one of which is the separation of scattered radiation from primary radiation. ARDEC has developed a large detector array system in which every detector element acts like a multi-channel analyzer. A radiographic image is created from the number of photons detected in each detector element, rather than from the total energy absorbed in the elements. For high energies, 25 KeV to 4 MeV, used in radiography, energy discriminating detectors have been limited to less than 20,000 photons per second per detector element. This rate is much too slow for practical radiography. Our detector system processes over two million events per second per detector pixel, making radiographic imaging practical. This paper expounds on the advantages of the ARDEC radiographic imaging process.

Introduction

X-ray Generation

X-ray sources for radiography normally are either line sources, using a radioactive isotope, or a Bremsstrahlung source with characteristic lines, that are electronically generated. A Bremsstrahlung source emits photons whose energy spectrum is a continuum from zero to kinetic energy of the accelerated electron in the x-ray generator.



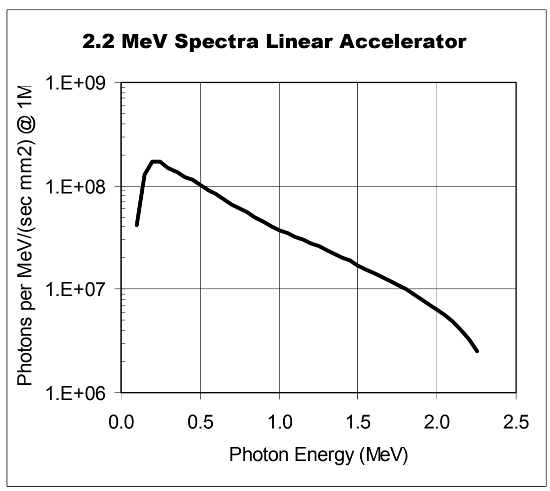


Figure 1: X-ray Spectrum, I_0, for 420 KeV and 2.2 MeV Bremsstrahlung Sources[1].

Because the x-ray photon interaction with matter is energy dependent, the type of source, that is, the source spectrum severely influences how to setup an optimal radiographic procedure.

X-ray Interaction with an Object

A beam of X or gamma rays interacts with matter with a characteristic exponential absorption. The intensity of the beam at location x along the beam path is expressed by the equation

$$I(x) = I_0 e^{-n\sigma x} \tag{1}$$

in which I_0 is the intensity of the incident beam, (see Figure 1) σ is the total probability per atom for scattering or absorption of a photon of the original energy (generally called the cross-section or total attenuation coefficient), *n* is the number of atoms per cubic centimeter in the absorber, and *x* is the distance in centimeters the photon has traversed in the material.

The energy range for X or gamma rays used in radiography is generally between 50 thousand electron volts (KeV) to several million electron volts (MeV). For this range of energy the X-ray photon's interaction with matter is a combination of coherent (also called Rayleigh) scattering, incoherent (also called Compton) scattering, the photoelectric effect, pair production, and photo disintegration.[2] That is for equation 1

$$\sigma = \sigma_{ph} + \sigma_r + \sigma_{pr} + \sigma_{pd} \qquad \textbf{(2)}$$

Photodisintegration is important only from 10 MeV to 20 MeV, and even then, the effect is too small to be of interest. Each of the attenuation coefficients are a different function of the photon energy. (See figure 2)

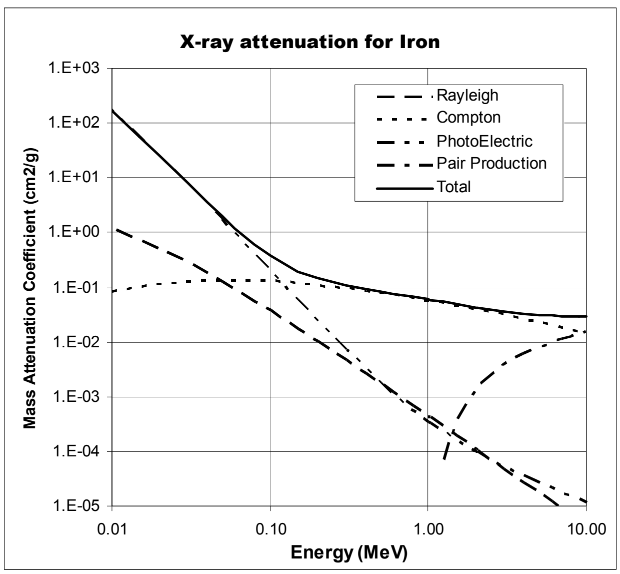


Figure 2. Attenuation coefficients as a function of energy for iron[3].

For photoelectric absorption the photon's energy is completely absorbed freeing electrons from their bound state. The photoelectric effect is the dominate process for low energy photons. In iron when the x-rays are less than 70 KeV (see Figure 2), the photoelectric attenuation is more than ten times that of any other attenuation process. The photoelectric attenuation coefficient decreases approximately as the photon energy raised to the -3.5 power.

For Rayleigh scattering the photon's energy is retained, but the photon's heading is altered. The altered photon path is primarily a small angle from the incident photon path. The total attenuation due to Rayleigh scattering is always small and is never greater than 20 percent of the total attenuation of the impinging x-ray beam. It decreases with increasing energy and is only important for photons below a few hundred KeV and when interacting with light elements.

In Compton scattering a photon of lower energy is created at the interaction site. The newly created photon follows a path at a determinable cone angle, θ, from the direction of the initial photon. The cone angle is calculated from the equation

$$\left(1/E\right)-\left(1/E_0\right)=\left(1-\cos\theta\right)/m_0C^2 \quad \textbf{(3)}$$

where E_0 is the incident energy, E is the energy of the scattered photon, and m_0C^2 = 0.51 MeV. The attenuation coefficient for the Compton scattering is predicted by the Klein-Nishina equation, where the differential scattering cross section is:

$$\frac{d\sigma}{d\Omega}=Zr_0^2\left(\frac{1}{1+\alpha\left(1-\cos\theta\right)}\right)^2\left(\frac{1+\cos^2\theta}{2}\right)\left(1+\frac{\alpha^2\left(1-\cos\theta\right)^2}{\left(1+\cos^2\theta\right)\left[1+\alpha\left(1-\cos\theta\right)\right]}\right) \quad \textbf{(4)}$$

with $\alpha = h\nu / m_0C^2$ and r_0 is the classical electron radius.

In pair production the photon disintegrates creating an electron and positron. This cannot occur until the photon's energy exceeds 1.02 MeV. Excess energy from the photon appears as kinetic energy of the pair particles. Scattered photons are not directly created, but the positron quickly interacts with an electron, disintegrating to create "scattered" photons. Probability of pair production rises sharply with energy, until it is the dominate factor.

Scatter in Radiography

A detector placed on the opposite side of the object to the x-ray source is used to record the transmission radiographic image (or simply the radiograph). Ideally the radiograph would only record the X-rays from the source which passed through the object unaltered, which is also referred to as the primary beam. Ideally all of the primary beam would be stopped and recorded in the detector. Under the ideal conditions, the radiograph would be an accurate recording of the thickness, x, of the object and probability, σ, of interaction along the primary ray paths. Interpretation of the radiograph would be simple and totally determinable. Analysis of the ideal radiograph could easily reveal defects in materials, missing items, broken parts, etc.

The ideal case never happens. All of the scatter interactions already described create secondary photons that can be recorded by the detector along with the primary beam. The basic problem is the detector does not know the path by which the scattered x-rays took to get to the detector. The detector, itself, also interacts with the x-rays in the same way as does the object. That is, many x-rays pass right though the detector, some are partially absorbed and emit a scattered photon, and some are fully absorbed. Because the scattered x-rays will mostly be of low energy, they are more apt to be recorded in the detector than the primary beam. The situation can be so bad that over 90 percent of all recorded x-rays may be scatter. **Scatter is the primary culprit which makes radiography (and tomography) difficult and limited in effectiveness.**

Figure 3: Comparison of two photographs, one without scatter and one with scatter.

Figure 3 compares two photographs of the same objects, one without scatter and one with scatter. The primary source of scatter in photography is from the medium between the detector and the object. The problem is worse in radiography because scatter not only comes from the enclosing medium, but also from the object being radiographed, from the recording medium and from nearby objects. Scatter originates from the air, from the floor, ceiling, from behind the detector or any nearby material.

The effect of scatter can to a high degree be predicted using Monte Carlo calculations. Such extensive calculations are not generally performed when setting up a radiographic method. Instead a radiographic method is designed based on past experience and “rules of thumb.” **Methods for film radiography are well developed and understood, but not for digital radiography.**

The procedures for medical radiography, which dominate the industry, differ considerably from industrial radiography, which is the concern of this paper. Objects to be radiographed in the medical field are mostly composed of elements of low atomic number and densities of near one and are live and moving subjects. As a result the medical field uses relatively low voltage, high current sources, with short exposures. The industrial field deals with objects of the whole span of elements, of a very wide range of densities and that are inert. As a result, industrial radiography uses high voltage sources, medium high currents, and exposures that need only to meet industrial manufacturing throughput. The discussion below will need adjustment, if applied to the medical field.

The standard methods for limiting the effects of scatter include:

1. Collimate the primary beam to the dimensions of the object, which reduces the scatter coming from ceiling, floor and nearby objects.
2. Use a spectral filter near the Bremsstrahlung source to cut the intensity of low energy x-rays.
3. Use a spectral filter between the object and the detector to cut the low energy scatter from the object being radiographed.
4. Move the detector some distance from the object. The scatter created by the object diminishes by the square of the distance. Unfortunately, the primary beam also diminishes and the intervening air further scatters the x-rays.
5. Use a gamma ray source that does not produce low energy x-rays.
6. Surround the detector with a lead to cut scattered rays not aligned with the path of the primary x-ray beam.
7. Place a lead sheet behind the detector to eliminate scatter from behind the detector.
8. Use a fine mesh collimating grid near the detector, called a Bucky grid, to cut x-rays not aligned with the path of the primary x-rays.

A good radiographic procedure normally combines many of these methods.

Lead is the normal material for collimation. It is cheap, dense and of high atomic number. Scatter that originates in the lead is mostly absorbed within the lead. Lead is malleable so that it can be formed around objects. Only thin layers are required because of its high absorption coefficient.

A standard film radiographic procedure is to sandwich the film between two thin layers of lead. The thickness of lead is chosen so that the low energy photons (mostly scatter) are mostly absorbed in the lead, far from the film, but the high energy photons (those transmitted through the object) will mostly interact with the lead near the film. The interaction creates free electrons, which, if the film is directly in contact with the lead, further "exposes" the film and intensifies the image. The lead on the back side of the film can also interact with the photons and expose the film. The backside lead will cut backscatter, that is, secondary radiation which might come from behind the film. Electrons freed in the lead create a more intense image in the film than would the photons interacting directly in the film. The freed electrons, which hit the film, are more effective in exposing the film than photons themselves, so there is an intensity boost from the process.

Each of these procedures is limited in its effectiveness:

1. Spectral filters are composed of one or more elements chosen for their x-ray attenuation. The attenuation curves in Figure 2 are typical. The cutoff is extremely flat causing the filtration process to be marginally effective.
2. Spectral filters create their own scatter, which can become a major problem.
3. Collimators also scatter x-rays into the detector.
4. Bucky grids caste an image onto the detector.
5. Air, which surrounds everything, scatters x-rays into the detector no matter what one does.
6. The lead intensifying screens weakly differentiate between the high energy and low energy photons, so the image, though improved, still suffers from scatter.

As previously stated, the film radiographic procedures are well established and provide amazingly high quality images. **Surrounding the film with thin lead in direct contact with the film is probably the most important and effective part of the process**.

Digital Radiography

In digital radiographic systems there exist several means of acquiring the digital image. The means of acquisition determines the possible means of eliminating x-ray scatter.

A common method uses a photo sensitive plate similar to film in size and format, which is read out with special scanning equipment into a pixilated digital image and can be erased. All of the scatter reduction procedures for film apply, except for the use of lead intensifying screens.

Another common digital method is the use of a scintillating material such as gadolinium oxysulfide, bismuth germanate, or cesium iodide placed in close proximity with a light detector such as an amorphous silicon sensor array or a photodiode array.[4] The scintillating material is chosen based on several criteria, one of which is the x-ray absorption coefficient. The data is digitized from the photo detector array and transferred to a computer. All of the scatter reduction procedures for film apply, except for the use of lead intensifying screens. The detector system is complicated enough to create its own scatter for which there is no simple means of elimination. Other problems that affect the quality of the image are crosstalk from visible light leakage, afterglow, low light yield, matching of light spectrum to light detector sensitivity. Because the scintillating material is chosen to have high density and high average atomic number, this method can be better than film without use of lead intensifying screens, but for many applications will not be as good as film combined with intensifying screens.

A third common method is using a scintillating screen in conjunction with a scientific CCD camera. This method has the advantage that CCD camera's signal to noise ratio has been continuously improving and the pixel count has been continuously increasing so the system can be upgraded by only replacing only the CCD. Spatial resolution is not fixed as in other digital methods, but is determined by the optics. Unfortunately, the objects holding the scintillator, the mirrors and the light tight enclosure around the scintillator can and do contribute scatter. All of the scatter reduction procedures for film apply, except for the use of lead intensifying screens. Because the scintillating material is chosen to have high density and average atomic number, this method can be better than film without the lead intensifying screens.

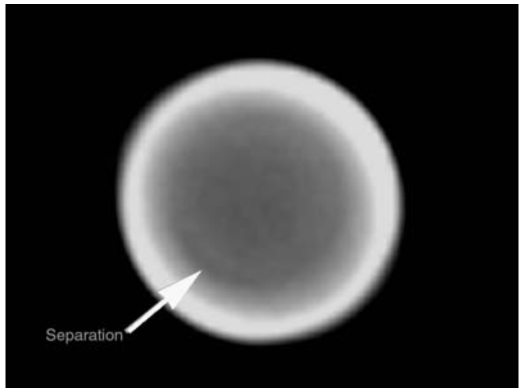


Figure 4 Axial tomographic slice through metal can with plastic insert.

Figure 4 above is a tomographic image of a steel cylinder filled with a plastic material of lower density. There exists an air gap between the cylinder wall and the plastic material. Notice the rather poor demarcation between the steel cylinder, air, and plastic. The demarcation is poor enough that it is difficult to discern where to call out the edges. This is typical of radiographs and tomographs whether acquired via film or digital systems, but more so for digital systems.

Figure 5 below is a plot of the x-ray density profile (solid line) measured from a radiograph of a steel strip that was five centimeter long, 13 millimeter thick and 2.5 millimeter wide. The x-ray source was a Bremsstrahlung x-ray tube with a tungsten target operated at 420 KeV. The dashed line in the figure is the calculated profile where there is no scatter and the point spread function is a delta function and the source consists of only the mean KeV of the x-ray tube. The system used to acquire the data for the solid line was a scintillator plus CCD camera system set at near optimal operational parameters. The wavy structure in the flat section of the 2.5 mm strip is real and comes from a plastic object that was also in the beam. It should be noted that over 50% of the radiation in the shadow region for 2.5 mm steel is scatter and nearly all of the radiation detected in the shadow region of the 13 mm steel is scatter.

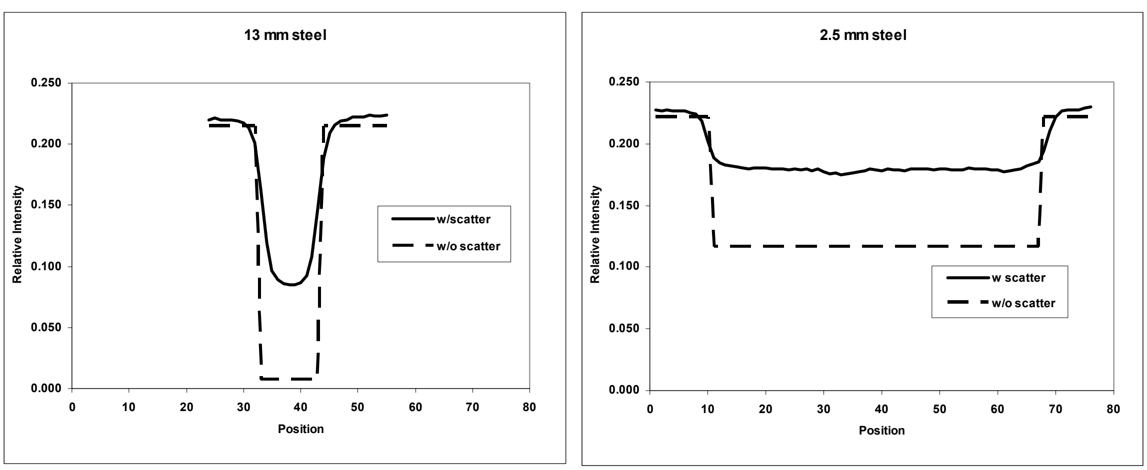


Figure 5: Measured profile from digital x-ray radiograph of a steel strip

ARDEC's Digital Radiography Detector

ARDEC has developed a very effective digital process in which scatter is nearly non-existent in the radiograph. It is done by using an energy discriminating detector system implemented by a custom Application Specific Integrated Circuit (ASIC) developed by NOVA R&D, Inc. under contract to ARDEC[5]. The pixels in the array are operated in pulse mode rather than current mode. The energy of every photon is measured and compared to a threshold. If the photon energy is below the threshold the photon is ignored. If above the threshold, the photon is counted. A radiograph is made from the photon count at each pixel rather than the total energy deposited into a pixel. Imaging by this method has been reported by us and by others without consideration of the advantage afforded for scatter reduction[67]. The energy discriminating detector has five discriminators which can be set for a wide range of energies, so that photons in up to five separate energy ranges can be separately counted. The energy cutoff is very sharp. **The method does not create scattered x-rays as a filter would**. High energy photons can scatter inside the pixel and not deposit all its energy, but no more than would happen in any other detector method. All of the means described previously for reduction of scatter, except intensifying screens, can be used with this detector. The method is superior to intensifying screens used in film radiography and the resulting radiographs are sharper than from other digital radiographic systems.

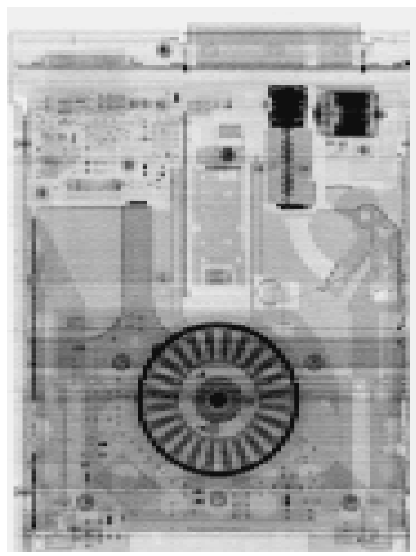


Figure 6 Digital radiograph created by ARDEC's energy discriminating detector

Because the ARDEC system is a multi-energy detector system, all of the advantages and analysis methods used in dual energy[8] systems are available. By using three or more energy bands with the sharp energy cutoff the ARDEC system can more precisely determine the average atomic number and density of the object than would dual energy systems. The ARDEC system is the first large scale imaging system of this type built for and intended to be used in commercial applications. The requirements for commercial applications, which the ARDEC system meets, include:

1. High flux throughput. ARDEC's system processes up to two million photons per second per detector pixel
2. High x-ray attenuation coefficient. ARDEC's first system was built using cadmium zinc telluride (CZT) detector material, thick enough to absorb 80% of the photons at 100 KeV
3. Small pixel size. ARDEC's first system's pixel pitch is 1 mm. This is too large for many applications, but the technology affords pixels of much smaller dimension. Our research shows that smaller pixels should actually improve throughput.
4. Fast Readout. Duty cycle exceeds 95%.
5. Good energy resolution. CZT has better than 7% energy resolution.
6. Large arrays. The ARDEC array is two millimeter by 100 centimeter. Work is underway to produce wider arrays.

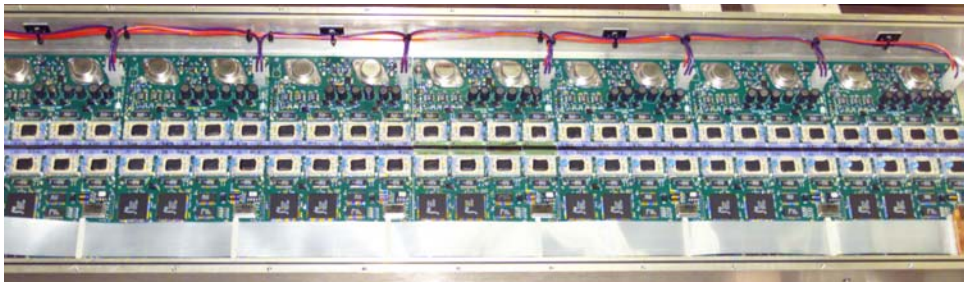


Figure 7 ARDEC's line scanning, x-ray energy discriminating detector.

Conclusion

Digital radiographic systems using standard current mode detectors provide a poorer radiographic image than does film because of their limited means of eliminating scatter. ARDEC's digital radiographic system using energy discriminating detection has sharp energy cutoff that very effectively eliminates scatter providing a crisper image. Such a system can exceed the film - intensifier screen combination in eliminating scatter, which is the best method in the film based radiography.

References

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