X-Ray Computed Tomography for Structural Ceramic Applications: Beam Hardening Corrections

by W. A. Ellingson, E. Segal, and M. W. Vannier

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X-RAY COMPUTED TOMOGRAPHY FOR STRUCTURAL CERAMIC APPLICATIONS: 
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W. A. Ellingson, E. Segal* and M. W. Vannier**

Materials and Components Technology Division

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ABSTRACT

Beam hardening (BH), caused by the energy dependence of X-ray attenuation in materials, reduces the reliability of images generated by computed tomographic (CT) when polychromatic X-ray sources are used. The magnitude of the BH effect was calculated, and four different approaches to BH correction for CT imaging of ceramics were investigated: the "water bag" approach, prehardening of the beam by use of a filter, linearization correction, and dual-energy methods. The dual-energy approach appears to be a promising means of BH correction for CT imaging of ceramics.

I. INTRODUCTION

Computed tomographic (CT) imaging with both monochromatic and polychromatic X-ray sources can be a powerful NDE method for characterization (e.g., measurement of density gradients) as well as detection of flaws (e.g., cracks, voids, inclusions) in ceramics. However, the accuracy of CT images is limited by partial volume effects, scatter, spectral shift, and the heterogeneous nature of ceramic specimens. Among these limitations, the most important in many ceramic applications of scanners with polychromatic X-ray sources is spectral shift, which can cause image artifacts and reduce the reliability of linear attenuation measurements through beam hardening (BH) effects [1]. Beam hardening occurs because X-ray attenuation in a given material is energy dependent. Without an appropriate correction, the BH effect prevents the reliable measurement of relative or absolute X-ray attenuation in ceramics. Thus, quantitative and even qualitative density comparisons between samples of the same material but of different sizes or shapes become unreliable [2].

Many different correction approaches can be considered in CT systems to eliminate or reduce the BH effect, as noted in Table 1. These can range from "water bag" (i.e., prehardening of the beam) and dual-energy approaches [3,4] to correction of the image after reconstruction [5,6]. An intensive correction effort undertaken for medical CT systems has reduced BH for tissue and tissue-like materials to less than a few Hounsfield units or to tenths of a percent. However, for many industrial components made of relatively high-density materials such as ceramics, the BH effect is considerably greater than encountered in medical applications, and very little has been done to cope with this problem [7]. Rather, the BH effect is avoided in many industrial CT systems by using monochromatic isotope


Table 1. Beam-Hardening Correction Methods

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<th>Preprocessing</th>
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<tr>
<td></td>
<td>- water bag</td>
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<td>- special convolution kernels</td>
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<td>- linearization</td>
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sources [8,9]. The main disadvantages of isotope-source CT systems are the low source intensity (which leads to longer image data acquisition times) and the more stringent safety measures required to protect personnel. The purpose of the work reported here is to develop a BH correction method applicable for CT examination of ceramic materials with polychromatic x-ray sources.

II. NATURE OF BEAM HARDENING IN CERAMICS

A CT scanner measures the attenuation of photons through an object along projection lines, as shown schematically in Fig. 1. The measurement of attenuation can be expressed [2,3] as

\[
I(p, \theta) = I_o e^{-\int \mu(x,y)ds},
\]

(1)

where

\[I(p, \theta)\] = normalized photon intensity (as a function of ray projection \(p\) and projection angle \(\theta\)) after penetrating an object of dimension \(s\) (in cm);

\[I_o\] = normalized X-ray (photon) intensity of the source; and

\[\mu(x,y)\] = total\(^*\) local linear attenuation coefficient (LAC) of the object in this line path, in \(cm^{-1}\).

\(^*\)That is, the total of the photoelectric, Compton, and Rayleigh components.
In the CT reconstruction process, the integral equations of all the ray projections are solved for the total local LAC, $\mu(x,y)$. The total LAC, $\mu_t$, of the object (in cm$^{-1}$) is dependent upon the energy, $E$, of the X-rays; the atomic numbers, $z$, of the elements composing the object; and the mass density, $\rho$, of the object:

$$\mu_L = \mu_L(E,z,\rho) \quad (2)$$

The dependence of $\mu_L$ on $\rho$ is linear and is given by

$$\mu_L = \rho \mu_M(E,z) \quad (3)$$

where $\mu_M$ is the mass attenuation coefficient in cm$^2$/g. The quantity $\mu_M$, which is defined [3] as

$$\frac{\mu_L}{\rho} = \mu_M(E,z) \quad (4)$$

is a complex function of $E$ and $z$. In order to calculate a total $\mu_M$ for a polychromatic photon source, the photon energy spectrum of the source must be known or assumed. For monoenergetic radiation, this is not a concern; $E$ is known, and an effective $z$ can be calculated* according to Walter [10] as

$$z_{\text{eff}} = \sqrt[2.94]{az_1^{2.94} + bz_2^{2.94} + cz_3^{2.94} + \ldots} \quad (5)$$

where $a$, $b$, $c$, etc. are the fractional content of electrons belonging to elements $z_1$, $z_2$, $z_3$, etc. Figure 2 shows the calculated $\mu_M$ as a function of energy for a few elements from which ceramic compounds are composed and Fig. 3 gives the $\mu_M$ of a few ceramic compounds. Water is included because it is a commonly used reference material for medical CT scanners. The calculated $\mu_M$ values of these compounds are based on the $\mu_M$ values of the constituent elements as given in Refs. 11-14.

*Calculation of effective atomic number, $z_{\text{eff}}$, is currently a matter of interest. The exponent 2.94 may need to be reconsidered.
As noted earlier, for a homogeneous material, z (or the effective z) is constant. Therefore, for a homogeneous material scanned with a monoenergetic beam, the \( \mu_M \) will be constant and the calculated \( \mu_L(x,y) \) will be directly proportional to the local density of the material, \( \rho(x,y) \). However, for a polychromatic photon beam this is not the case and the effective total LAC, \( \mu_L^{\text{eff}} \), for homogeneous material becomes

\[
\mu_L^{\text{eff}}(x,y) = \rho(x,y) \int_{E_L}^{E_U} \mu_M(E) dE ,
\]

where \( E_L \) and \( E_U \) are the lower and upper limits, respectively, of the X-ray head photon energies (see Fig. 4).

Figures 2 and 3 indicate that for ceramic materials, \( \mu_M \) changes by an order of magnitude or more in the energy region of a typical medical scanner. This implies that the effective total LAC (see Eq. 6) is no longer proportional to the local density of the material and unless a correction is made, the measured attenuation will not be a measure of the material density.

---

**Fig. 2.** Energy Dependence of the Mass Attenuation Coefficient for Four Elements.

**Fig. 3.** Energy Dependence of the Mass Attenuation Coefficient for Three Ceramic Compounds.
III. THEORETICAL BEAM HARDENING RESULTS

In order to evaluate the severity of BH in ceramics imaged with a polychromatic X-ray source, theoretical calculations were made from available information about X-ray attenuation [2] and typical X-ray tube spectra for medical CT scanners. The typical polychromatic X-ray tube spectrum selected was that of a Siemens Somatom Model DR-H scanner, as experiments could be conducted on this machine for verification. The spectra of the X-ray source in the Model DR-H scanner (as published by Siemens) for two different head voltages are shown in Fig. 4.

The X-ray spectrum varies from point to point along the beam path through an object examined in the CT scanner. This can be illustrated by showing the alteration in the X-ray spectrum for different thicknesses of a material. The X-ray spectrum may be characterized by computing effective energy and comparing the ratio of the source intensity, \( I_0 \), to the attenuated intensity, \( I(p,\theta) \). Beam hardening causes a shift toward a higher effective energy and diminution of the overall intensity, as illustrated in Fig. 5.

![Fig. 4. X-Ray Spectra for Siemens Somatom Model DR-H CT Scanner Operated Head Voltages of (a) 96 and (b) 125 kV.](image)

The effect of object thickness on X-ray beam quality was calculated for several ceramics, on the basis of the published X-ray spectra for the Model DR-H CT scanner and our knowledge of the energy dependence of X-ray attenuation (Fig. 3). Figure 6 shows the calculated attenuation in green and dense \( \text{Si}_3\text{N}_4 \) specimens ranging from 1 to 5 cm in thickness. Green ceramics have reasonably low densities (\( \rho = 1.3-2 \text{ g/cm}^3 \)) relative to densified ceramics (3 to 5 g/cm\(^3\)). Of primary interest is the marked low-energy attenuation in both green and dense ceramics. This is, of course, expected from the attenuation data shown in Figs. 2 and 3. Figure 7 shows the calculated attenuation in two ceramic compounds of much higher z and mass density than the \( \text{Si}_3\text{N}_4 \) shown in Fig. 6. The thickness ranges shown in Fig. 7 are 1-10 mm for Monofrax S5 (40% \( \text{ZrO}_2 \), 48% \( \text{Al}_2\text{O}_3 \)) and 50 \( \mu \text{m} \) to 1 mm for the electronic ceramic \( \text{LaMnO}_3 \). A strong effect of the La K-edge (38.9 keV) is evident in the spectra for \( \text{LaMnO}_3 \) (Fig. 7b); this K-edge adds a low-energy component to the total received photon intensity.
125 kVp Spectrum  
(Filtration: 3 mm Al + 0.25 mm Cu)

<table>
<thead>
<tr>
<th>Curve</th>
<th>( \frac{I_0}{I(p, \theta)} )</th>
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<tbody>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>46.6</td>
</tr>
<tr>
<td>3</td>
<td>297.8</td>
</tr>
<tr>
<td>4</td>
<td>1846.0</td>
</tr>
<tr>
<td>5</td>
<td>296.5</td>
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Fig. 5. Variation in X-Ray Spectrum As a Function of Absorber Thickness. (1) Original X-ray spectrum; (2) through 20 cm of water; (3) through 30 cm of water; (4) through 40 cm of water; and (5) through 20 cm of water and 3.4 cm of calcium.

Fig. 6. Effect of Specimen Thickness (in the 1 to 5-cm Range) on X-Ray Attenuation in Si\textsubscript{3}N\textsubscript{4}.
Fig. 7. Effect of Specimen Thickness on X-Ray Attenuation in Two Ceramic Compounds of Higher \( z \) and Higher Mass Density than the \( \text{Si}_3\text{N}_4 \) Specimens of Fig. 6.

IV. APPROACHES TO CORRECTION FOR THE BEAM HARDENING EFFECT

A. The "Water Bag" Approach

Beam hardening is a function of the depth of penetration in an object. In a noncylindrical object, different CT projections will undergo different BH effects because of different ray-path lengths. To overcome the limitations imposed by BH, a number of approaches have been applied. These may be conceptualized as shown in Fig. 8. In the early days of medical tomographic scanning with polychromatic radiation, patients were surrounded by a water bag to reduce BH artifacts in the resulting images. A "water bag equivalent" for ceramics is a fitted symmetrical structure composed of a material that is similar in mass and electron density, as suggested in Fig. 9. Putting an object of interest inside a cylindrical container filled with a liquid material that has the same or similar X-ray attenuation properties ensures that rays from all directions undergo nearly the same BH effect.
To experimentally estimate the effectiveness of this method, a cold-pressed MgO cylinder ($\rho = 1.8 \text{ g/cm}^3$, $z_{\text{eff}} = 10.7$) was scanned with and without a ceramic "water bag equivalent" -- in this case, a Teflon ring ($\rho = 2.15 \text{ g/cm}^3$, $z_{\text{eff}} = 8.2$). Figure 10 shows a CT image of the MgO ceramic scanned without a "bag"; the BH effect is about 8.7%. Figure 11 is a similar CT scan with the MgO surrounded by the Teflon ring. As the object and the ring are symmetrical, the BH is the same for all directions. The ring reduces the BH effect in the ceramic to <3%. In this case, however, since the ring reduces the number of photons reaching the object, it increases the statistical noise in the image and reduces the contrast resolution of the reconstructed image. This approach, in principle, can reduce the BH effect but not eliminate it.
Fig. 11
CT Scan and Density Trace of MgO Specimen 1 Inside Teflon Ring. The density trace no longer shows the very high-density outer region seen within the MgO in Fig. 10.

B. Prehardening of the X-Ray Beam

A second approach is to make the BH correction in the X-ray CT machine itself, by using an equivalent filter made of a material which is placed between the X-ray head and the object under interrogation. The thickness and shape of the filter will vary with the material and geometry of the object, to ensure that all parts of the object have the same effective BH. For example, a cylindrical object would require a filter geometry similar to that shown in Fig. 12.

Fig. 12
Prehardening of the X-Ray Beam to Reduce BH Effects.

The disadvantages of this BH correction approach, besides the inconvenience of designing the filter, are similar to those of the water bag approach: (1) it will reduce the BH but will not eliminate it and (2) the hardening of the beam lowers the contrast resolution and increases the noise of the image, because the optimal energy for typical ceramic components is in the low region of the X-ray spectrum (Fig. 3) [15,16].

C. Software Methods

Another approach to the BH problem is to use sophisticated software solutions. One such method is linearization correction [17]. This method requires exact knowledge of the spectrum of the X-ray head and the composition of the material being studied, as well as access to the raw detector data. Such BH correction relationships, in theory, can be put into the CT reconstruction algorithm as a polynomial or as a look-up table.
It has been recognized for some time that the nonlinear CT image reconstruction process can be linearized if the material being scanned can be assumed to be homogeneous. This linearization process can be mathematically explained as follows: The intensity, \( I(x) \), of a polychromatic X-ray beam after penetrating a homogeneous material to a depth \( x \) is given by

\[
I(x) = \int S(E) e^{-\mu_L(E)x} dE ,
\]

(7)

where \( S(E) \) is the spectrum of the polychromatic source and \( \mu_L(E) \) is the total LAC. The polychromatic x-ray beam can be represented by an equivalent monoenergetic x-ray beam as follows: Substituting

\[
\mu_L^{(\text{eff})}(x) = \mu_L(E)
\]

(8)

and

\[
I_o = \int S(E)dE
\]

(9)

into Eq. (7), one obtains

\[
I(x) = I_o e^{-\mu_L^{(\text{eff})}(x)x} ,
\]

(10)

where \( \mu_L^{(\text{eff})}(x) \) is the effective total LAC obtained over the energy spectrum of interest. Having obtained \( \mu_L^{(\text{eff})}(x) \), one can refer to an attenuation vs. energy plot and obtain an equivalent monoenergetic photon energy. Figures 4b and 13 may be used to illustrate this process for the case of Si\(_3\)N\(_4\) and a typical polychromatic X-ray spectrum. Figure 4b shows the X-ray spectrum for a Siemens Somatom DR-H CT scanner operated at 125 kV. Figure 13 is a plot of \( \mu_t(x) \) as a function of photon energy for dense and green Si\(_3\)N\(_4\) and for a fluorinated hydrocarbon, Freon TF. At each of 100 points on the X-ray energy spectrum curve of Fig. 4b, the relative flux was multiplied by the \( \mu_t(x) \) value shown for that energy in Fig. 13. The weighted average of the 100 values thus obtained is \( \mu_L^{(\text{eff})}(x) \); this average was 0.901 for dense Si\(_3\)N\(_4\). This effective total LAC is independent of the depth of penetration, and thus the total attenuation becomes a linear function of \( x \).

From the linear attenuation curve for dense Si\(_3\)N\(_4\) (Fig. 13) and the \( \mu_L^{(\text{eff})}(x) \) value of 0.901, the equivalent monoenergetic photon energy is found to be 60.6 keV.

Figure 14 shows this effect graphically by comparing the uncorrected LAC's with the corresponding \( \mu_L^{(\text{eff})}(x) \) values for two Si\(_3\)N\(_4\) densities. Note that the uncorrected LAC has a thickness dependence which is significant at specimen sizes of engineering interest (e.g., > 1 cm). From Fig. 14, the BH correction value for specimens of different thickness can be theoretically determined.
In order to evaluate the accuracy of the $\mu_{L(\text{eff})}(x)$ method for a known X-ray spectrum and a homogeneous material, a theoretical calculation was completed and compared with an experimental measurement on a green-state $\text{Si}_3\text{N}_4$ specimen ($\rho = 1.995 \text{ g/cm}^3$) with dimensions of $5.7 \times 4.3 \times 3.1 \text{ cm}$. Figure 15 shows a comparison between the experimental data and theoretical calculations based on the X-ray head spectrum shown in Fig. 4. The agreement between the experimental and theoretical results demonstrates that a relative BH effect can be calculated for ceramic materials. Figure 15 also shows how severe the BH effect can be.

**Fig. 13**
Total Linear Attenuation Coefficient for Dense and Green-State $\text{Si}_3\text{N}_4$ and Freon TF.

**Fig. 14.** Comparison Between Linear Attenuation Coefficients with No Correction for X-Ray Polychromaticity (Solid Curves) and the Effective Total Linear Attenuation Coefficients Used in the Linearization Correction Process (Dashed Curves), for Green-State and Dense $\text{Si}_3\text{N}_4$. 
The difficulty of implementing such a linearization BH correction method for ceramic materials was experimentally tested with an Elscint Excel 2002 second-generation medical CT scanner. Partial access to the normalized detector data for this scanner was obtained. An approximate energy spectrum, $S(E)$, was used to represent the polychromatic source. Freon TF was chosen as the test material because this fluid has a mass density ($\rho = 1.565 \text{ g/cm}^3$) and an electron density ($Z_{eff} = 14.4$) close to those of both green and dense $\text{Si}_3\text{N}_4$ (see Fig. 13). The test specimen was a 53-mm-diameter thin-walled polyethylene bottle filled with Freon TF and placed in the CT machine so as to produce a nominally circular cross-sectional image. Figure 16 shows a plot of the uncorrected nonlinear attenuation and the linearization correction obtained by using $\mu_1(\text{eff})$ at the equivalent monoenergetic photon energy (60.6 keV). The nonlinear polynomial-curve coefficients were empirically established during tests on the machine.

Figure 17 shows a CT image of Freon TF, obtained with a standard "water equivalent" BH correction. The BH effect is about 10%. Figure 18 shows the CT image obtained when an empirically derived linearization BH correction was implemented. In this case the BH was reduced to $<1\%$.

Fig. 15
Comparison between Theoretically Calculated and Experimentally Measured BH Effect for a Green-State $\text{Si}_3\text{N}_4$ Specimen.

Fig. 16
Comparison of Theoretically Derived Uncorrected Nonlinear Attenuation with Corrected Linear Attenuation for Estimated X-Ray Spectrum of Polychromatic Source from Elscint Excel 2002 CT Scanner.
Dual-Energy Methods

Dual-energy methods [19,20] provide an analytically correct solution to the BH problem, unlike the previously discussed water-bag and linearization methods, which provide only approximate solutions. In current medical practice, dual-energy methods have been found to be more accurate, reproducible, and reliable for quantifying the mineral content of bone than the
use of polychromatic sources operated at single kVp values [21]. The drawbacks are the increased cost and complexity of the instrumentation, larger data sets with associated increased data processing requirements, and noise limitations.

A basic assumption underlying dual-energy reconstruction methods is that within the X-ray energy range of interest, the energy-dependent mass attenuation coefficient \((\mu/\rho)(E)\) of materials can be expressed with sufficient accuracy as a linear combination of the Compton and photoelectric coefficients [22]. The mass attenuation coefficient can be expressed as a sum of two linearly independent basis vectors that span its space:

\[
(\mu/\rho)(E) = \sum_{i=1}^{\infty} a_i f_i(E), \tag{11}
\]

Among the pairs of vectors that can be used to span this space are X-ray attenuations for a pair of basis or calibration materials (Fig. 19). Provided that the energy dependence of the coefficients of these materials is known, the X-ray spectra at two different tube energies are known, and the measured attenuation values for the sample object are given at the corresponding energies, it is possible to compute conventional CT values as well as many new equivalent values for each voxel in the reconstructed images. For example, one can compute images at equivalent monochromatic energies (which are relatively immune to BH artifacts), equivalent basis-material composition images, electron density images, and effective-z images. The principal applications of these computed or synthesized images are removal of BH effects and selective display of different material densities (Fe, Si, Al, ...). It can be shown [19] that any material's mass attenuation coefficient can be expressed as a linear combination of the coefficients of two so-called basis or calibration materials:

\[
(\mu/\rho)(E) = a_1 \cdot (\mu/\rho)_1(E) + a_2 \cdot (\mu/\rho)_2(E), \tag{12}
\]

where subscripts 1 and 2 refer to reference material 1 and 2, respectively. Since any two linearly independent sums of two basis functions (the Compton and photoelectric components) span the space, they are also adequate basis functions. It follows then that any material \(\xi\) can be expressed as a linear combination of any other two materials, \(\alpha\) and \(\beta\), which are designated the basis-set materials:
where

\[
\frac{\mu_\xi(E)}{\rho_\xi} = a_1 \frac{\mu_\alpha(E)}{\rho_\alpha} + a_2 \frac{\mu_\beta(E)}{\rho_\beta},
\]  

(13)

\[
a_1 = \frac{N_{\xi}(Z_{3.8} - Z_\beta)}{N_{\alpha}(Z_{3.8} - Z_\beta)},
\]

(14)

\[
a_2 = \frac{N_{\xi}(Z_{3.8} - Z_{3.8})}{N_{\beta}(Z_{3.8} - Z_{3.8})},
\]

(15)

and \(N_{\text{ex}}\) is the electron mean density for material x. The two basis or calibration materials should be sufficiently different in their atomic number \(Z\) to demonstrate measurable differences in their Compton and photoelectric attenuation characteristics. In CT imaging, the line integral over the LAC is determined for each focus position and detector element. This integral can be expressed accordingly as

\[
\int \mu(r,E)ds = (\mu/\rho)_1(E) \cdot \delta_1 + (\mu/\rho)_2(E) \cdot \delta_2,
\]

(16)

where

\[
\delta_1 = \int \rho_1(r)ds.
\]

(17)

The symbol \(\delta_1\) represents an "area density" in g/cm\(^2\), and \(\rho_1(r)\) represents the local mass density in g/cm\(^3\), of basis material i. When materials other than the basis materials are present, the densities are referred to as equivalent basis-material densities, a linear combination of which reflects the physical density of the attenuating material.

The equivalent "area densities" \(\delta_1\) and \(\delta_2\) of the two basis materials have to be determined for each ray path. By measuring the attenuation with two different spectra, we obtain two nonlinear equations for each ray path:

\[
I_h = \int I_{oh}(E) \cdot \exp \left[ -(\mu/\rho)_1(E) \cdot \delta_1 - (\mu/\rho)_2(E) \cdot \delta_2 \right] dE,
\]

(18)

\[
I_\ell = \int I_{o\ell}(E) \cdot \exp \left[ -(\mu/\rho)_1(E) \cdot \delta_1 - (\mu/\rho)_2(E) \cdot \delta_2 \right] dE,
\]

(19)

where \(I_h\) and \(I_\ell\) are the attenuated and primary intensities and the subscripts \(h\) and \(\ell\) refer to the high- and low-kVp X-ray head voltages, respectively. Equations (17) and (18) can be solved for the equivalent "area densities" \(\delta_1\) and \(\delta_2\), characterizing the unknown material.
The basis-material decomposition is thus accomplished by calculating the $\delta_1$ and $\delta_2$ values from the measured projection values. Materials with an atomic number $z$ different from those of the two basis materials will contribute to both $\delta_1$ and $\delta_2$ in a specific fashion [23]. The values $\delta_1$ can be interpreted as components in a two-dimensional vector space with the basis materials defining the basis vectors.

The dual-energy correction is usually implemented by use of table look-up procedures. Figure 20 summarizes the basic procedure for the rapid kVp-switching method, which we have chosen for our application. Profiles of attenuation measurements made along the X-ray beam path demonstrate significant BH in Freon TF on medical CT scanners operated in this energy range, as shown in Fig. 17. This effect is virtually completely removed by dual-energy monochromatic-equivalent reconstruction using rapid kVp-switching (Fig. 22).

![Diagram](image-url)

**Fig. 20**
Processing Scheme for Dual-kVp Data Evaluation (Adapted from Ref. 19).

We have applied dual-energy CT scanning to demonstrate its potential for reducing BH artifacts in images of ceramic materials. Using calcium and water as the basis materials, we computed equivalent monochromatic images as illustrated in Fig. 21. The initial test object, a container filled with Freon TF fluid, was scanned at room temperature at 85 and 125 kVp.

As mentioned earlier, dual-energy CT scanning techniques are not without drawbacks. Additional X-ray accelerating potential hardware and specialized reconstruction hardware and software are required to provide reconstructed results in a timely fashion. The complexity of the data processing is certainly increased, and the success of the method is based on accurate knowledge of the original X-ray tube spectra, their respective accelerating potentials, and the attenuation characteristics of the basis materials. Beam hardening effects are suppressed, but not completely eliminated. It is often assumed that all of the density errors near the borders of scanned objects are due to BH, but this is not the case in practice. Most investigators have neglected the contributions of partial volume effects, specimen inhomogeneity, and off-focal radiation (scatter).
Dose-related noise is a limitation in dual-energy methods, especially at the lower kVp setting. The spectral separation obtained in practice by switching the X-ray source from 85 to 125 kVp is not ideal for all situations. The decomposition table that is used to perform the dual-energy X-ray computations can be inaccurate owing to variations of the X-ray spectra and incorrect assumptions regarding the basis materials and the energy dependence of their X-ray attenuations.

Fig. 21. Illustration of the Dual-Energy Principle and Resulting CT Images. The low-density ceramic matrix is significantly different from the high-density inclusions with regard to attenuation properties at the two X-ray energies, owing to differences in the energy dependence of X-ray attenuation in the two materials. The basis-material decomposition process (see text) makes use of this information to calculate material density images.
Fig. 22
CT Image of Freon TF with Dual-Energy Reconstruction Package. An 80-keV equivalent monoenergetic photon image is shown with densitometer trace.

V. CONCLUSIONS

We have considered several aspects of CT imaging for structural ceramics. Specifically, we have focused on BH problems and initial work on basis or equivalent materials for phantom/calibration use. These efforts have led to the conclusions that (1) dual-energy methods have the greatest potential for BH corrections on polychromatic CT scanners and (2) Freon TF can be used as a fluid for phantom design.

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