A MODEL OF X-RAY FILM RESPONSE

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INTRODUCTION

In the 100 years since Roentgen produced the first X-ray radiograph, many useful images have been produced for medical and industrial applications. To ensure high quality and reproducibility, standards have been developed to describe different types of film and methods of exposure and development[1]. It is desired to relate these film properties and other X-ray inspection parameters to a probability of detection for a certain type of flaw in a given object.

At the Center for NDE we have been developing a computer model of radiographic inspection (XRSIM)[2], which can be used by design engineers to address issues of component inspectibility and probability of detection. A key element of this model is the representation of the response of different types of film to a wide range of X-ray exposures. In this paper we describe the basic X-ray film properties which should be addressed in a model of film radiography. We present our method for calibrating film density as a function of X-ray exposure and discuss methods for modeling intrinsic noise present in film radiographs.

X-RAY FILM PROPERTIES

A vast amount of literature is available describing all aspects of the photographic process[3]. The most widely used photosensitive materials are the silver halide crystals, AgCl, AgBr, and AgI. Industrial radiography films are typically composed of AgBr emulsion layers a few microns thick coating both sides of a polyester substrate approximately 200 μm thick. The size of the AgBr film grains will dictate the spatial resolution and speed of the film. Figure 1 shows photomicrographs of several types of film. These films have been exposed to the point of saturation and then developed. It can be seen that the Kodak Industrix AA-1 and Agfa Gevaert Structurix D7 films are similar in appearance, whereas the Kodak Industrix M-5 film has a finer grain structure. It is also

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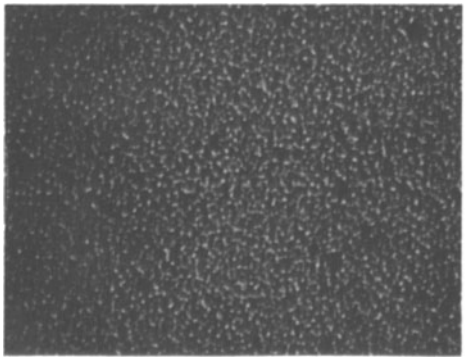
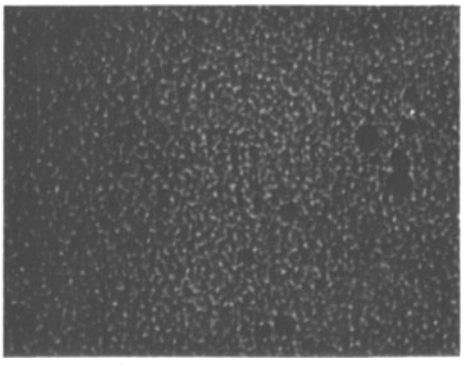
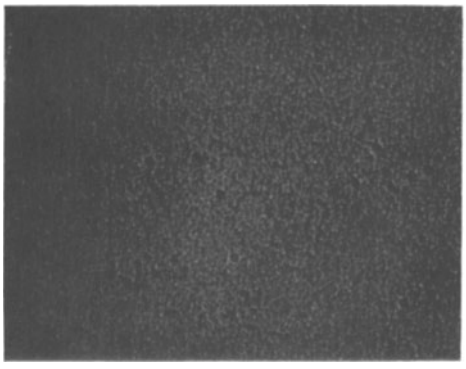


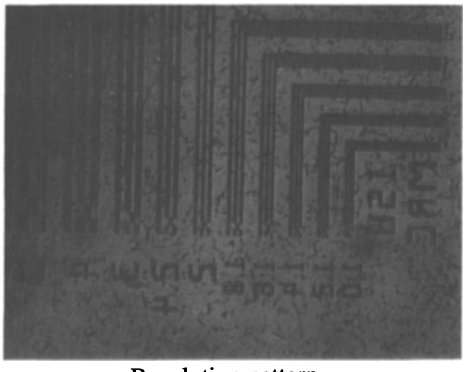
Kodak Industrix AA-1



Agfa Gevaert Structurix D7



Kodak Industrix M-5



Resolution pattern

Figure 1. Photomicrographs of three different types of radiographic film along with a resolution scale composed of bars ranging from 1.0 to 5.0 μm wide.

evident that there is a distribution of film grain sizes for a given film. However, due to the limited depth of field in these images, it is difficult to obtain a quantitative measure of the grain sizes. As film properties are considered proprietary information, it is generally not possible to obtain grain size information from the manufacturers either.

A film grain is rendered developable upon interaction with a single X-ray, usually through the photoelectric or compton process. The linear attenuation coefficient for silver bromide is plotted in Fig. 2a as a function of X-ray energy. At energies below 100 keV absorption is dominated by the photoelectric effect in silver. However, because there is such a thin layer (~ 5 μm) of AgBr present in radiographic films, the efficiency for detecting X-rays falls very rapidly with increasing energy as indicated in Fig. 2b. For this reason radiography at higher energies (>100 kVp) is often done using intensifying screens (typically thin lead sheets) in direct contact with the film.

After exposure to X-rays, a film is chemically processed to develop to metallic silver those grains which were struck by X-rays. The unexposed AgBr grains are then washed away and we are left with an image which can be viewed using transmitted light. The optical density is defined as

$$D = \log(I_0 / I), \tag{1}$$

where I_0 is the incident light intensity, and I is the intensity of light transmitted through the film. For industrial radiography films the maximum density is approximately 6.0.

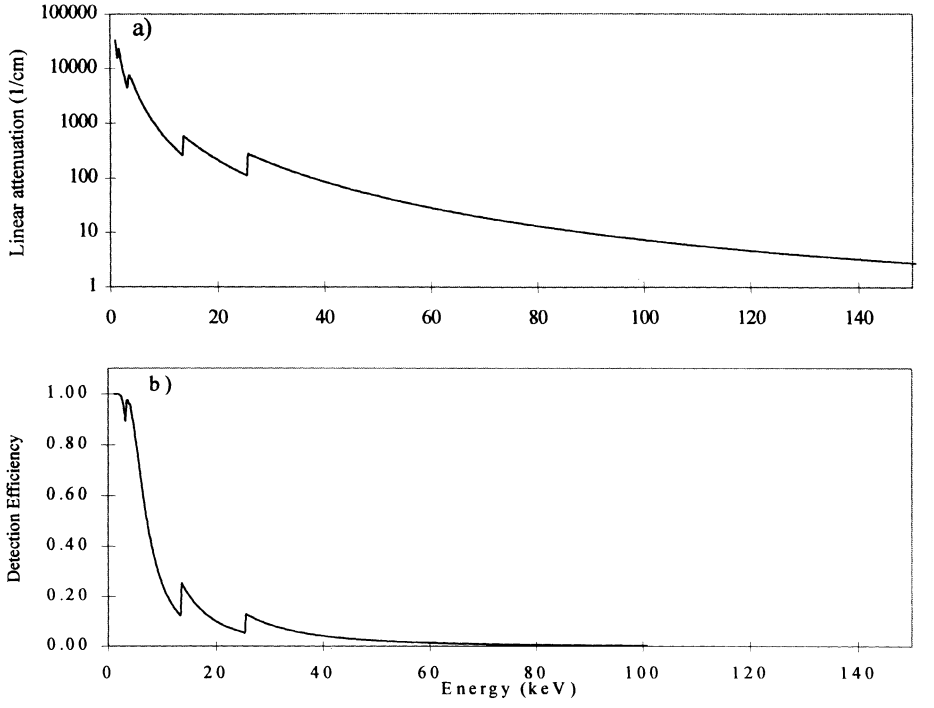


Figure 2. a) Linear attenuation coefficients for silver bromide. b) Absorption efficiency for a 5 μm thick layer of silver bromide.

A model of film response should accurately predict the average density and random variations in density for different types of film under a variety of inspection conditions. Furthermore, to be useful in simulation of radiographs of complex components, this model must be computationally efficient.

FILM DENSITY CALIBRATION

The radiography model XRSIM[2] calculates the energy spectrum generated by an X-ray tube and determines the energy- and position-dependent attenuation of the X-ray flux by a sample. For each point on the film (pixel) this transmitted spectrum must then be used to predict the resulting film density. As seen above, the absorption of X-rays by silver bromide has a strong energy dependence which must be taken into account. When an X-ray interacts in the film via the photoelectric or compton process, secondary electrons are produced. It is the energy transfer of these electrons which renders the AgBr grains developable. The absorbed dose[4] gives a measure of this energy transfer:

$$\text{Dose} = \int dE\left(d\Phi/dE\right)\left(\mu_a/\rho\right)E, \qquad (2)$$

where $d\Phi/dE$ is the energy-dependent X-ray flux, and μ_a/ρ is the mass energy absorption coefficient for the material. Values of μ_a/ρ for all the elements are tabulated[5].

The setup we have used to measure film density as a function of exposure is shown in Fig. 3. The X-ray generator system was a 160 kVp unit. The film holder was placed

approximately one meter from the tubehead and adjacent to a collimated germanium detector. At the same time that the film was exposed, the energy spectrum observed using the germanium detector was recorded. Using this spectrum in Eq. 2 we calculated the dose to which the film was exposed.

We have evaluated Kodak Industrix AA1 and M5 films as well as Agfa Gevaert Structurix D7 film. We have not used intensifying screens in our studies. The film holder was of cardboard with a back sheet of 0.005 inch lead to cut down backscattered radiation. There was no sign of significant backscatter in the calibration radiographs. The films were processed using an Agfa Structurix NDT M automatic film processor, and density measurements were made with a Victoreen model 07-424 digital densitometer calibrated against a NIST standard.

The resulting calibration curves are plotted in Fig. 4 for the three types of film. Each data point represents the average of several density measurements, and data from tube voltage settings of 40, 60, 90, and 110 kVp are included. It is apparent that the energy-dependent film response is properly accounted for by using the absorbed dose. In contrast, if we had used Roentgens (measuring energy deposited in air) for the exposure axis, the energy dependence would not have been accounted for. The relative accuracy of the dose values is estimated to be better than 3%. However, the absolute scale could be off by as much as 50% due to uncertainty in the effective size of the Ge detector collimator aperture. A quadratic fit was made to the data for each film type, and it is this simple paramaterization that is used in the XRSIM model.

We have made some preliminary validation tests of this film model by placing varying thicknesses of aluminum in front of the film and Ge detector. Examples of the transmitted energy spectra are shown in Fig. 5, and the results of a series of tests are shown in Table 1. It should be noted that the calculated densities do not account for buildup due to scattering. This is most likely the reason the measured densities are consistently greater than the calculated densities for the thicker samples. In the future we will be incorporating scattering information[6] into the model. Nonetheless, there is agreement within 10% between calculated and measured values of density for a fairly wide range of exposure conditions.

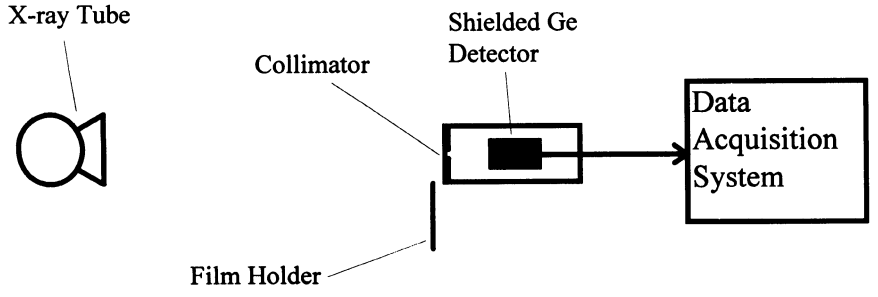


Figure 3. The experimental setup used for film density vs. exposure calibration.

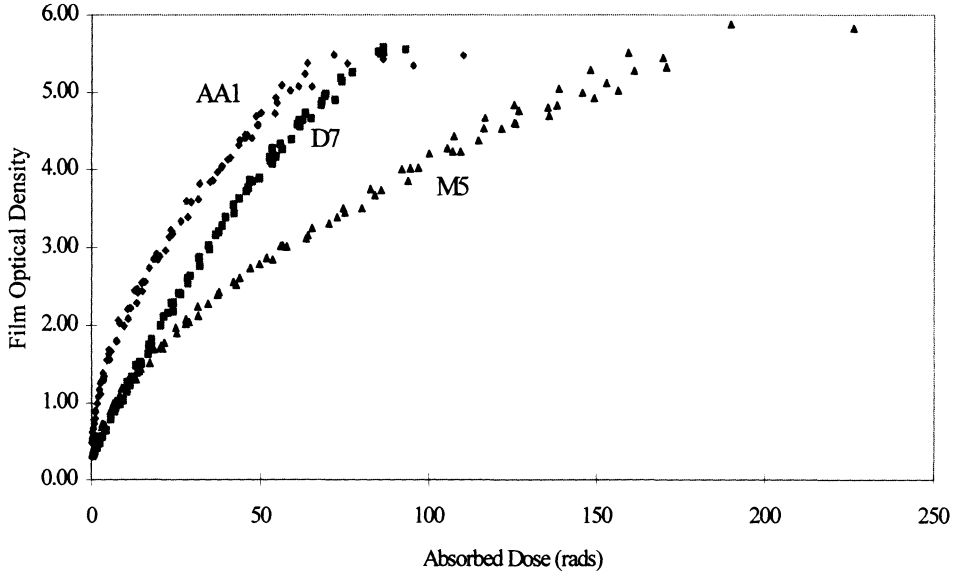


Figure 4. Calibration curves for different types of film.

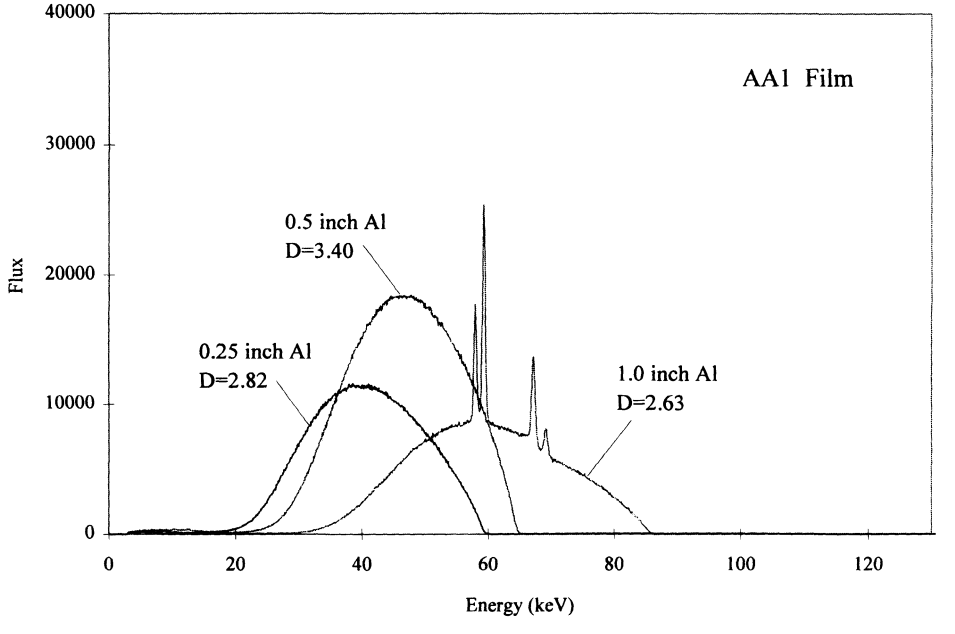


Figure 5. X-ray energy spectra observed for different exposure conditions. The corresponding film densities are indicated.

Table 1. Comparison between predicted and measured film densities for different exposure conditions.

Al thickness	Film type	kVp	mA*sec	Density	
				Calculated	Measured
1/4"	AA1	60	110	1.67	1.78
1/4"	AA1	60	280	2.85	2.82
1/4"	M5	60	540	2.22	2.29
1/2"	AA1	65	825	3.44	3.40
3/4"	AA1	75	414	2.19	2.37
3/4"	M5	75	1050	1.90	2.06
1"	AA1	85	540	2.38	2.63

FILM NOISE

For a complete model of film response it is necessary to represent the noise or graininess of an image. These random variations in density can be due to fluctuations in the incident X-ray flux, fluctuations in the rate of absorption in the emulsion, and variations in the size and distribution of film grains. At high energies (>1 MeV) a single X-ray can cause several adjacent grains to become developable, leading to further variations. The film development process and density measurement procedure can also introduce random as well as systematic variation. In our model we have considered only fluctuations in absorbed X-ray flux and random variations in the distribution of film grains.

In high-magnification images such as Fig. 1 the grainy structure of the film is obvious. A densitometer (or the eye) will integrate over an area (typically 10-100 μm diameter) covering many film grains. Thus the fluctuations in density will depend on the size of the aperture considered.

A simple model of film noise which works quite well is referred to as the random dot model[3]. Developed grains are represented by circular disks of area a and uniform absorbtance g. The disks are distributed randomly with an average of n disks per unit area. Then, from geometric considerations, the average density will be

$$D = 0.434nag. \tag{3}$$

If $na<<1$, then for an aperture of area A, the fluctuations in density will follow

$$\sigma_D = \sqrt{0.434ag\,D/A}\,. \tag{4}$$

This expression gives fairly good agreement with observations for low to medium densities. Notice, however, that Eq. 4 predicts that the fluctuations will continue to rise with density, which is not observed as saturation is reached.

A noise model which avoids this problem is the binomial model[7]. In a given film pixel there will be a finite number, N_0, of grains. Upon development, on average $<n>$ of

these grains will be black. The distribution of black grains should follow a binomial distribution:

$$P_n = \frac{N_0!}{n!(N_0 - n)!}(1 - <\eta>)^{(N_0 - n)}(<\eta>)^n, \tag{5}$$

where $<\eta> = <n>/N_0$.

Under assumptions of uniform grain size and no light scattering the density can be expressed as

$$D = \eta^{1/\beta} D_{max}, \tag{6}$$

where D_{max} is the maximum density, and β accounts for correlation between grains. $\beta=1$ corresponds to no correlation, while $\beta>1$ for correlated grains. Under this model the standard deviation of the density is

$$\sigma_D = \frac{1}{\beta\sqrt{N_0}}\sqrt{D^{2-\beta}\left(D_{max}^{\beta} - D^{\beta}\right)}. \tag{7}$$

Notice that at low density this will behave in a manner similar to the random dot model. At high density though, the fluctuations go to zero as D approaches D_{max}.

In the radiography model, XRSIM, we have used this binomial model with $\beta=1$. At present we use estimates of the film grain densities, N_0, for the different film types. Qualitatively the simulated radiographs compare well with real images at moderate film densities. However, one should note that at very high densities the binomial model does not account for variations in the distribution of the film grains inherent in the manufacturing process.

SUMMARY AND DISCUSSION

We have demonstrated a simple technique for modeling the density-exposure relation for radiographic films. Simulated results are in good agreement with measurements for a wide range of exposure conditions. Improvement is needed in the absolute normalization of the exposure measurements. For this purpose we plan to relate the measurements from the Ge detector to measurements from a calibrated ionization chamber. Proper accounting for scattering buildup will allow us to extend the model to even thicker materials. In the future we also plan to extend the model to cover the use of intensifying screens.

Film noise models currently in use are somewhat ad hoc and break down at high density. Nevertheless they provide a fairly good representation of film noise at densities typically encountered in radiography. However, as film digitization and image processing become more prevalent, it will become more important to consider the higher densities. For purposes of image simulation, the most efficient approach may be to determine empirically a relation between film density and film noise for each film type. This is an approach we are currently evaluating.

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REFERENCES

1. ASTM E94-92, E999-90, Annual Book of ASTM Standards, Vol. 03.03 (1993).
2. J. Xu et al., "Recent Developments in the X-Ray Radiography Simulation Code: XRSIM", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 13, p. 557, Edited by D.O.Thompson and D.E.Chimenti, Plenum Press, New York, (1994).
3. See, for example, T.H. James, The Theory of the Photographic Process (Fourth Edition), Macmillan Publishing Co., Inc., New York (1977).
4. See, for example, H.E. Johns and J.R. Cunningham, The Physics of Radiology (Fourth Edition), Charles C. Thomas, Publisher, Springfield, IL (1983).
5. E.F. Plechaty, D.E. Cullen, and R.J. Howerton, "Tables and Graphs of Photon Interaction Cross Sections from 1.0 keV to 100 MeV Derived from the LLL Evaluated Nuclear Data Library", UCRL-50400, Vol. 6, Rev. 1, National Technical Information Service, Springfield, VA (1975).
6. Taher L. Aljundi., "Modeling X-ray Scattering Process and Applications of the Scattering Model", Ph.D. Thesis, Iowa State University (1995).
7. Y. Segal, D. Ingman, and Y. Bushlin, "Noise and Granularity in Radiographs", Materials Evaluation Vol. 46, p. 513 (1988).