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Computed Tomography on Small Explosive Parts

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Computed Tomography On Small Explosive Parts

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Abstract:

We have investigated three small explosive parts for the Pantex Plant in Amarillo, Texas using computed tomography (CT). A medium resolution, fan beam system was used to test imaging capabilities for small holes drilled into one of the parts, and to identify any inhomogeneities, cracks, voids, and inclusions if present in the other two parts. This system provides volumetric imaging. Its information is qualitative in that it allows us to see interior features but it cannot provide quantitative attenuation data.

A second part of the investigation was to perform effective atomic number computed tomography on the parts using energy dispersive spectroscopy methods. We wanted to experimentally identify the "average" chemical composition of the materials in the explosive and its shell and to detect any possible inhomogeneities in composition. A single beam, nuclear spectroscopy based system was used for this work. The radiation source was a silver anode x-ray tube. By measuring x-ray attenuation at *specific energies* (characteristic lines and narrow bands of continuum) we are able to quantitatively determine linear attenuation coefficients. By using ratios of such measurements, density cancels out and we effectively have ratios of mass attenuation coefficients. Through a look-up scheme of mass attenuation coefficients for different elements, we can determine the weighted average chemical composition, as averaged by x-ray attenuation. We call this averaged composition the effective atomic number (" Z_{eff} "). We thereby obtain cross sectional images of a parameter related to the averaged chemistry of the object. Such images and the underlying data can reveal, for instance, segregation of explosive and binder.

Introduction:

A previous project for Pantex investigated the size of voids and inclusions which could be found in large billets of explosives (15-40 cm) by computed tomography¹. The scanner used in this previous study had a single detector, which limited the rate of data throughput. In order to get reasonable counts, resolution was traded for time by opening apertures. We therefore wanted to use a multiple element detector to demonstrate the ability to find small voids in the explosive parts. Dual energy techniques were also used in the previous study to find compositional and density variations. Due to the large part size and therefore the high energy of radiation required for penetration, such determinations lacked sensitivity. It was suggested that smaller parts could yield positive results. This suggestion leads to the current study.

Parts Description:

All three parts are cone-shaped, and flat on top:

- 1.) A specially prepared unfilled cone-shaped shell made of PBX9501 explosive. The part has small voids machined into the outer surface. At the base, this part is 22.2 mm (7/8") in diameter. At the top, there are three drill holes, approximately 0.35, 0.50, and 0.80 mm in diameter. Along the side, there are likewise three drilled holes, approximately 0.30, 0.50, and 0.90 mm diameter. We call this part "phantom" in reference to resolution phantoms used in tomography.

2.) Two filled cone-shaped parts. There is a plastic sheath with LX-13 explosive in the interior region. At the base, these parts are 25.4 mm (1.0") in diameter. The parts are labeled f1204 and a938.

Photographs of these three parts are shown in Figures 1-3.

Figure 1a. Photographs of the resolution phantom. The plastic shell is empty.

Figure 1b. Resolution phantom. Close-up of the holes drilled into the side and top.

Figure 2. Photographs of explosive part a938. The outer sheath is plastic, which is filled with LX-13 explosive.

Figure 3. Explosive part f1204. The part is made of the same material as a938.

Experimental:

Tomographic scans were made on two LLNL tomography systems known as "LCAT" and "PBCAT." LCAT is a fan beam system. The x-ray tube can be run as high as 160 kV; for these experiments, it was run at 40 kV with a current of 3.2 mA. The detector is a Thomson THX-2023 linear array with 1024 elements, dividing the 460 mm length. The detector elements have a center to center distance of 0.45 mm. The source to detector distance was 1358.4 mm. When specimens a938 and f1204 were run, the source to object distance was 406.4 mm, giving a geometric magnification of 3.34X, or an equivalent detector resolution of $0.45/3.34 = 0.135$ mm. When the phantom was run, the source to object distance was reduced to 387.35 mm, giving a slightly greater magnification of 3.51X. In this case, the detector resolution was $0.45/3.51 = 0.128$ mm = .005 in. (The smallest hole in the resolution phantom is therefore about 2.3X larger than the effective detector resolution.) The specimens were rotated through 360 degrees in 360 steps.

The PBCAT scanner is a single collimated beam ("pencil beam") system. A rhodium target x-ray tube was used, running at 40 kV and 0.25 mA. The source and detector were both apertured at approximately 0.38 mm; the scanning step size was either 0.20 or 0.25 mm. (Such a collimation system could have detected the holes in the resolution phantom, but there is no way to know precisely where the beam intersects the specimen. The tomographic slices shown later missed the plain where the holes were located.) What makes this system unique is the detector, which is high purity germanium run in pulse height analysis mode. With this mode of detection, x-ray attenuation measurements are made at specific energies. The measurements are therefore a function of the linear attenuation coefficients of the chemical elements comprising the specimen. The average composition (Z_{eff}) of a voxel element in the tomographic image can therefore be determined basically by a look-up procedure, where ratios of measurements at different energies are used. In order to determine effective Z's, measurements were made at five energy regions:

Region 1: 11.0 to 12.0 keV

Region 2: 15.0 to 17.0 keV

Region 3: 22.17 keV (Rh $K\alpha$), x-ray tube target material characteristic line

Region 4: 22.76 keV (Rh $K\beta$), x-ray tube target material characteristic line

Region 5: 29.0 to 31.0 keV

The Medium Resolution Tomography:

Figures 4-6 are digital radiographs made with the LCAT fan-beam system. The holes in the resolution phantom (Figure 4) are clearly visible. Tomographs were constructed from 360 such angular views. A fan-beam, 360 degree, convolution back projection algorithm was used to reconstruct 175 tomographic slices. Some of those slices are shown in Figure 7 for the resolution phantom, where the slices intersect the holes. All the holes are clearly visible. In Figure 8, numerical values for lines drawn across the holes at the top of the specimen are shown. The smallest hole has an attenuation three quarters of the way between that of the plastic shell and void, even though the hole is only something more than two pixels wide. (Ideally, the attenuation is that of void = 0.) By examining these tomographic slices, the approximate holes sizes are estimated to be:

	pixels	appx. mm	visible light, appx mm
holes on top:	1.5	.19	.35
	3	.38	.50
	6	.77	.80
holes on the side:	2	.26	.30
	4	.51	.50
	6	.77	.90

Except at edges where there is a partial volume effect, the material appears uniform. No flaws or voids other than those intentionally made are visible in any of the tomographic views.

Figure 9 shows several slices for specimen a938, starting at the stem and progressing upward. Other than the reconstruction circular artifact, the material is seen to be uniform and devoid of flaws. Numerical values for image lines in the stem area and in the next two slices are shown in the figure. Typical cupping artifacts are seen here, which arise from beam hardening of the "white" radiation used. Specimen f1204 is sliced along each of the three Cartesian coordinates in Figure 10. The circular reconstruction artifacts appear as vertical stripes in the slices perpendicular to the reconstruction plane. Again, no flaws are visible.

Spectroscopy Based Tomography:

Reconstructed images at each of the five energy regions are shown in Figure 11 for specimen a938. The lines at the edges of each image are for the plastic tape used to mount the specimen on the translation pedestal. Cupping due to beam hardening of the softest band is clearly evident in the plots of numerical values for lines drawn across the images (top curve). The first image was made with a 2 keV wide band of continuum x-rays, centered at a rather soft 9.5 keV. It is the preferential absorption of the softer x-rays in this band that causes the cupping. At the higher energies, the attenuation is uniform across the specimen (within statistical noise). Also demonstrated is the progressive diminishment of attenuation as the energy is stepped up. (Note: the attenuation scale has not been converted to cm^{-1} .)

Figure 12 shows slices for all three specimens, taken at the energy band 15-17 keV. The plastic shell clearly has different attenuation compared to the explosive which fills the two cone-shaped explosive parts a938 and f1204. The explosive is fairly uniform across the parts, within pixel to pixel statistical fluctuations. No flaws such as voids or inclusions are discernible.

Effective Z Calculations:

In order to find effective atomic numbers (Z_{eff}), we make use of ratios of attenuation measurements made at different energies. The rationale for this approach is implicit in Beer's Law for attenuation:

$$\begin{aligned} I/I_0 @ e_1 &= \exp(-(\mu/\rho)_{e1} \rho x) \\ I/I_0 @ e_2 &= \exp(-(\mu/\rho)_{e2} \rho x) \end{aligned} \quad \text{Eqns. 1}$$

where e_1 and e_2 designate different energies, $(\mu/\rho)_{e1}$ and $(\mu/\rho)_{e2}$ are the mass attenuation coefficients at those energies, ρ is the density, and x is the path length. If we take the negative logarithms of the measurements we obtain:

$$\begin{aligned} -\ln(I/I_0 @ e_1) &= (\mu/\rho)_{e1} \rho x \\ -\ln(I/I_0 @ e_2) &= (\mu/\rho)_{e2} \rho x \end{aligned} \quad \text{Eqns. 2}$$

The linear attenuation coefficient $\mu\rho$ (in units of cm^{-1}) is the parameter displayed in the tomographic images. By taking the ratio of two such images, the effect of density ρ cancels and we obtain:

$$\text{Ratio} = \frac{(\mu/\rho)_{e1}}{(\mu/\rho)_{e2}} \quad \text{Eqn. 3}$$

When the measurements are made at sufficiently different and optimized energies, the attenuation coefficients ((μ/ρ) 's) will be significantly different from each other, the ratio will differ significantly from unity, and the ratio will be sensitive to both composition and energy. Since the (μ/ρ) 's are related to atomic numbers, Z_{eff} can be found.

The procedure for finding Z_{eff} is as follows. A search is made through the attenuation coefficients for the elements, using McMaster's² fitting coefficients. Once a near match is found, a quadratic fit for the attenuation coefficient ratio as a function of atomic number ($Z \pm 1$) is made, from which Z_{eff} is interpolated. An alternative method is depicted in Figure 13. A table of attenuation coefficients for materials in the range of the "unknowns" is made at the energies of the measurements. A second table is then made of the ratios of these attenuation coefficients. Polynomial fits of Z_{eff} vs. the ratios is then made. Z_{eff} is determined directly from the fitted curve for each ratio. Inspection of Figure 13 emphasizes something which is intuitively clear: it is best to have measurements at significantly different energies. The attenuation coefficient ratio is not very sensitive to composition when the energies are close together. When energies are close together, small errors in the ratio will translate into large errors in Z_{eff} . (In the example here, the curve for the ratio $(\mu/\rho)_{16 \text{ keV}}/(\mu/\rho)_{20.17 \text{ keV}}$ has an average slope over six times steeper than for the ratio $(\mu/\rho)_{16 \text{ keV}}/(\mu/\rho)_{30 \text{ keV}}$.) Therefore, when averaging the results from several ratios, the values are weighted inversely to the pixel-to-pixel variance.

Measurements were made at five energy "windows." Attenuation was too great and there was beam hardening for the lowest energy band. We therefore have four measurements and 6 ratios with which to calculate Z_{eff} . Once Z_{eff} is known from the attenuation ratios, curves such as Figure 14 are used to obtain mass attenuation coefficients. Knowing μ/ρ , we can then go back to Equations 1 to calculate the density, ρ .

In order to test the procedure, to investigate error propagation, and to determine precision and accuracy in measuring Z_{eff} for a homogeneous material, a Lucite cylinder was both "synthetically" measured and actually measured. The synthetic data were generated from a model, assuming that Lucite is polymethylmethacrylate. (The plastic could be other

methacrylates.) Data were synthetically generated both noise-free and with counting statistical noise of the same size as encountered in the actual measurements. The Lucite cylinder was measured using PBCAT. After reconstructing the images by filtered backprojection, the results in Table 1 were obtained.

Table 1 Results for Lucite Synthetic and Real Data			
<u>Energy Ratio</u>	<u>Lucite Z_{eff} Modeled, no noise</u>	<u>Lucite Z_{eff} Modeled, Poisson noise</u>	<u>Lucite Z_{eff} Measured</u>
16.00/22.17	6.49 $\pm$.051	6.50 $\pm$ 1.68	6.54 $\pm$ 1.68
16.00/22.76	6.50 $\pm$.035	6.51 $\pm$ 1.31	6.62 $\pm$ 1.33
16.00/30.00	6.52 $\pm$.020	6.53 $\pm$ 1.13	6.48 $\pm$ 1.08
22.17/22.76	6.52 $\pm$.032	6.51 $\pm$ 2.98	6.74 $\pm$ 3.04
22.17/30.00	6.53 $\pm$.051	6.53 $\pm$ 1.63	6.44 $\pm$ 1.53
22.76/30.00		6.54 $\pm$ 2.57	6.30 $\pm$ 2.35
Weighted Avg. (inversely with variance)	6.52 $\pm$.014	6.52 $\pm$ 0.65	6.51 $\pm$ 0.63

The error bands are in units of one standard deviation. The agreement between the synthetic and measured data is almost too good to be believed. What can be seen is that the measurement system and methodology do not add any detectable imprecision beyond that intrinsic in the counting statistics. Since the Lucite cylinder is homogeneous, the measured variance can be compared to those found for the explosives as one test for material inhomogeneity.

The resolution phantom was measured three times with PBCAT while attempting to locate the holes (without success). The other two specimens were measured once each. The average linear attenuation coefficient and its standard deviation were determined for an extracted region from each tomographic slice at each of the energy windows. The effective atomic number and its range were then determined as described above. The results are summarized in Table 2.

Table 2 Effective Atomic Numbers for Explosive Specimens		
	<u>Z_{eff} center material</u>	<u>Z_{eff} edge material</u>
Resolution "phantom"		7.34 $\pm$ 0.69
		7.52 $\pm$ 0.36
		<u>7.16 $\pm$ 0.46</u>
Weighted average		7.38 $\pm$.26
a938	8.03 $\pm$ 0.37	6.90 $\pm$ 0.61
f1204	<u>7.91 $\pm$ 0.37</u>	<u>6.37 $\pm$ 0.40</u>
Weighted average	9.97 $\pm$.26	6.53 $\pm$.34

Compare these results with the calculated values for some representative materials in Table 3. The resolution "phantom" is specified as PBX-9501 explosive; the measured average Z_{eff} (7.38 $\pm$.26) is 102.1 $\pm$ 3.6% of the calculated value. The cone-shaped parts are LX-13 explosive; the measured average Z_{eff} (7.97 $\pm$.26) is 97.2 $\pm$ 3.2% of the calculated value. The average value

for the plastic sheaths on the parts ($6.53 \pm .34$) indicates that it must contain a component with Z greater than that of carbon, such as oxygen or nitrogen, and is very similar to polymethylmethacrylate (Lucite).

Table 3
Calculated Effective Atomic Numbers (Z_{eff}) for
Representative Materials and Explosives

boron	5.00
paraffin: $\text{CH}_{2.06}$	5.49
polyethylene: CH_2	5.51
polypropylene: CH_2	5.51
polystyrene: CH	5.73
carbon	6.00
nylon: $\text{C}_{12}\text{H}_{22}\text{O}_3\text{N}_2$	6.33
Lucite: $\text{C}_5\text{H}_8\text{O}_2$	6.52
Mylar: $\text{C}_{10}\text{H}_8\text{O}_4$	6.67
nitrogen	7.01
Comp C-4 *	7.13
Comp B *	7.18
cellulose acetate: $\text{C}_{10}\text{H}_{21}\text{O}_{15}$	7.22
PBX-9501 *	7.23
PETN: $\text{C}_5\text{H}_8\text{N}_4\text{O}_{12}$	7.42
water	7.49
wool @ 65% humidity *	7.506
wool 17 amino acids *	7.509
PBX-9502 *	7.58
oxygen	8.00
LX-13 *	8.22
Teflon: CF_2	8.42
fluorine	9.00
neon	10.00
Sylgard binder: $\text{C}_2\text{H}_6\text{SiO}$	10.46
Kel-F binder: $\text{C}_8\text{H}_2\text{Cl}_3\text{F}_{11}$	10.99
sodium	11.00

*** Atomic compositions³:**

Comp-B: RDX(63%), TNT(36%), wax(1%); [$\text{C}_{2.03}\text{H}_{2.64}\text{N}_{2.18}\text{O}_{2.67}$]

Comp C-4: RDX(91%), Di(2-ethylhexyl) sebacate(5.3%), Polyisobutylene(2.1%), Motor oil 1.6%); [$\text{C}_{1.82}\text{H}_{3.54}\text{N}_{2.46}\text{O}_{2.51}$]

LX-13: PETN (80%), Sylgard-182 (20%) [$\text{C}_{1.80}\text{H}_{3.64}\text{N}_{1.01}\text{O}_{3.31}\text{Si}_{0.27}$]

PBX-9501: HMX (95%), estane (2.5%), BDNPA-F (2.5%)
[$\text{C}_{1.47}\text{H}_{2.86}\text{N}_{2.60}\text{O}_{2.69}$]

PBX9502: TATB(95%), Kel-F(5%); [$\text{C}_{2.30}\text{H}_{2.23}\text{N}_{2.21}\text{O}_{2.21}\text{Cl}_{0.038}\text{F}_{0.13}$]

wool : $\text{C}_{4.00}\text{H}_{6.69}\text{N}_{1.11}\text{O}_{1.65}\text{S}_{0.104}$

at 21.2°C and 65% humidity, add 16% water

Note: The intrinsic variation in Z_{eff} calculated from the McMaster fits for the six ratios is about $\pm .05$, which sets a lower limit on precision

When the Z_{eff} tomographic cross section was examined, something interesting was initially observed. Figure 15 shows Z_{eff} for the part f1204 which was initially derived pixel-by-pixel (rather than from the mean) for each of the six ratios, and then summed with each image weighted inversely to its variance. High Z_{eff} values are seen scattered throughout the material, but with more of them located near the edge where the plastic shell is located. This suggests that the binder is not well mixed and that it has segregated preferentially near the shell. This was an exciting and significant finding which, however, did not survive closer examination.

Figure 16 shows Z_{eff} maps for each of the individual ratios for part f1204. The clustering of higher atomic number material near the edge is only discernible in the first two images, for the ratios 16keV/20.17 keV and 16keV/22.76 keV. Note the streaks. The numbers represented there are identical! Apparently somewhere in the process something got clipped, thresholded, or otherwise set to a constant number, perhaps while dividing zero by zero, taking the log of a negative number, or some such mathematical problem.

The images were reconstructed a second time from the original data, with no automatic processing. The weighted average image is shown in Figure 17 (rotated 180° from previously). The individual contributors to the average are shown in Figure 18. There is not a lot of difference in the individual images from those determined previously and shown in Figure 16, but the composite no longer shows the clustering of high atomic number material near the edges. The spread of values for an individual line in the composite image is shown in Figure 19; the distribution of high atomic number material throughout the image is shown in Figure 20. In Figure 20, the display has been thresholded at the upper 2 sigma and 3 sigma levels (taken from the mean value for the central region). Since the probability of finding values above the three sigma level is very small, it appears that there are some points where binder is not completely mixed with the explosive.

A more quantitative consideration of Figure 20 is given in Table 4. The central region has Z_{eff} of 8.03 ± 0.73 . There are 3453 pixels above the three sigma level in this region. Based upon a normal distribution, we would expect 78 pixels above the 2 sigma level of $Z_{\text{eff}} = 9.49$. In fact, there are 139 pixels in Figure 20 above 9.49. Likewise, we would expect only 4.5 pixels above the 3 sigma level of 10.22; there are 28 such points actually found. Such a high number cannot be explained by random statistics, so some segregation between explosive and silicone rubber binder (Sylgard, table 3) is strongly suggested.

Table 4
Frequency of Occurrence of High Z Pixels in Specimen f1204

	<u>Percent</u>	<u>Number</u>
Number of points above the 3 sigma lower level ($Z_{\text{eff}} > 5.85$)	100%	3453
Single tail 2 sigma probability	2.27%	78
Single tail 2 sigma actual pixels	4.03%	139
Single tail 3 sigma probability	0.13%	4.5
Single tail 3 sigma actual pixels	0.81%	28

Once the effective atomic numbers are known, curves such as that in Figure 14 can be used to calculate the attenuation coefficients ((μ/ρ) , cm^2/g) at any particular energy (Figure 21). Results extracted from the figure are compared to values for LX-13 explosive in Table 5. At all energies, LX-13 is above and to the left of the fitted curves, as typified in Figure 14. The attenuation coefficient calculated will therefore be lower than the look-up value. Good agreement is found with LX-13 from which the specimen is made when the comparison is made to values calculated in the same manner using the regression fits.

Table 5				
<u>Mass Attenuation Coefficients (cm^2/g) for Specimen f1204*</u>				
	<u>16 keV</u>	<u>20.17 keV</u>	<u>22.76 keV</u>	<u>30 keV</u>
LX-13 (look-up)	1.70	0.936	0.707	0.414
LX-13 (regression)	1.58	0.870	0.660	0.392
Measured	$1.53 \pm .43$	$0.853 \pm .22$	$0.641 \pm .14$	$0.388 \pm .064$

* from polynomial fits to $(\mu/\rho)_{\text{ej}}$ vs. Z_{eff}

After the attenuation coefficients are determined, reference to Eqns. 1 yields densities simply by dividing the images for the linear attenuation coefficients (μ , cm^{-1}) by the image for the mass attenuation coefficient (μ/ρ , cm^2/g) at the corresponding energy. The average result for the four energies is depicted in Figure 22. The average density is $1.70 \pm .35 \text{ g/cm}^3$ using the low values for (μ/ρ) . When corrected for the 7.0% low values of (μ/ρ) , the density is found to be $1.59 \pm .33 \text{ g/cm}^3$. This value compares quite favorably with the nominal value for LX-13 explosive³ of 1.53.

Summary:

Very small voids or other imperfections can be imaged in small explosive parts using CT systems based upon one and two dimensional arrays of detectors, where the resolution can be from about 10 to 100 μm . In the present study, where detector resolution was 130 μm , holes 300 μm were easily imaged.

Spectroscopy based systems which produce images at specific energies can be used to *quantitatively* provide volumetric mapping of x-ray attenuation. X-ray attenuation is a function of composition and density. By making measurements at two or more energies, density and "average composition" (or effective atomic number, Z_{eff}) can be separated. Here, we have measured Z_{eff} to within a few percent of expected values. Close agreement is also found between expected values for mass attenuation coefficients and density.

From Z_{eff} measurements, there is a strong indication of some separation between explosive and binder, averaged over areas of about $0.38 \times 0.38 \text{ mm}^2$.

Future Work:

Segregation of explosive and binder was suggested in an earlier study⁴. This suggestion has been strengthened, but not proven, in the present study. We want to lay this question to rest. We have a system, similar to PBCAT used here, which is based upon a rotating anode x-ray source and which has collimators as small as 10 μm diameter. This system can be used to tomographically inspect the same explosive parts as inspected here with much finer resolution. Once tomographic examination of the parts is completed, they could be cross-sectioned and inspected by microscopy techniques, including optical and scanning electron microprobe analysis. The electron microprobe can identify the silicon in the Sylgard binder, pixel by pixel, by x-ray fluorescence. We could thereby conclusively prove whether or not segregation occurs, and on what dimensional scale.

We also want to study and further verify our effective atomic number techniques as they apply to high explosives. It has been suggested that small rods or other objects of various materials be inserted into the explosive parts to confirm our measurements and to learn what differences in Z_{eff} can be distinguished. It would be useful to know what subtleties can be seen in Z_{eff} as a function of the part size.

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Caption Headings

- Figure 1a. Photographs of the resolution phantom. The plastic shell is empty.
- Figure 1b. Resolution phantom. Close-up of holes drilled into the side and top.
- Figure 2. Photographs of explosive part a938. The outer sheath is plastic, which is filled with LX-13 explosive.
- Figure 3. Photographs of explosive part f1204. The part is made of the same material as a938.
- Figure 4. Digital radiographs of the resolution phantom at two rotational views
- Figure 5. Digital radiographs of the explosive part a938 at three rotational views
- Figures 6a and b. Digital radiographs of explosive part f1204 at two rotational views. 6a and 6b differ only in the display contrast.
- Figure 7. Tomographic slices of the resolution phantom. Slices were taken where the slice plane intersected on or more holes.
- Figure 8. Two dimensional slices taken at the hole locations in the top of the resolution phantom, together with numerical values for one dimensional lines in the images.
- Figure 9. Tomographic slices and numerical values for individual image lines ("line-outs") for explosive part a938. See Figure 2 for photographs of the part. Slices are shown, starting at the bottom of the part, at image plains 5 (near the stem), 65, 85, 125, and 155 (near the top). The line-outs for slice plains 65 and 85 clearly show the "cupping" artifact due to beam hardening of the "white" incident radiation. Beam hardening is due to preferential attenuation of softer x-rays.
- Figure 10. Tomographic slices of explosive part f1204, taken along three orthogonal coordinates. See Figure 3 for photographs of the part. At the left are slices taken along the x axis (in the y-z plain); in the middle are slices taken along the y axis (in the x-z plain); at the right are slices taken along the z axis (in the x-y plain).
- Figure 11. Tomographic slice of specimen a938, made with PBCAT. Each view is for one of the energy "windows" centered at 9.5, 16, 20.17, 22.76, and 30 keV.
- Figure 12. PBCAT tomographic slices of the three specimens for the energy band 15-17 keV. Shown are: upper left, resolution phantom; lower left, specimen f1204; right, specimen a938. The lower curves are attenuation values for a typical line in each image.
- Figure 13. Effective atomic number (Z_{eff}) as a function of two typical attenuation coefficient ratios for a variety of materials.
- Figure 14. Attenuation coefficient at a typical energy as a function of Z_{eff} . Z_{eff} is first determined from ratios of attenuation measurements (as in Figure 13). The attenuation coefficient for the material at any energy can then be calculated from curves such as this.
- Figure 15. Initial average Z_{eff} cross-section for explosive specimen f1204. Note the preponderance of high Z material near the edge (blue color).

Figure 16. Individual Z_{eff} cross sections derived from each of the six linear attenuation coefficient ratios (specimen f1204). The effective atomic number was determined for each individual pixel. The images were then averaged to produce Figure 15. Note that the high Z material clustered near the edge is only seen in the first two images.

Figure 17. Recalculated average Z_{eff} cross-section for explosive specimen f1204. Note the preponderance of high Z material near the edge is no longer apparent (as it was in Figure 15).

Figure 18. Individual Z_{eff} cross sections derived from each of the six linear attenuation coefficient ratios (specimen f1204). The effective atomic number was determined for each individual pixel. The images were then averaged to produce Figure 17. Note that the high Z material clustered near the edge is only seen in the first two images.

Figure 19. Numerical values of Z_{eff} taken from a typical line in Figure 17.

Figure 20. The display of data in Figure 17 is thresholded at the upper 2 sigma and 3 sigma levels (above the mean for the central region) in order to emphasize the number and distribution of pixels representing higher Z material.

Figure 21. Attenuation coefficient maps of specimen f1204 at the four energies used. These images were derived using equations such as that in Figure 14 from the pixel-by-pixel Z_{eff} data (Figure 17).

Figure 22. Recalculation of the data to yield a density map. Equation 1 was used at the four energies, where the mass attenuation coefficient (μ/ρ) is now known.

Phantom radiograph section at angle 0

Phantom radiograph section at angle 125

Figure 4

Figure 5

Figure 6a

Figure 6b

High explosive with small drilled holes

Figure 7

High explosive with small drilled holes

Figure 8

Figure 9

Figure 10

Figure 12

Figure 13

Once Z_{eff} is known, μ can be determined

μ at 20.17 keV for various materials

Figure 14

20.17 keV

a938 Effective Z weighted average

Figure 15

ZeFF images for each energy pair ratio

Figure 16

f1204 composite Zeff

Figure 17

Figure 18

Figure 19

Effective atomic number

Specimen f1204

$Z_{\text{eff}} = 8.03 \pm 0.73$

Figure 20

± 2 sigma

± 3 sigma

Frequency of Occurrence of High Z Pixels

Number of points = 3453

Above 2 sigma: expect 78 points, observe 139 points

Above 3 sigma: expect 5 points, observe 28 points

Absorption coefficients after determining Zeff Specimen f1204

$\mu(16) = 1.52 \pm .43$
 $\mu(20,17) = .853 \pm .22$
 $\mu(22,76) = .641 \pm .14$
 $\mu(30) = .388 \pm .064$

Figure 21

Density map for f1204
 $\rho = 1.70 \pm .35$

Figure 22

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