1 of 1

High Resolution Tomography of Objects with Access to a Single Side

Robert S. Thoe

This paper was prepared for submittal to the OE/Aerospace,
Underground & Obscured Object Imaging and Detection Conference,
SPIE, Orlando, FL
April 12-16, 1993

March 24, 1993

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

Lawrence
Livermore
National
Laboratory

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

High Resolution Tomography of Objects with Access to a Single Side

R. S. Thoe

L Division

Lawrence Livermore National Laboratory, Livermore, CA 94550

ABSTRACT

We are developing a technique which will enable us to obtain high-contrast, high-spatial resolution, three-dimensional images in opaque objects. Our only constraint will be the radiation source and detector(s) will be located on the same side of the object. Our goal is to obtain images with a spatial resolution of ~1 mm at depths of 10 mm and ~3 mm at depths of 30 mm in materials of moderate density (brass, steel, etc.).

Our technique uses a highly-collimated beam of monochromatic gamma rays and a slit collimated high-resolution, high-efficiency, coaxial germanium spectrometer. If the geometry is well known, the spectrum of Compton scattered radiation can be used to map out the density as a function of depth. By scanning the object in two dimensions, a full three-dimensional image of the electron density can be reconstructed. The resolution is, of course, dependent on the incident beam collimation and the energy resolution of the spectrometer. For our system, we anticipate a resolution of about 1 mm³.

The apparatus, reconstruction algorithms, and current data verifying our predictions are presented here. Also included are the details on how our system can be modified to increase the efficiency by over two orders of magnitude. This system will have several advantages over conventional transmission radiographic and tomographic systems:

- It requires the use of a high specific intensity isotopic source of modest activity (< 100 mCi).
- It requires only a single high-resolution spectrometer used in conjunction with an array of low-resolution detectors (all readily available).
- It allows for the recording of three-dimensional images of objects even though both detector and source are located on the same side of the object.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

1. INTRODUCTION AND BACKGROUND

We feel one-sided tomography has the potential to define state-of-the-art technology in the fields of nondestructive evaluation, quality control, inspection and interdiction. Previously, however, progress in this field has been incremental, primarily due to the intrinsic inefficiency of the x-ray scattering process and the inadequacy of high-energy photon imaging detectors.

Previous attempts to image, using scattered photons, have involved the use of both highly collimated detectors and an equally highly collimated source¹⁻⁴. Although such systems were able to obtain reasonably high resolution and contrast, the consequences of using such drastic collimation were twofold: (1) It was necessary to raster the entire volume being imaged. This meant that the amount of time required for an image scaled directly with the volume of the object. (2) For penetrating radiation, the collimation on the detector and the source had to be thick and heavy. This resulted in a large and unwieldy apparatus. Incremental advances in this technology would be of small value; therefore, a method that would increase the efficiency of the system by factors of a hundred or more was needed.

As a result, Uncollimated Compton Backscattering Tomography (UCBT) evolved, which eliminates the collimation process. Briefly, the kinematic energy shift of the scattered radiation is measured and used to calculate where the scattering has occurred. To achieve this, it is necessary to use monochromatic (or possibly polychromatic) incident photons and to measure accurately the spectrum of the scattered photons. The basic principles of this technique, results of my calculations, and preliminary results from my tomography apparatus are summarized here.

1.1 Conventional One-Sided X-Ray Tomography

The conventional technique typically uses an intense (~ 10 ci) x-ray or gamma ray source. Both source and detector are highly collimated into a pencil of very small angular size. The collimators must be highly opaque to both the incident and scattered radiation since it is the collimation that determines the resolution of the system. The system of collimators define a scattering volume. If the specific intensity of the source is known, the detector efficiency is known, and the geometry is understood, then it is possible to use the measured x-ray flux to determine the electron density of the object. To do this, however, the entire volume must be scanned a voxel at a time. The small magnitude of the scattered signal together with the necessity of scanning the entire volume makes this technology unattractive. Figure 1 illustrates the basic components of the apparatus.

1.2 Uncollimated Compton Backscattering Tomography (UCBT)

By removing the constraints imposed by drastic collimation, the performance of one-sided radiography can be radically improved. Two specific problems of the collimators are: (1) It is necessary to scan the entire volume of interest, and (2) They radically reduce the efficiency of the system.

To understand the principles of UCBT, a review of some of the basic principles of the interaction of radiation and matter and radiography have been included.

Figure 2 shows a graph of the x-ray cross sections as a function of photon energy for all the dominant processes that occur in the range plotted. For relatively low energies, the total interaction cross section is high and is dominated by the photoelectric effect. The photoelectric effect represents true absorption. Scattering can occur from one of two processes: coherent (Rayleigh) scattering and incoherent (Compton) scattering. Coherent scattering dominates at low energies where the primary interaction is dominated by absorption. At higher energies, the Compton effect not only dominates scattering but is the dominant interaction. Note that this dominance occurs in the very region where matter is most transparent. These interactions are also dependent on material properties. The absorption and Rayleigh scattering are both highly dependent on the atomic number Z (absorption $\sim Z^{3.6}$ and Rayleigh scattering $\sim Z^2$). To the contrary, Compton scattering represents the photons' interaction with individual electrons. The strength of this interaction is therefore dependent on the electron density and is relatively independent of the atomic number.

Contrast can be defined as the fractional change in flux density due to the objects inhomogeneity. For absorption radiography/tomography see Figure 3a. As shown, if the argument of the exponent $kd'w$ is small, the contrast will also be small. This implies that for absorption radiography, the contrast decreases as the energy of the radiation increases (i.e., as the radiation becomes more penetrating). The case of Compton scattered radiation imaging is illustrated in Figure 3b. In this

case, the contrast is proportional only to density variations and is independent of photon energy. The implication is that imaging techniques that use scattered photons may use photons of very high energy (highly penetrating) without a subsequent loss of contrast. This is an oversimplification, because it neglects the effects of backgrounds and counting statistics. Using these assumptions, not only does scattering tomography allow detector and source to be on the same side of the object, but scattering will, in principle, outperform absorption when the spatial resolution desired is smaller than the mean free path of the radiation.

Figure 4 illustrates the kinematics of the scattering of a photon with a single electron—the Compton effect. To conserve both momentum and energy, it is necessary that the recoiling electron receive a fraction of the incident photons' energy. The scattered photons' energy must therefore be decreased by this same amount. The equation shown in Figure 4 expresses the relationship between energy of the scattered photon as a function of its scattering angle and its initial energy. This energy shift can be very large and easily measurable for incident photons of energies over about 200 keV—the very region where the Compton starts to dominate in many materials. Figure 5a shows a plot of this equation for incident photons of 5 Mev, 2 Mev, 1 Mev, and .5 Mev. Figure 5b is a plot of the first derivative—the dispersion as a function of scattering angle. As the incident photon energy is increased, the peak in the dispersion moves to forward angles; and at angles > 90 degrees the dispersion is much smaller. However, even at 135 degrees for .5 Mev incident radiation the dispersion is about 50 keV/radian or almost 1 keV per degree. One keV is very close to the resolution of most gamma ray spectrometers. Therefore, one could expect angular resolution of this order by simply measuring the energy spectrum of the detected photons. This corresponds to a spatial resolution of about 2 mm at a distance of 10 cm.

As shown in Figure 6, it is possible to obtain information about where a scattering event occurred without the need for collimating the detector. This is the method employed by Farmer and Collins⁵. Clearly, the energy of the detected photons is directly related to the scattering position. Furthermore, if the scan proceeds from the outside inward, the attenuation of the incident and scattered beam can be determined. A more efficient method was developed by Prettyman⁶. His apparatus is shown in Figure 7. In this technique, neither incident beam nor detector is collimated. Therefore each energy interval in the spectrum, as measured by the detector, corresponds to photons that are scattered from the locus of all points of a given scattering angle. If the object is then rotated and spectra are obtained for each angle of rotation, enough information is obtained to reconstruct the image. The techniques are similar to, and more complex than, those used by conventional tomographic reconstructions. In both of these methods, the ultimate resolution is a direct function of the width of the source, the width of the detector, and the resolution of the detector.

Implicit in the above description is the restriction of the detected photons to single-scatter events. Any contamination of the spectrum, due to multiple scattering in the material would destroy the chain of angle-to-energy-to-position. During the past year, we estimated the magnitude of multiple scattering and devised schemes to minimize its effects⁷.

For one-sided imaging, the Prettyman method is of little value because it requires rotating the object. Although the Farmer and Collins method has more potential, it is still too inefficient to be practical. Again what is needed is large area detectors and an uncollimated source.

1.3 Superman—Virtual Collimation

Figure 8 illustrates our UCBT apparatus. The source is collimated to an approximate pencil by a tantalum cylinder. The detector is uncollimated and views the intersection of the beam with the object through a set of tantalum baffles. The design of these baffles is critical and not yet optimized. The baffles serve two purposes: (1) They are coplanar to the incident beam and confine the detectors field of view to this plane. This reduces the backgrounds due to multiply scattered radiation by about two orders of magnitude.⁷ (2) The field of view is strongly vignetted by these slits. This vignetting allows different depths to be discriminated by its spectrum. If the spectrum from various depths is known, by adding these spectra together, it is possible to obtain the spectrum of the entire object. However, obtaining the spectrum as a function of depth is not straightforward.

According to the results of Monte Carlo simulations of this system⁷, the best efficiency expected is about 10–8. Although this would provide reasonable count rates for sources of moderate activity, it would still require several minutes to obtain a spectrum with adequate statistics, and this spectrum would reconstruct a volume equal to only the cross section of the beam multiplied by the length of the beam ($\sim .02 \text{ cm}^3$). To obtain information about large volumes would be very

difficult. The efficiency could be increased by simply using multiple beams incident or arrays of detectors. Designs along these lines have been tried by investigators using collimated detectors with only limited success. A more effective approach might be to use a technique we call "virtual collimation," shown schematically in Figure 9. (We call this apparatus superman.)

This technique does away with the physical collimation of the source entirely and instead uses the coincidence technique to determine the path of the incident radiation. The radioactive source must be a positron emitter. Positrons emitted by the source nuclei are quickly brought to rest inside the source where they decay by annihilation with their antiparticle, the electron. To conserve both momentum and energy this decay results in the release of two photons—each with an energy of 511 keV and traveling in opposite directions. Therefore, detection of photons by one of the virtual collimator array detectors guarantees that another photon was launched in the opposite direction. If a photon were detected in the spectrometer in time coincidence with a photon detected by the virtual collimator array it would be the same as if that photon had traveled through a collimator. These collimator detectors could consist of one-dimensional arrays and perhaps could be arranged in rows, as shown. It is not difficult to imagine several square centimeters of these detectors giving an increase in sensitivity of perhaps several hundred. But that is not all, in going to virtual collimation, the source can be transported to within a centimeter or two of the object giving another factor of 10 increase in efficiency! Furthermore, the spatial resolution for this system could be greatly enhanced without loss of efficiency.

For a numerical example, consider a virtually collimated source placed 5 cm from the object, and an array of detectors arranged so that the incident beam has a cross section of 3 mm x 1 cm (an increase in nine [solid angle of source] times 30 [beam area] or almost 300. For a 100 mCi source, the count rate in the virtual collimator array would be about three million per second. For an array consisting of 100 detectors of 50% efficiency, the count rate would be about ten thousand per second per detector, which is about 10 to 100 times slower than the throughput of commonly used commercially available coincidence electronics. This detector array does not need good energy resolution.

2. RECONSTRUCTION ALGORITHM

Developing a reconstruction algorithm was difficult because the scattered signals were strongly attenuated in the object being measured and the attenuation coefficients varied considerably with energy (angle). Since the detector subtended a large region in the dispersion direction, the place where the scattering occurred was indeterminate by this same amount. The expression for the intensity of the singly scattered photons as a function of energy is:

$$(dN / dE)dE = S \iint d\Omega dr d\eta \left(\frac{d\sigma}{d\Omega} \right) \frac{e^{-k_1 r_1 - k_2 r_2}}{R_1^2} \quad (1)$$

where:

- S = constant dependent on the source activity and geometry
- $d\Omega$ = solid angle of the detector as seen from the volume element dn
- η = number of atoms per unit volume
- $\frac{d\sigma}{d\Omega}$ = differential scattering cross section per atom
- R_1 = distance from source to volume element $dn = da \cdot dr$
- da = area of beam
- r_1 = distance incident beam travels inside the object
- r_2 = distance scattered beam travels inside object
- k_1 = attenuation coefficient of incident beam
- k_2 = attenuation coefficient of scattered radiation

To reconstruct the object from its spectrum, we first discretized the object by describing the object as a density matrix $d(x,y,z)$. In this matrix, x , y , and z represent the number of elements in the x , y , and z direction, respectively. If y is the direction of the surface normal, and x is normal to y and in the plane defined by the surface normal and beam, then, in this case the z direction is irrelevant (and therefore not mentioned further). A numerical integration of the above integral results in:

$$\left(\frac{dN}{d\epsilon}\right)_j = D(1 - k_1 d_1 dr_1)(1 - k_1 d_2 dr_2) \dots (1 - k_2 dr_1' d_1')(1 - k_2 dr_2' d_2') \dots \left(\frac{d\sigma}{d\Omega}\right)_j d_j dr_j \quad (2)$$

where:

- D = nearly constant
- dr_n = path of incident beam inside n th cell
- dr_n' = path of scattered beam inside n 'th cell
- d_n = a density multiplier (i.e., $d(x,y,z) = d_n \cdot \rho$, ρ = normal density)

As shown, the path of integration is along the incident beam direction and out in the direction specified by the Compton equation. If each volume element is small compared to the mean-free path this equation can be rewritten as follows:

$$\left(\frac{dN}{d\epsilon}\right)_j = D \left(\frac{d\sigma}{d\Omega}\right)_j d_j dr_j + O(kdrd)^2 \quad (3)$$

where: $O(Kdrd)^2$ represents the sum of all terms of second order or higher in $(Kdrd)$.

As long as the cell size is smaller than the mean-free path, the first order term is due to scattering. Absorption may be very strong but contributes only in second order. This analysis does not identify the location where the scattering occurs, but it does show that it is the highest order interaction.

Based on this, it is possible to reconstruct an object from a set of spectra obtained by scanning in the x and z direction. (1) The density matrix is initialized so that each element has normal density. (2) The spectrum is calculated for each depth for the object using this density matrix. This basis (spectra) is used to do a linear-least-squares fit to the last spectra obtained from the scan. The fitting parameters then correspond to density multipliers for all the voxels intersected by the beam at each depth (i.e., a diagonal in the density matrix for an incident beam angle of 45 degrees). (3) These multipliers are used to correct these elements in the density matrix. This new density matrix is then used to calculate a new basis (spectra). (4) A least-squares fit is obtained for the second to the last spectra. This gives a new set of density multipliers corresponding to the second to the last diagonal on the density matrix. This process is continued until all spectra have been fitted. Then, the process begins again with the last spectra (the first one calculated). This process is iterated until convergence (i.e., no further change in density multipliers is obtained). Tables 1-3 represent examples of reconstructions by this program for the superman geometry described earlier. In each case, the voxel size is 1 mm cubed. Table 1 is an example of two voids, one behind the other (as seen by the source). The reconstruction converged in only three iterations. Each iteration took approximately 3 hrs on an amiga 2000 with a 33 MHz accelerator card and floating-point processor. Tables 2 and 3 are examples of reconstructions where statistical noise was added to the spectra. In these tables, the voids are diamond shaped. The data in Table 2 had 3% noise added to it; in Table 3, the data had 2.5% noise added to it and the void was changed to a region of half-normal density. In all these examples, we assumed the object to be made of steel. Figure 10 shows an example of a calculated basis set along with the calculated spectrum.

Tables 1-3 indicate that the reconstruction is not perfect. Currently, we are developing an improved method to enhance the code. One of the weaknesses of the above calculations is in the radiation transport algorithm. When the code is initialized, the angles corresponding to each energy bin in the spectra are calculated and stored. At the same time, the mean-free paths corresponding to each of these angles is also calculated and stored.

The numerical integration is performed along the beam direction (inward and outward) in small increments " dr ," where dr is generally about 0.2 times the voxel dimension. This calculation proceeds as follows.

For each increment "dr," the code performs a test to identify in which cell it is located. It then uses the mean-free path associated with its energy (angle) multiplied by that particular cell's density multiplier. This process continues until the edge of the object is reached. The problem with this method, other than its slowness, is that it does not consider the finite width of the beam. This width is typically greater than the width of a voxel. Therefore, the assumption that photons scattered from a given depth all traversed the same voxels is not valid. The current method under development implicitly integrates over the width of the beam. In addition to better reconstruction, this method is expected to be about 10 to 20 times faster.

3. DATA

Figure 11 is a photograph of the superman apparatus. In this figure, the cylinder with the small padlock on it is the lead pig that holds the radioactive source. In our experiments, this source is 300 mci of Cs-137. Physically, the source is in the shape of a small, right, circular-cylinder, 3 mm in diameter and 3 mm long. The intrinsic germanium spectrometer is shown about 10 cm away from the pig, surrounded by lead bricks. These lead bricks are necessary to reduce both the natural background radiation and the background from the pig. Without this shielding, these backgrounds would be considerably brighter than the signal.

The 3-mm wide source was three times the width of the resolution we were trying to achieve. Collimating the source to 1 mm results in a very large penalty in efficiency. Not only does the solid angle decrease a factor of nine, but unless one is very careful, the area of the source as viewed through the collimator also decreases a factor of nine for a grand total of over eighty. By tapering the collimator, it is possible to view the entire source (at the cost of increasing the divergence of the beam). This beam divergence drastically degrades the contrast obtainable.

The baffles consist of two sets of tantalum slit jaws with apertures of from 1- to 3-mm wide by 1- to 3-cm long. The subtended average angle of these slits is approximately 70 degrees.

Finally, below that is the phantom, positioned on an X-Y-Z translation stage. Two other phantoms are shown in front of the apparatus along with two additional collimation cylinders. The phantoms consist of two identical blocks in which a stairstep shaped wedge has been cut. By sliding the blocks apart, and shimming one of the blocks a void of almost any size can be created at various depths. Then by scanning the phantom in the direction normal to this wedge, the depth of this void can be varied systematically. Thus, spectra from a phantom with known voids at varying depths could be obtained using automation.

Although considerable effort was expended developing a first-principles reconstruction method, actual reconstruction is proceeding somewhat differently. The basis set we are using for the actual reconstruction is semi-empirical and obtained by a separate basis measurement. This is because it is extremely difficult to accurately calculate all the effects of geometry and detector resolution. On the other hand, it is extremely easy to measure this basis set, and this measurement necessarily includes all these effects. The development of this procedure is not yet complete, but most of the routines have been written and verified.

Therefore, a basis set is generated by measuring the spectrum from a thin plate that is placed at the corresponding basis position. The thickness of the plate is equal to the voxel thickness. The spectra obtained from these measurements are then corrected for what the attenuation would have been had the scattering been from a layer corresponding to this position inside the object. These corrected spectra are then the basis set complete with the exact geometry and detector efficiencies. Figure 12 is a plot of some of these basis spectra. Figure 13 is a plot comparing the spectra obtained from a 0.1 in. (2.5 mm) void buried in a 0.45 in. (11.4 mm), solid brass block to a similar void buried 0.35 in. (8.9 mm) in the same solid brass block. Although these are raw data, and no attempt has been made to subtract backgrounds or remove lines, the difference in the two is apparent. We anticipate the reconstruction code for these spectra to be completed in the near future.

4. CONCLUSION

We are currently developing a method of obtaining three dimensional images of opaque objects. This technique should be capable of obtaining millimeter-scale resolutions at depths of up to 25 mm of objects imbedded in solid steel. It will not require access to both sides of the object to be imaged. By using virtual collimation, its efficiency can be improved by about three orders of magnitude.

Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract #W-7405-Eng-48.

5. ACKNOWLEDGEMENT

I would like to thank Dean Rippee and Ken Visbeck for their technical expertise in the design and construction of this apparatus. I also wish to acknowledge Bob Steinhaus for his efforts in assembling the electronics package.

6. REFERENCES

1. Stokes, J.A., *et al.*, (1982), "Some New Applications of Collimated Photon Scattering for Nondestructive Examination," *Nucl. Instru. and Meth.*, 193, pp. 261-267.
2. Harding, G. and J. Kosanetzky (1989), "Scattered X-ray Beam Nondestructive Testing," *Nucl. Instr. and Meth. in Phys. Res.*, A280, pp. 517-528.
3. Battista, J.J., L.W. Santon, and M.J. Bronskill (1977), "Compton Scatter Imaging of Transverse Sections: Corrections for Multiple Scatter and Attenuations," *Phys. Med. Biol.*, 22 (2), pp. 229-244.
4. Holt, R.S. and M.J. Cooper (1984), "Gamma-Ray Scattering Techniques for Nondestructive Testing and Imaging," *Nucl. Instr. and Meth. in Phys Res.*, A221, pp. 98-104.
5. Farmer, F.T. and M.P. Collins (1971), "A New Approach to the Determination of Anatomical Cross-Sections of the Body by Compton Scattering of Gamma-Rays," *Phys. Med. Biol.*, 16 (4), pp. 577-586.
6. T. H. Prettyman "Composition and Density Imaging of Industrial Samples by a Combination of Photon Transmission Tomography and Projective Compton Scatterometry." Ph.D. thesis: North Carolina State University, 1991.
7. R. S. Thoe, "Single-sided tomography of extremely large dense objects," (accompanying paper), Lawrence Livermore National Laboratory, Livermore, Calif., (Session: 1942-32).

Table 3. Diamond-shaped volume of half-normal density, 2.5% statistical uncertainty in basis.

1.10	1.09	1.11	1.10	1.10	1.08	1.08	1.09	1.08	1.08	1.06	1.06	1.05	1.05	1.06	1.06	1.05	1.05	1.06	1.05	1.05	1.04	1.02
1.00	1.08	1.08	1.06	1.06	1.05	1.04	1.06	1.04	1.05	1.03	1.04	1.03	1.02	1.03	1.04	1.03	1.02	1.03	1.02	1.01	1.02	1.01
1.00	1.00	1.07	1.06	1.07	1.05	1.05	1.05	1.04	1.05	1.04	1.05	1.04	1.03	1.02	1.03	1.03	1.02	1.03	1.03	1.02	1.01	1.03
1.00	1.00	1.00	1.06	1.07	1.04	1.04	1.07	1.04	1.03	1.04	1.03	1.02	1.02	1.01	1.01	1.02	1.02	1.01	1.02	1.02	1.03	1.03
1.00	1.00	1.00	1.00	1.08	1.06	1.06	1.04	1.04	1.05	1.03	1.02	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.00	1.00	1.03
1.00	1.00	1.00	1.00	1.00	1.05	1.05	1.04	1.06	1.05	1.05	1.05	1.03	1.05	1.02	1.06	1.03	1.04	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.05	1.06	1.05	1.06	1.04	1.02	0.98	0.98	<u>0.51</u>	1.00	1.01	1.01	1.05	1.00	0.99	1.00	0.99	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.09	1.06	1.05	1.05	1.01	<u>0.50</u>	<u>0.49</u>	<u>0.54</u>	1.05	1.04	0.97	1.01	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	1.07	1.00	<u>0.55</u>	<u>0.43</u>	<u>0.51</u>	<u>0.53</u>	<u>0.61</u>	1.02	1.03	1.02	1.03	1.02	0.89	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.15	0.97	0.80	<u>0.35</u>	<u>0.52</u>	<u>0.36</u>	1.15	1.29	1.11	1.24	0.70	1.24	0.70	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.73	0.99	1.44	<u>0.72</u>	1.13	1.43	0.79	0.35	0.75	0.70	1.24	1.24	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.35	0.98	0.84	1.37	1.15	1.12	0.99	1.61	1.24	1.05	1.05	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.95	1.26	0.91	0.51	0.82	0.78	1.40	1.05	1.27	1.27	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.30	0.75	1.05	1.42	1.14	1.12	1.27	0.94	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.21	1.18	0.98	0.68	0.96	0.94	2.00	2.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.15	2.00	1.45	1.02	2.00	1.47	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00	0.00	1.09	1.47	1.94	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00	1.94	0.56	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.65	1.00	1.00	1.00

Figure 1. Conventional gamma-ray scattering tomography.

Figure 2. X-ray cross sections as a function of energy for iron.

$$I_0 = A e^{-kdx}$$

where: k = mass attn coeff
 d = density
 x = path length

$$I = A e^{-kd(x-w)} e^{-kd'w}$$

Therefore: $C = 1 - \frac{e^{-kd(x-w)} e^{-kd'w}}{e^{-kdx}} = 1 - e^{-kd'w}$

where: d'' = change in density

(a)

$$I_0 = A e^{-kdL}$$

$$I_1 = A e^{-kd(L_1 + L_2)}$$

$$L = L_1 + L_2$$

$$C = (d - d') / d$$

(b)

Figure 3. Contrast defined for: (a) Conventional projection radiography and (b) Scattering radiography.

Figure 4. The Compton effect.

Figure 5. Energy versus angle for Compton: (a) scattered photons and (b) Dispersion versus angle for Compton scattered photons.

Figure 6. Diagram of Farmer-Collins apparatus.

Figure 7. Geometry employed by Prettyman.

Figure 8. UCBT apparatus.

Figure 9. The method of virtual collimation.

Figure 10. Sample basis set used for the superman reconstruction.

Figure 11. Superman apparatus.

1942-22 - THO E/FIG. 11. Pg. 14

Figure 12. Representative basis spectra each row .050 in. deeper than the preceding row.

Figure 13. Measured spectra from a brass phantom with 0.1 in. void at a depth of .035 and .045 in.

**DATE
FILMED**

9/28/93

END