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FLASH X-RAY WITH IMAGE ENHANCEMENT
APPLIED TO COMBUSTION EVENTS

Kevin J. White
Donald G. McCoy

August 1985

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Flow visualization of interior ballistic processes by use of x-rays has placed more stringent requirements on flash x-ray techniques. The problem of improving radiographic contrast of propellants in x-ray transparent chambers has been studied by devising techniques for evaluating, measuring and reducing the effects of scattering from both the test object and structures in the test area. X-ray film and processing is reviewed and techniques for evaluating and calibrating these are outlined. Finally, after x-ray techniques have been		

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20. ABSTRACT (cont'd)

optimized, the application of image enhancement processing which can improve image quality is described . This technique has been applied to x-ray studies of the combustion of Very High Burning Rate (VHBR) propellants and stick propellant charges.

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I. INTRODUCTION

Over the past several decades ballistic laboratories both in the US and abroad have used flash x-rays as a diagnostic tool for studying terminal ballistic events. Since the flash x-ray pulses have a duration of a few tens of nanoseconds they are aptly suited for ballistic processes in which velocities up to several millimetres per microsecond can occur. Moreover, detonation (and combustion) phenomena are usually optically "dirty" containing a great deal of luminosity and particulate matter. This makes normal high speed optical techniques of only limited use in studying these phenomena. The high energy x-rays can easily penetrate these potentially interfering events and record such things as spall patterns, shaped-charge formation and metal fragmentation patterns. More recently, flash x-rays have been applied to interior ballistic events^{1,2,3} to record propellant processes that take place during the interior ballistic cycle. The application of x-ray techniques for recording low density materials such as propellants (as opposed to high density materials such as steel) can entail certain problems, however. For the data to be useful, one must be able to perceive differences in propellant configuration throughout the chamber. Contrasts are affected by a number of factors, including the density and atomic number, Z, of materials. Ordinarily, combustion processes are carried out in high density, high Z steel chambers, which, because of their strong absorption characteristics, make it difficult to differentiate contrast in the propellant. This difficulty can be partially overcome by using aluminum, fiberglass or other composite materials for the chambers. Another problem affecting contrast is Compton scattering. This scattering of x-rays produces "fog" on the radiographs, reducing contrast. With x-ray sources in which the photon energies range from 50 to 150 keV, most of the interaction with metals takes place in the photoelectric region which results in absorption and little scattering. However, as will be seen, interaction with hydrocarbons produces a great deal of scattering causing a degradation of the image. Medical x-ray imaging has been troubled by this for many years and techniques have been developed to reduce this.

Considerably more penetrating ability along with a higher x-ray dose can be achieved by using higher energy x-ray sources such as the 1 MV peak voltage systems. However, with these high energy sources more problems are encountered with scattering. Even metals and other high atomic Z materials which may be located in the test area can produce room scattering and seriously degrade the image contrast. The thrust of this paper is aimed at how to overcome the negative aspects of scattering.

¹W. R. Burrell and J. L. East, "Effects of Production Packing Depth and Ignition Techniques on Propelling Charge Reaction and Projectile Response," NWSC/DC TR-3705, Naval Surface Weapons Center, Dahlgren, VA, 1979.

²T. C. Minor, "Characterization of Ignition Systems for Bagged Artillery Charges," ARBRL-TR-02377, USA ARRADCOM/Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1981. (AD A108 119)

³U. Hornemann, "Investigation of Propellant Combustion in X-Ray Transparent Gun Tubes," Ernst-Mach-Institut/Abteilung fuer Ballistik Report No. 3/79, Weil am Rhein, West Germany, 1979.



Motivation for the work reported here came from a feasibility study of using flash x-rays to produce data for a ballistic Computed Tomography (CT) scanner⁴ which would produce cross-sectional views of an interior ballistic process in an x-ray transparent gun chamber. To accomplish this the highest quality radiographs must be produced in which scattering problems must be minimized. The films must also be calibrated so that optical densities can be related to material densities. Film processing variables were studied to produce optimum results. Even after optimization of photographic recording, contrast and detail are generally marginal. An image analysis system was used to enhance features and average out film noise.

Although the techniques described in the following sections were used to generate data for tomographic images, they can readily be applied to many conventional radiographic conditions producing better qualitative and quantitative radiographs. The application of imaging techniques to flash x-rays of burning VHBR propellants and stick propellant charges will be demonstrated.

II. X-RAY SCATTERING

The purpose of this section is to describe the interaction of x-ray photons with an object to demonstrate the scattering process and its effect on x-ray images. An x-ray beam of intensity I_0 is attenuated in passing through an object of thickness x and density, p , by,

$$I = I_0 \exp(-upx),$$

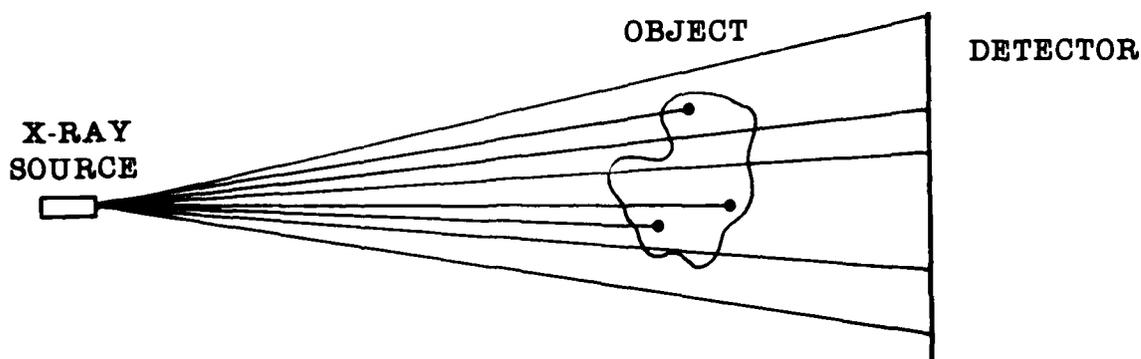
where u , the mass absorption coefficient, is made up of two components,

$$u = u_p + u_c$$

u_p , is the photoelectric absorption coefficient, and u_c is the Compton scattering coefficient. The physical representations of these processes are shown in Figure 1a and 1b. For purposes of this discussion the photoelectric process effectively removes the photon from the beam. The Compton process scatters the photon to lower energy and causes it to emerge from the object at a different angle. Thus the ideal radiograph is produced (Figure 1a) by the photoelectric process whereas the Compton scattering will produce a fogging of the image on the detector (for example, film) as illustrated in Figure 1b. These coefficients, u , vary with the object material and x-ray energy and are shown for a number of materials in Figure 2a through Figure 2d. We have plotted here the linear absorption coefficient which is the mass absorption coefficient, u , times the density, p , in order to more readily compare different materials. The mean-free-path (mfp) is plotted on the right hand axis. This shows the amount of material required to reduce the initial intensity to $1/e$ of its original value from either photoelectric absorption or Compton scattering. It is clear that for lead (Figure 2a) photoelectric absorption dominates the interaction at x-ray energies below 300 keV.

⁴C. K. Zoltani, K. J. White and R. P. Kruger, "Results of Feasibility Study on Computer Assisted Tomography for Ballistic Applications," ARBRL-TR-02513, USA ARRADCOM/Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1983. (AD A133 214)

(a)



(b)

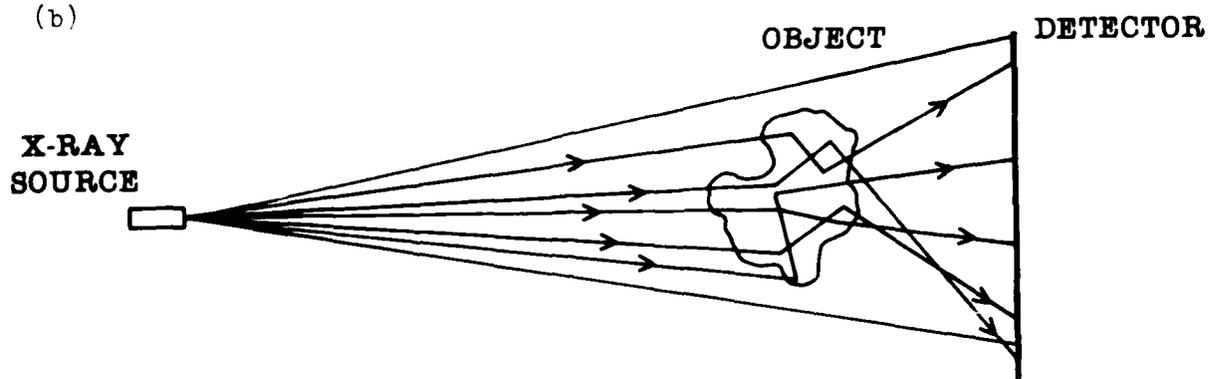


Figure 1. (a) Photoelectric Absorption, (b) Compton Scattering

However, Figure 2b, carbon, shows that Compton scattering dominates at energies as low as 30 keV, with a mfp of several centimetres. At energies greater than 150 keV the mfp is greater than 5 cm and objects smaller than this will produce little scattered radiation. Many ballistic applications involve studying chambers in excess of 20 cm. In these cases it is seen that scattering can occur at photon energies as large as 1 MeV. The photoelectric absorption is seen to be so small that any imaging of a hydrocarbon is the result of Compton scattering. This clearly illustrates that when hydrocarbon objects are being studied by x-rays an effort should be made to deal with the scattering problem, as this is the chief mechanism that results in the image.

If the source itself is not properly collimated so that the x-ray photons are allowed to interact with other objects in the test area, then such items as concrete and steel can be sources of unwanted "test site" scattered radiation. Figures 2c and 2d show the coefficients for silicon and iron as an example of atomic species in construction materials. Above 150 keV, 2-cm of iron can cause considerable scattering. In the case of silicon, scattering can be a problem with energies as low as 60 KeV for a thickness of silicon of between 3 and 5 cm. Since soil and concrete consist largely of silicon compounds they can be a source of scattering problems.

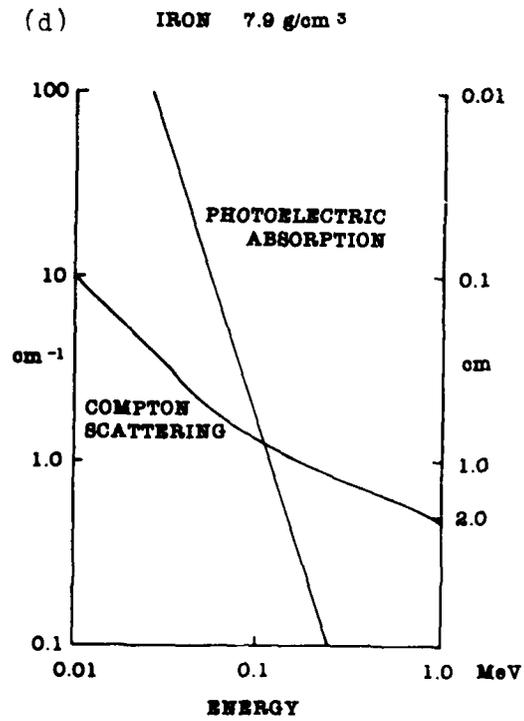
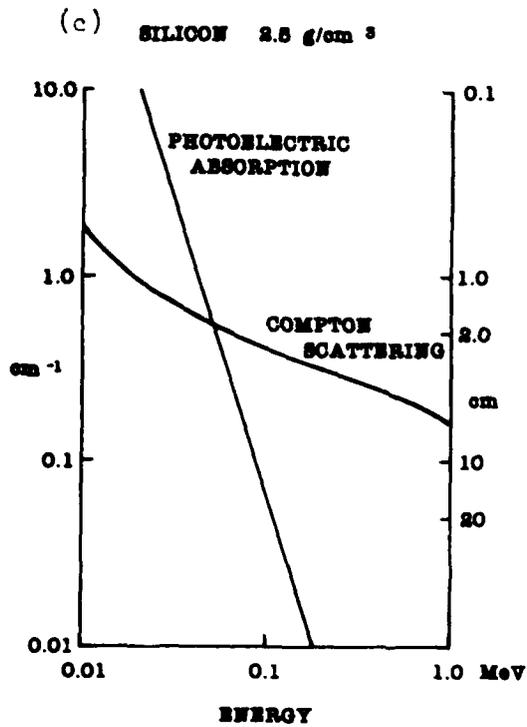
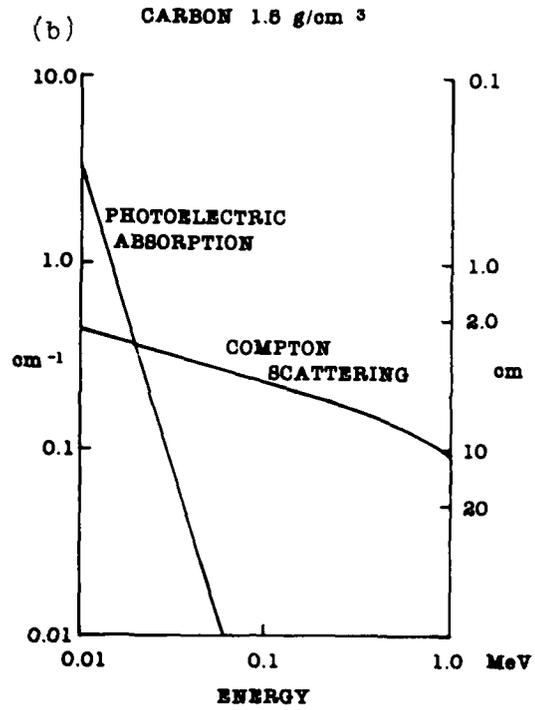
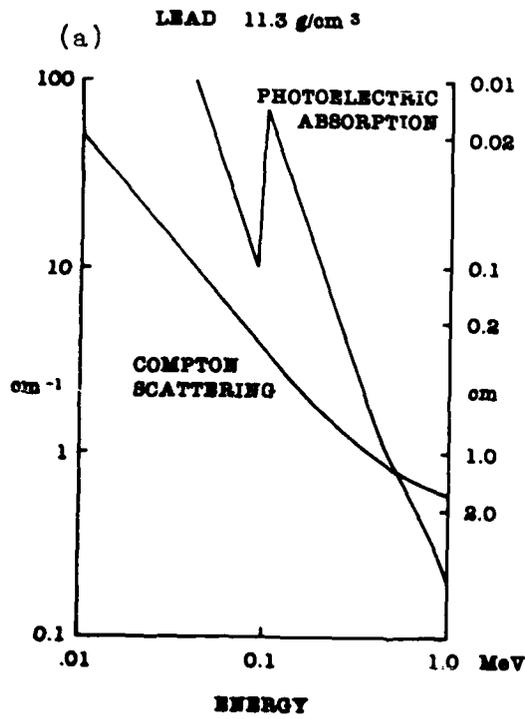


Figure 2. Linear Absorption Coefficient for (a) Lead, (b) Carbon, (c) Silicon, (d) Iron.

It should be understood that the arguments presented thus far on scattering are largely qualitative in nature and do not specifically address the severity of the problem in individual cases. Quantitative evaluation of the problem can be carried out by three dimensional Monte-Carlo calculations including the spectral output of the x-ray tubes and the complete geometry of the test site. Alternatively, some simple experiments can be performed to determine the magnitude of the problem. Figure 3 illustrates a test to evaluate the test site scattering. The lead brick mid-way between the source and the cassette detector should appear as an unexposed object on the film. Any site scattering will reach the screen behind the brick's shadow causing some exposure, however. The film behind the lead brick directly against the cassette should also be unexposed. However, transmission of radiation through the cassette may scatter off of other objects within the test area. Although most cassettes have a lead backing, it is generally 0.1-to 0.2-mm in thickness and offers little attenuation at energies greater than 200 keV. The opaque material in the cassette between the screens and the film will produce a non-exposed region on the film that can be used as a reference. Scattering from

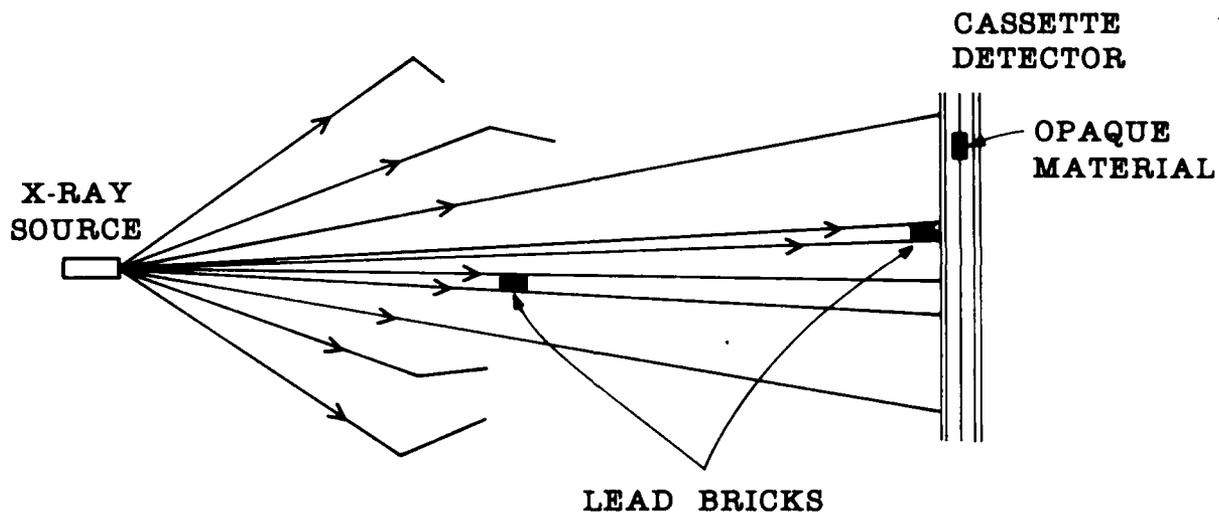


Figure 3. Source Scattering Test

the object under study can also lead to a degraded image. Figure 4 illustrates a technique for measuring this scattering. In (a), the profile determines the total radiation. The scattered radiation can be found in (b) as the signal measured in the shadow of the opaque material. The collimator shown in (c) will eliminate all but the uncollided radiation from the object. A comparison of these three signals will determine the amount of scattered radiation. A technique for collimating the source and detector is illustrated in Figure 5. In medical radiology it is common practice to limit the field of view on the patient only to that region of interest and to use collimators known as "Bucky" grids as a film collimator. The radiological thickness of the collimator is also important. Figure 2a, representing lead, illustrates this point. Consider a photon of energy 800 keV interacting with lead of thickness 0.5 cm. Photoelectric absorption is negligible and the mfp for

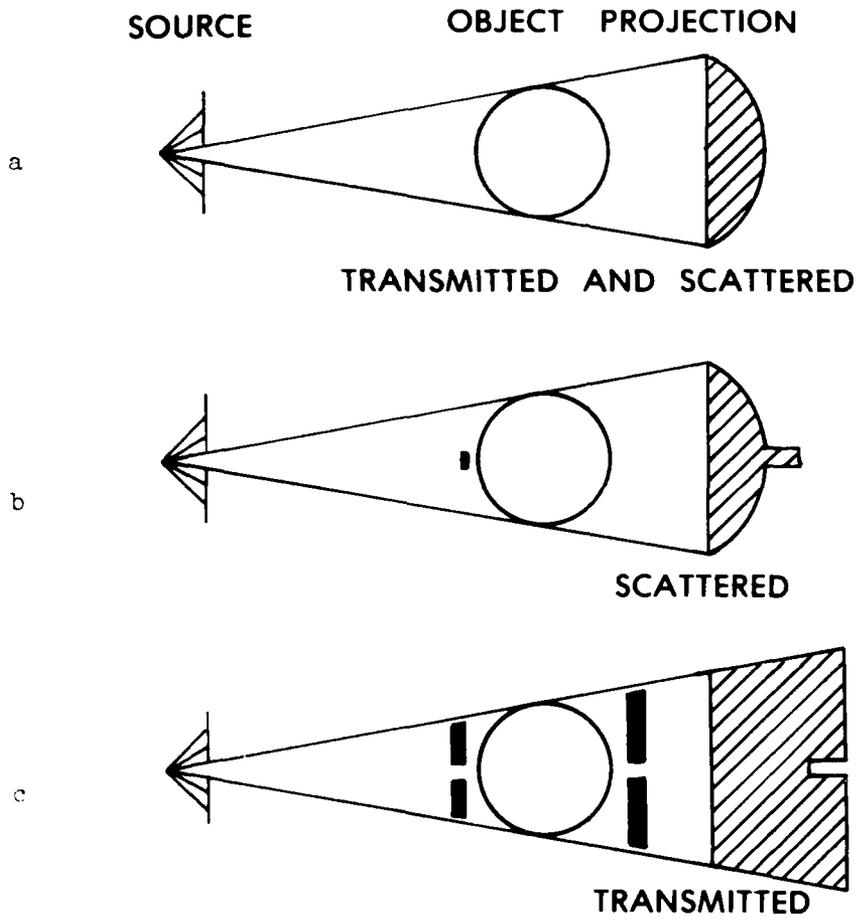


Figure 4. Object Scattering Test

APPENDIX

PROCESSOR SET UP AND CONTROL

Temperature and Replenishment Rates

Report prepared by the Technical Services Department, 3M Imaging Systems Division, 3M Center, 209-BS-002, St. Paul MI 55144.

A. Introduction

A simple calculation which includes the various 3M Brand films, the number of domestically manufactured processors and the number of domestic x-ray chemistries shows that there are more than 1200 possible combinations of 3M film, processor and chemistry. This calculation does not include the additional effects introduced by temperature, chemistry age, processor condition, chemistry batch variability, and fixer of Account volume.

The enormous number of possible conditions which are available preclude using tables of numbers to cover all conditions. The following guidelines however should enable one to set up or "steer" a processor, and to produce films which maintain the quality desired by the Account. It should be understood that the data in this document refers to 3M films produced in a particular time frame. These results will vary from manufacturer to manufacturer and may change for other 3M products as they are developed.

B. Bromide and Sulfite (Hydroquinone)

The three constituents of the working developers which have the largest effect on the sensitometry are bromide (the development restrainer), sulfite (the anti-oxidant) and the developing agent, hydroquinone. The sulfite and hydroquinone consumed in the development of film are maintained by replenishment while the bromide is maintained as a result of the development of exposed areas of the film.

The sulfite and bromide are not independent variables but are related inversely in the replenished working solution. Oxidation of the developer, however, reduces the sulfite independent of the bromide. This is discussed later.

A small amount of bromide is added initially by use of the starter solution.

The hydroquinone and sulfite are intimately related to each other because the development process and air oxidation consume exactly equivalent quantities of each. Thus a measurement of sulfite is an indirect measure of hydroquinone.

Freshly mixed chemistry with starter will generally have a low value of bromide and a high value of sulfite. As film is processed, the bromide level increases and the sulfite level decreases until a steady state is reached. The steady state levels of bromide and sulfite will be determined primarily by the replenishment rate but also important are the Account volume (oxidation),



APPENDIX
PROCESSOR SET UP AND CONTROL

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1. W. R. Burrell and J. L. East, "Effects of Production Packing Depth and Ignition Techniques on Propelling Charge Reaction and Projectile Response," NWS/DC TR-3705, Naval Surface Weapons Center, Dahlgren, VA, 1979.
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3. U. Hornemann, "Investigation of Propellant Combustion in X-Ray Transparent Gun Tubes," Ernst-Mach-Institut/Abteilung fuer Ballistik Report No. 3/79, Weil am Rhein, West Germany, 1979.
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8. Technical Services Department, 3M Imaging Systems Division, 3M Center, 209-BS-02, St. Paul, MN, 1983.

V. ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of T. Minor, D. Henry, A. Baran, C. Zoltani. We also wish to thank Mr. W. Frank, 3M Imaging Systems Division, 3M Center, St. Paul, Minnesota for supplying us with the write-up in film processing reported in Appendix.

of the sample at the igniter end was larger than that at the far end, indicating that the sample was under compression but that this had not reached the far end of the sample, perhaps due to a plugging effect of the sample midway down the tube. These techniques were also applied to other Very High Burn Rate (VHBR) propellants with some success. Interesting effects were also observed in radiographs of stick propellant burning in a x-ray transparent chamber. It appeared that there was a compaction of the propellant at the rear end of the charge.

Though the above data are very preliminary, taken well before the problems associated with scattering, film processing and field uniformity were fully appreciated, they do point to an important area of application in systems where mechanical loading and subsequent density changes can affect combustion behavior. For most radiographic applications of high contrast objects, such precautions are unnecessary.

IV. CONCLUSIONS

Contrast and image quality can be improved by removing scattered radiation. A simple test has been described that determines the amount of scattering in a given setup.

Collimation techniques for the radiation source and the object have been described which can minimize scattering problems. As small an area as is possible of the object under study should be illuminated with the x-ray radiation. Required thickness of collimator material depends on the average energy as well as the fluence of the x-ray source.

Several references are available that review the characteristics of various films and screens. Selection is based on a particular application or requirement as there are trade-offs between sensitivity and resolution.

For low contrast radiographs film processing should be carefully controlled, the chemicals should be fresh, the replenishment rates and temperatures set according to film manufacturers specifications and the processor clean.

Image analysis offers good opportunities for enhancing marginal radiographs via smoothing, contrast enhancement and application of pseudocolor. To effectively apply this technique, radiation field uniformity should be measured and processing should be controlled so that artifacts are not represented as physical events.

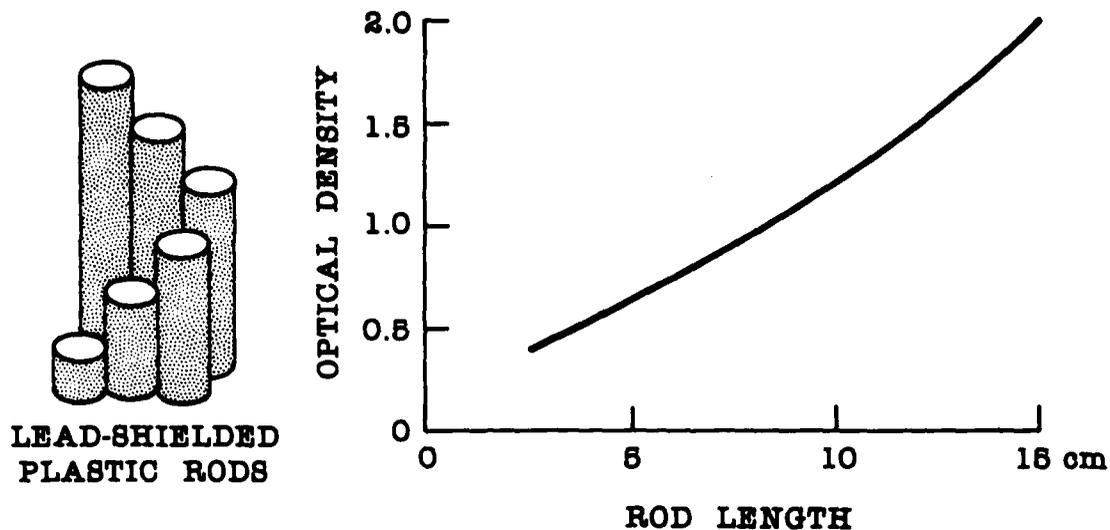


Figure 11. Film Calibration Device for Hydrocarbons

spatial frequency components such as a gradual change in density over the entire image, many such smoothing operations are possible without degradation of the important data.

Another very useful operation in image enhancement is the concept of pseudocolor. In concept, each gray scale or range of gray scales is assigned a specific and unique color. We have found it helpful in interpretation if the lowest gray scale of interest is assigned violet and the highest assigned red, with the intervening values being assigned to corresponding colors of the visible spectrum. Optical density gradients can be more readily observed than in the black-and-white radiographs.

It must be emphasized here that a number of precautions should be exercised before interpreting radiographs that have been subjected to these operations. X-ray radiation field uniformity/reproducibility should be measured by taking static radiographs in the region of the object. Variations here could be misinterpreted as object density variations when, in fact, they may be variations in the radiation field. We have measured the field radiation variation at a distance of 2 meters from a 1 MV flash radiation source over a solid angle of 10 msr and found an intensity variation of less than 5%. This measurement should be done on a case-by-case basis to insure uniformity.

Contrast enhancement, smoothing and pseudocolor assignment operations have been applied to radiographs of propellants burning in chambers. A cylindrical sample of a HIVELITE formulation was ignited at one end and burned cigarette fashion in a cylinder of an inside diameter equal to the sample diameter. The radiograph indicated a deconsolidation or breaking up of the sample. Application of pseudocolor to the radiograph showed that the density

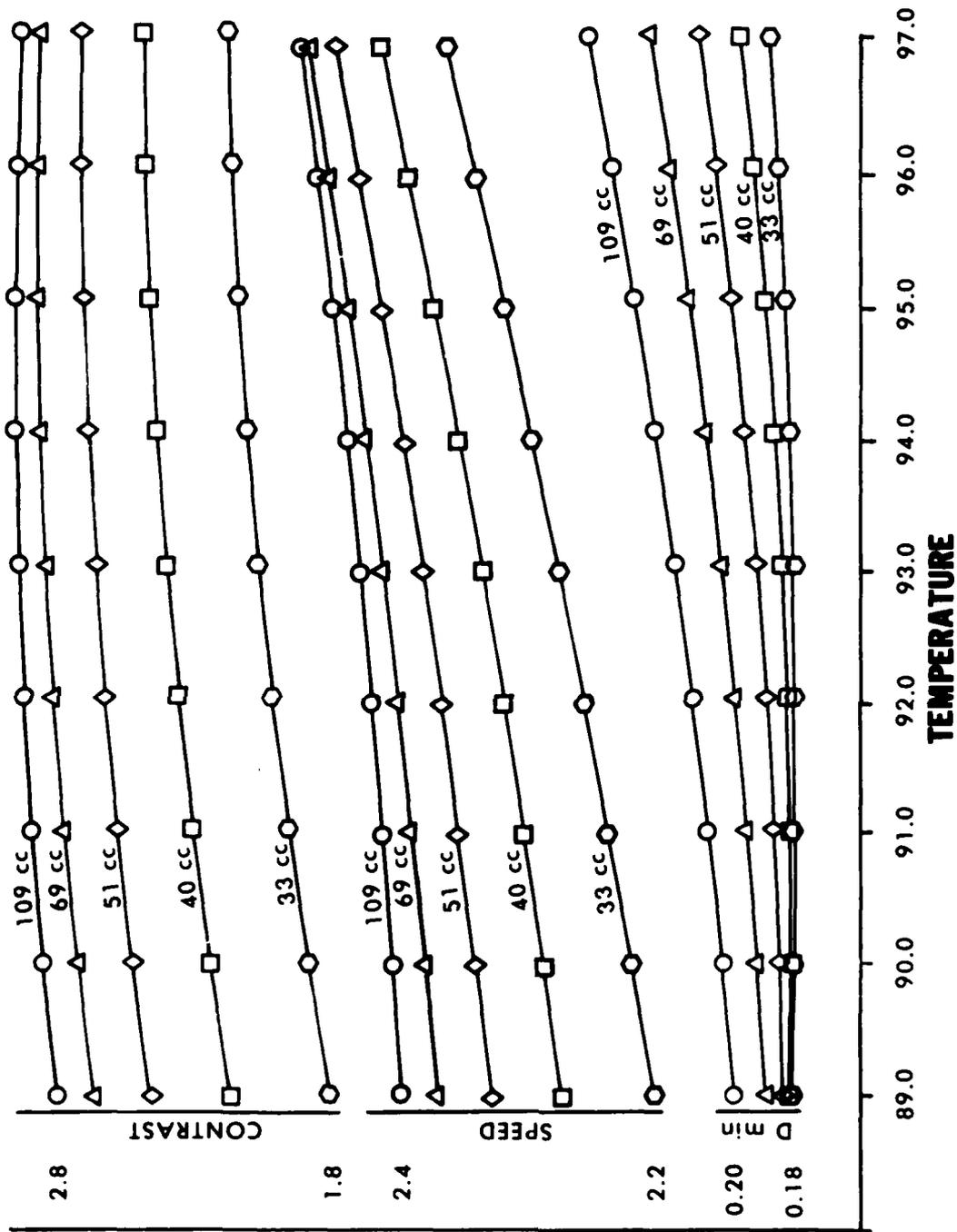


Figure 10. Effect of Developer Temperature and Replenishment Rate on Film Characteristics

(<45°) otherwise water marks will be evident. Our experience has been that the film should be removed when it is moving from the water bath to the dryer and hand washed in a water solution containing a wetting agent. It can then be re-inserted into the dryer rollers.

The report given in the Appendix has described the effect of developer replenishment rate and temperature on film characteristics and an example is shown in Figure 10. It is clear that the replenishment rate (the volume of developer chemicals added to the original developer bath after processing one sheet of film) has a dramatic effect on the contrast, sensitivity and fog (D_{min}). Thus, small changes in developer chemistry can have a large effect on a measured film density profile. In general, closed tank lifetime of developer is on the order of two months but only two weeks in the processor developer tank. Because of this sensitivity it is necessary to internally calibrate the entire x-ray-screen system. In many applications we will be taking radiographs of hydrocarbon materials. A calibration device is shown in Figure 11. Plastic rods of varying length are radiolytically isolated from each other by lead sheets. A radiograph is taken of this step function and a plot is made of the film optical density vs. length of the plastic rods. Any nonlinearities in the system such as intensifying screen or film response, x-ray beam hardening, can be corrected by applying this function to the optical density data. This step function can also be used to give a quantitative evaluation of the contrast capabilities of various film-screen combinations. The graph shown in Figure 11 can be generated for a number of systems.

C. Image Processing

Optimizing film processing, selecting suitable film-screen combinations and minimizing scattering will enhance the quality of the radiographs. However, under the best of circumstances low contrast objects will give marginal radiographs. Image analyzers have been applied with great success in enhancing satellite and space photography. These techniques can also be usefully employed to enhance radiographs. Many such systems are commercially available. In principle the radiograph is digitized either by a TV vidicon, charge coupled device (CCD), or programable optical densitometer. The image, for example, is stored in an array of picture elements or pixels of magnitude 512 by 512 with each pixel having a range of 256 (8 bit) gray scales. Various algorithms have been developed to enhance and otherwise alter the image. For example, the contrast can be enhanced by expanding the range of gray scales. If the image gray scale range extended from 100 to 150, this could be changed from 50 to 250 which would greatly increase the contrast of the image.

In some instances, noise in the image can cause difficulty in interpretation. This noise may be due to a number of things including scattering but also to graininess in the film. This is generally of a much higher spatial frequency than the data in the film and can be reduced by smoothing via a nine-element matrix (convolver). In concept, the value of each pixel is replaced by the average of the surrounding 8 pixels, weighted by the corresponding element in the matrix. Thus, if all elements in the matrix are equal to 0.11, each pixel will be replaced by the average of the 8 surrounding pixels. This is done for all 512 by 512 pixels and the resulting image will be smoothed with the same average brightness. This process can be repeated and is only limited by the spatial frequency required for the relevant data to be observed. Thus, if one is looking only for very low

source which is a reasonable approximation to a point source. The distance from the film to source can be varied and a second small section of the film illuminated. This can be done for a number of distances and the $1/r^2$ change in intensity can be used to determine the relationship of film optical density D to intensity of the exposing light source. Alternatively a calibrated optical step wedge can be placed between the light source and the film. In carrying out this test one must insure that there are no sources of reflection of the point source in the test area as this will lead to incorrect results. An example of a calibration is shown in Figure 9 for a specific film processor, developer time and temperature. It is seen that the film response

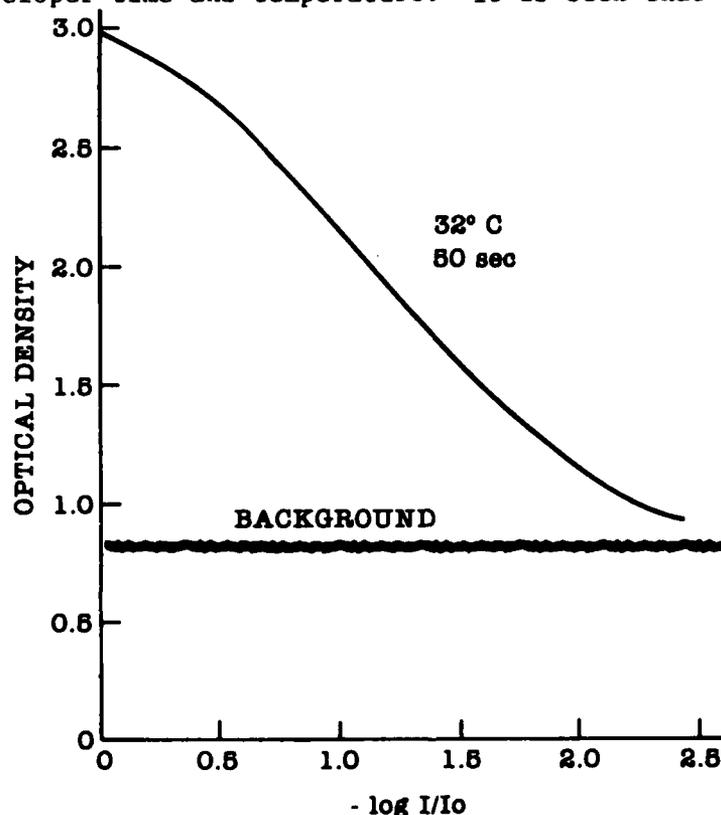


Figure 9. Film Optical Density as a Function of Intensity

is linear in the region from $D = 1.2$ up to $D = 2.5$, an important piece of information if optical densities are to be related to x-ray attenuation through the object. Other film characteristics can be determined from these data such as fog, or D_{min} , which is the background signal on the film. Film contrast is obtained from the slope of the linear portion of the curve and is an indication of the "gain" of the film. Film speed is obtained from the magnitude of the D for a given illuminating intensity and is an indicator of the sensitivity of the film. These can be compared to manufacturer's specification to insure that conditions are optimum. Comparisons can be made with other types of films.

Careful maintenance of the processor is also necessary so as not to introduce artifacts in the image. Rollers in the developer, fixer and dryer should be clean of any buildup of chemicals as their presence will lead to pressure marks on the film. Worn gears will also result in periodic artifacts on the developed film. The dryer should not be set at too high a temperature

radiation as it moves parallel to the screen thus reducing the light spill-over which leads to a blurred image. Picture contrast and image quality can sometimes be increased by using two pieces of film instead of one inside the intensifying screen cassettes. An example of this is shown in Figure 8. An optical density profile was measured of a plastic step wedge with one piece of film and with two pieces of film. A small increase in signal-to-noise is observed.

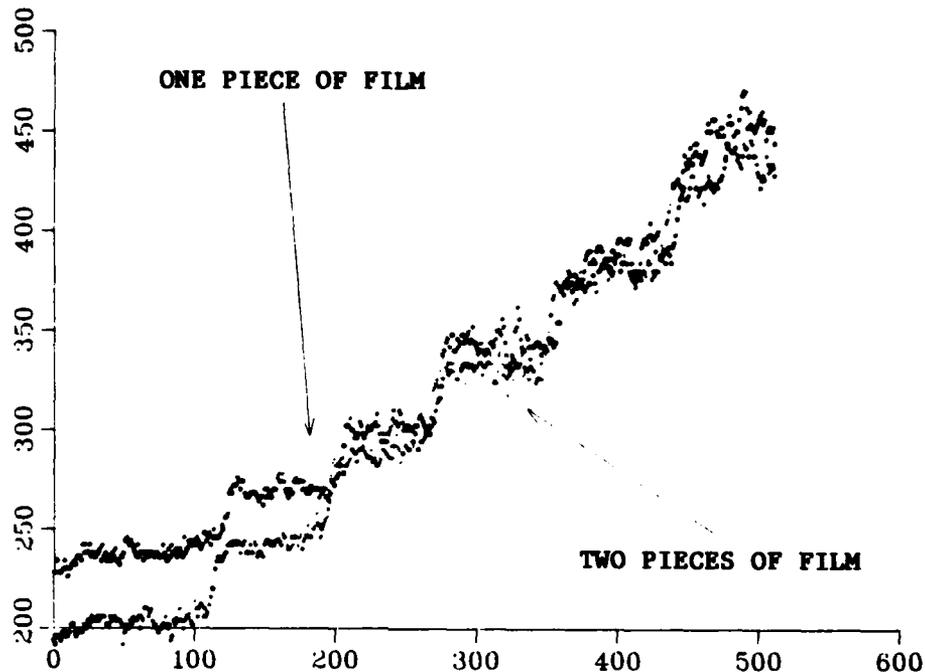


Figure 8. Optical Density Profile of Step Wedge With One and Two Pieces of Film

B. Film Processing and Calibration

Quantitative film data requires that there be a minimum of gray scale variation in the films due to processing. The report by the 3M Imaging Systems Division⁸ is an excellent guideline for processor set-up and control which clearly shows the dramatic effect of developer immersion time, temperature and chemistry on fog, or background level, contrast and speed of the film.

Although x-ray film characteristics are generally available from the manufacturer, a simple on-site test can be carried out to insure that the film is not seriously degraded, or that the processor and processor chemistry is in order, since film and chemical shelf-life can be an important problem. A small section of the film is illuminated by a single pulse from a strobe light

⁸Technical Services Department, 3M Imaging Systems Division, 3M Center 209-BS-02, St. Paul, MN, 1983.

could be detected by the medical screens, thus enhancing the sensitivity. The test was not successful as the sensitivity was in fact reduced, most probably due to the attenuation of the lower energy radiation by the lead screen.

Medical film is frequently referred to as "blue" or "green" sensitive and screens as "blue" or "green" emitting. The reason for this is shown in Figure 7 where the spectral sensitivities of the two types of films are shown along with the emission spectra of both the calcium tungstate and rare earth screens. Naturally it is imperative that the screen and film be spectrally matched. Rare earth screens require films that are sensitive in the green whereas blue sensitive film is adequate for the calcium tungstate screens. Detailed information on intensifying screens is generally proprietary and not available but the matrix in which most of the x-ray absorption takes place is gadolinium-oxy-sulfide (Gd_2O_2S), which has a density of 7.35 g/cm^3 and an equal volume of binder. This matrix is doped with small concentrations of various rare earth materials such as terbium (Tb) or praseodymium (Pr), which are the source of the visible emitted radiation. The sensitivity is controlled by the thickness of the screen but this cannot be increased indefinitely. These materials are amorphous and are not transparent. This results in scattering of visible radiation. Self absorption and scattering of

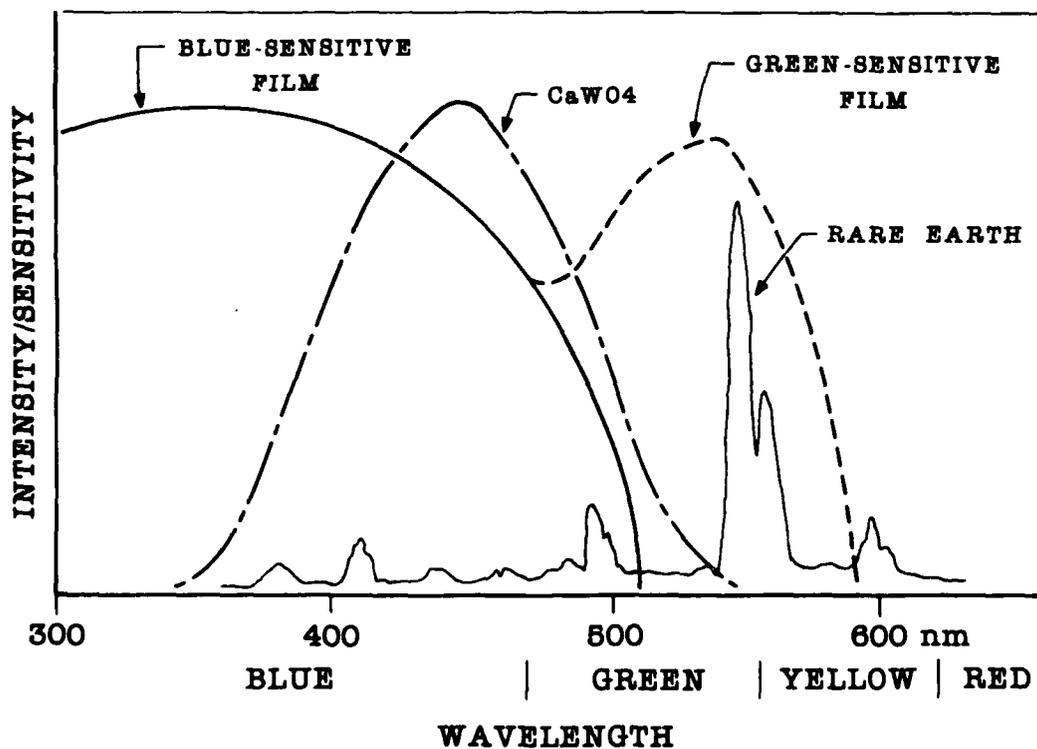


Figure 7. Spectral Characteristics of Screens and Films

the visible radiation takes place so that if the material is too thick the light output will actually decrease. Additionally, as the screen becomes thicker the sharp edges of a radiographic shadow on the screen will be blurred due to scattered light within the screen. To minimize this problem visible radiation absorbers are introduced into the screen which attenuate light

A. Film-Screen Selection

Numerous articles^{5,6,7} have been written in recent years on the characteristics of radiographic film-screen combinations. The interested reader is referred to these sources for more detail on this subject. Here we will review some of the physics involved in the detection process so that film-screen selection can be made on a more rational basis.

There are two types of film in use in radiography, industrial and medical. The former, in general, have a thicker emulsion than the latter and do not have ingredients which sensitize the film to visible light, especially the longer wavelength region. These films are exposed by direct x-ray radiation. Since medical film is generally used with screens that fluoresce in the visible region when they interact with x-rays, they contain dyes that extend the spectral response towards the longer wavelengths. The industrial films are usually optically slower because of the finer grain silver halide used in the emulsion. This slower film can be used since there is no constraint on the dose absorbed by the object. This fine grain emulsion in the industrial film leads to a resolution greater than that for medical film. In medical radiology dosage is an important consideration and some resolution is sacrificed for increased sensitivity. Because of the thick emulsion the optical density D^* range for industrial film runs from approximately 0.3 up to 6, whereas for medical film the range is from 0.3 up to 3.5. Automatic processing conditions are also very different; industrial films are processed in the developer for 150 seconds at 28°C whereas medical films require 22 seconds at 35°C. Thin lead screens (0.25 and 0.12 mm) are used with industrial films to increase sensitivity. These screens are supposed to filter out low energy scattered radiation from the subject which will produce fog. Additionally the lead interacting with the primary x-ray beam will produce electrons and lower energy photons that will sensitize the film and enhance the image. We have attempted to apply this idea to medical film-screen systems considering that we were using a 1 MV peak flash x-ray source. The thin lead screens are transparent to the high energy x-rays (Figure 2a). The concept here was that the high energy x-rays would be converted by scattering within the lead screen to lower energy so that they

*The optical density D is defined as,

$$D = -\log (i/i_0),$$

where i/i_0 is the measured fraction of light transmitted through the exposed and developed film.

⁵L. E. Bryant, J. P. Lucero, And R. P. Espejo, "X-Ray Film/Intensifying Screen Study for Flash Radiography," H-P 5952-6838, Hewlett-Packard, McMinnville, OR, 1980.

⁶C. E. Dick and J. W. Motz, "Image Information Transfer Properties of X-Ray Fluorescent Screens," Med. Phys., Vol 8, pp 337-346, 1981.

⁷G. Hagemann, D. Tollner, D. Saure and J. Freyschmidt, "Neue Verstaerkerfolien in der Klinischen Radiologie, Fortschr. Roentgenstr., Vol 124, pp 483-489, 1976.

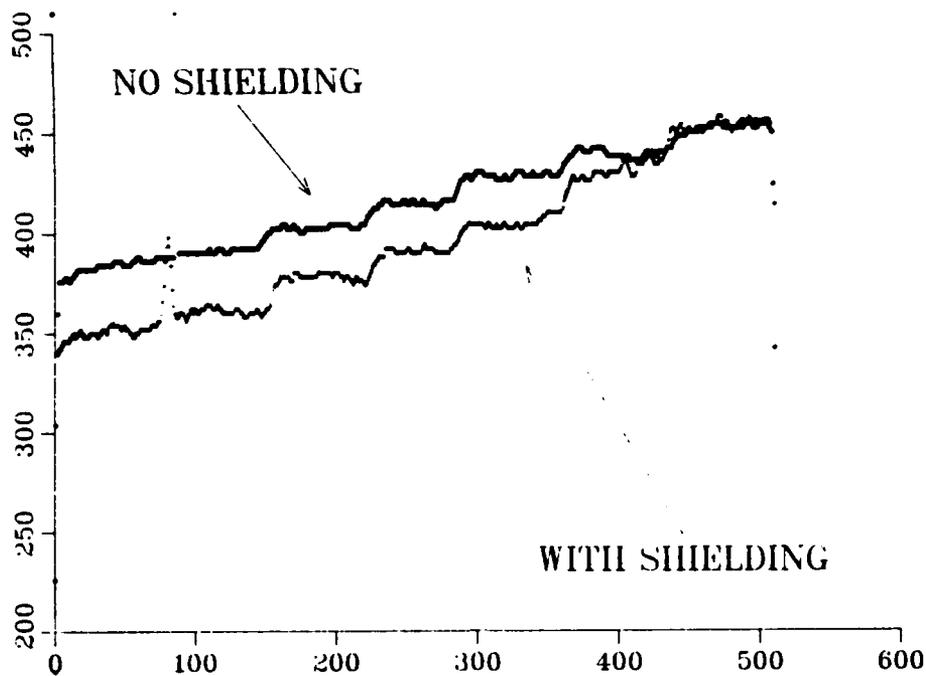


Figure 6. Optical Density Profile of Step Wedge With and Without Shielding

III. X-RAY FILM AND SCREEN CHARACTERISTICS AND IMAGE PROCESSING

There were essentially two motivations for initiating this study on x-ray techniques. As was discussed earlier, we were interested in investigating the feasibility of applying tomography to ballistic systems. To accomplish this, good quantitative radiographic data were needed of such ballistic systems as the interior processes in a gun. Since the propellant materials are essentially hydrocarbons they have very low contrast characteristics for radiographs. Various film characteristics, processing and film calibration techniques were investigated to optimize the data. Secondly, we were interested in applying image enhancement techniques such as smoothing, differentiating contrast enhancement and pseudocolor to conventional radiographs of low contrast ballistic events. To effectively apply these operations, radiographic techniques must be optimized, otherwise processing artifacts could be misinterpreted as physical events. In applications such as observation of projectile parts or spall patterns, contrast is large and useful radiographs are relatively easy to obtain. However, objects which have small density gradients (such as propellants) result in low contrast radiographs and require the optimization of all techniques.

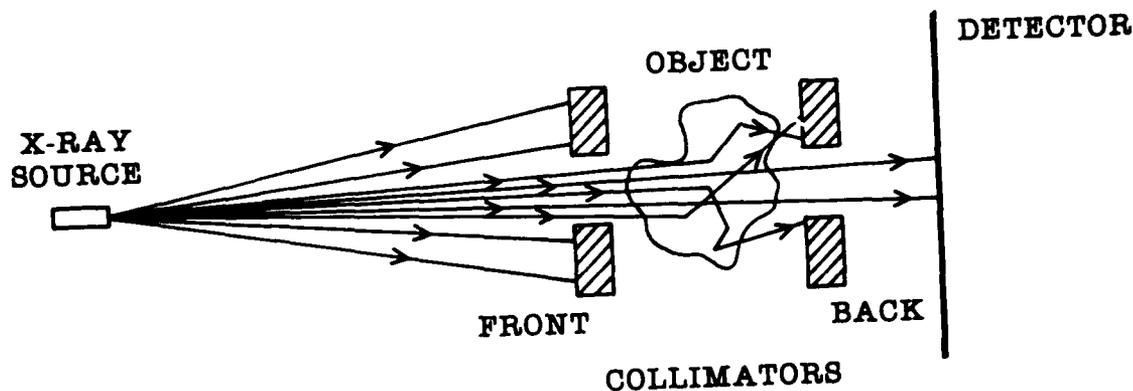


Figure 5. Collimator Design

scattering is approximately 1.5 cm. Thus there will be a small amount of scattering within the lead. The scattered photon is reduced in energy which, if low enough (200 keV), will be absorbed within the lead by the photoelectric absorption since the mfp at this energy is 0.3 cm. However, if the scattered photon has an energy of 500 keV, the mfp for both scattering and absorption are 1.3 cm. This photon may then emerge from the lead and be a source of scattered radiation. If the incoming radiation is all at an energy below 200 keV, it is clear that 0.5-cm of lead will produce only a small amount of scattered radiation. Since in medical radiology energies used are generally below 200 keV, the thin lead material used in "Bucky" grids is adequate. If high energy sources such as 1 MV are used, these may not be sufficient for removing the high energy scattered radiation. Again a proper evaluation of the problem can only be done with a quantitative Monte Carlo calculation. The purpose of this discussion was to illustrate the potential difficulties in constructing collimators for high energy sources. In practice we have found that the collimator design of Figure 5 removes a substantial portion of scattered radiation with an x-ray source of 1 MeV peak energy. In an application of this technique, a fiberglass tube was used as a test object. A step wedge was placed inside the tube, with each step being 1/4 inch in thickness. Two radiographs were taken of this set-up. Profiles of the optical densities of the radiographs are shown in Figure 6. The results in 6, "With Shielding" were obtained with the chamber well collimated as shown in Figure 5. All collimation was removed to obtain the results shown in Figure 6, as "No Shielding." It is clear that the collimation has increased the signal to noise. Although the increase is small, this can become important when studying low contrast objects such as propellants.

It should be noted that surfaces of collimators can also be a source of scattered radiation. Thus, as shown in Figure 5, the surface of the back collimator that is parallel to the x-ray beam (the thickness of the collimator), should be as small as possible so that this surface will not be a source of scattering. Tests as shown in Figure 3, will give an indication of the severity of the problem.

average exposure levels and sulfite concentration in the replenisher.

The effect of increasing levels of bromide (decreasing sulfite) is to decrease the fog, speed, and contrast.

Thus in general:

Fresh chemistry with starter	Very low bromide Very high sulfite Very high fog High speed High contrast
High replenishment	Low bromide High sulfite High fog High speed High contrast
Low replenishment	High bromide Low sulfite Low fog Low speed Low contrast

C. Account Volume (Oxidation)

Developer standing in either the replenishment barrel or the working tank is subject to oxidation from the air. The oxidation is more rapid in the working tank because of the elevated temperatures.

The effect of this oxidation is to lower the sulfite level (independent of the bromide level) and produce a developer solution which has generally lower activity. The result of this lower activity will be reduced speed and contrast.

Compensation for normal oxidation in the working solution can be made by increased replenishment rates. Excessive oxidation in either the working solution or replenisher cannot be corrected and the chemistry must be discarded.

Oxidation effects are enhanced in Accounts using a low volume of film and minimized in "high volume Account." Guidelines are presented later (Section H) for making adjustments to compensate for Account-volume. The following general rules should be observed.

- 1) Developer which appears black is probably unusable.
- 2) Normal oxidation in the working tank can be compensated for by an increased replenishment rate.
- 3) Excessive oxidation cannot be corrected.

- 4) If the working solution is replaced entirely with replenisher (plus starter) and acceptably high levels of speed and contrast cannot be met or exceeded (speed and contrast should be high) the replenisher is unusable and should be discarded.
- 5) In no case should the replenisher barrel contain more than a two week supply of developer replenisher.
- 6) Mixed replenisher should be used as completely as possible before freshly mixed solution is added.
- 7) Brands of developer which are low in initial sulfite (low activity) will have a shorter mixed shelf life than those which are high in initial sulfite (high activity).
- 8) Brands of developer with relatively low activity require a higher replenishment rate than relatively high activity developer.
- 9) Do not intermix replenisher from different brands of developer.

D. Average Exposure Levels

The guideline rates which are presented later are based on an average exposure level which results in the development of 35% of the available silver. This is believed to be typical of a large proportion of radiographs. Instances will occur where this average figure does not represent the exposure level being processed. If the level is higher or lower than 35% the replenishment rate will have to be increased or decreased accordingly.

Procedures for making this adjustment are presented later (Section H).

E. Size Mix

The guideline figures presented are based on a distribution of sizes which is believed to represent a large proportion of Accounts. This typical distribution is 60% 14X17, 18% 10X12, 11% 8X10 and lesser amounts of other sizes. Instances will occur where a processor is being used for a size mix which is not represented by this typical distribution. In these cases adjustments in replenishment rates are called for.

Examples of this kind of situation are:

- 1) A processor devoted to films from a chest changer - all 14X17.
- 2) A processor in a pediatric area - all 10X12 or 11X14.
- 3) A processor in a special procedures area - All 10X12, 14X14, or roll film.

Procedures for making this adjustment are presented later (Section H).

F. Processing Time

Although the attached curves apply only to processing times between 90 and 145 seconds the adjustment criteria and guidelines can be applied to 3-1/2 minute processing as well. The replenishment rate (in cc/14X17) producing optimal sensitometry does not depend on cycle time. The temperature will, of course, have to be adjusted according to the development time.

In dealing with various processors, it is important to note that processor total cycle time is not necessarily a measure of actual development time. For example, a Profexray Low Cap processor having a 145 second total cycle actually only develops the film for 16 seconds while a Kodak M-6 processor having a 90 second total cycle develops the film for 21-1/2 seconds.

G. Making Adjustments

Figures 1, 2, and 3 show, for various replenishment rates, the response of D_{min} , speed and contrast as a function of temperature. The shaded areas indicate the average operating area for a 90 second processor.

A study of these curves will enable one to make the adjustments necessary to produce the sort of films the Account desires.

For example:

The account is currently operating with Type R at 93° and 60 cc replenishment but the contrast is too high.

A study of the graphs shows that a change of 45 cc replenishment and 95° will:

- 1) Lower the contrast by about 0.25 (a detectable but not a large change).
- 2) Keep the speed the same.
- 3) Keep the fog the same.

When using these curves, one should note the following items.

- 1) These figures are for Type R, 35% average exposures, normal size mix in an average size Account, with chemistry of normal sulfite level. Section H gives the corrections to be applied to obtain a replenishment rate equivalent to the value of 60 cc shown on the graphs.
- 2) The effects of going above 70 cc replenishment are usually minimal. Higher rates can in some cases, however, provide two distinct benefits, namely, minimizing the oxidation falloff in low volume Accounts and minimizing the difference in sensitometry between fresh and seasoned chemistry.
- 3) Below 50 cc, the effects are pronounced - Be careful!

- 4) The chemistry will change slowly after a change in replenishment rate is made. Section I gives details on how slowly and how to speed the change in sensitometry.
- 5) These figures are for seasoned chemistry. Don't expect fresh chemistry to give the desired value. Section I gives details on how long one can expect it will take for the chemistry to season.
- 6) If you obtain the desired sensitometry with fresh chemistry you can expect to see a fairly significant falloff on seasoning.

H. Proper Replenishment

The following procedure should yield a replenishment rate which will give good results under the conditions specified.

- 1) Using Figure 1, 2, and 3, pick an "effective" replenishment rate based on the sensitometry desired and the expected temperature. For example 60 cc/14X17 will yield good fog, speed and contrast at 94° in a 90 second processor.
- 2) Multiply by the following factor for the type of film being used.

Types R, HL or XM	X 1.0
Type XD	X 0.75

If one encounters a mix of Type XD with other types, multiply instead by the factor L

Where:

$$L = \frac{(0.75 \times \% \text{ of Type XD} + 1.0 \times \% \text{ of other types})}{100}$$

- 3) Multiply by the factor M if the average exposure is other than 35%.

Where:

$$M = \frac{(\text{Estimated percent exposure})}{35}$$

- 4) Multiply by the following factor if other than normal size mix is present

All 14X17	1.2
All 14X17 or Franklin roll	1.0
All Elema roll	0.9
All 10X12	0.8

For other conditions, an interpolation between the above values should be used.

5) For other than an average Account (~ 100 films/day) multiply by the following appropriate factor

Very small Account	X 1.2
Small Account (<75 films/day)	X 1.1
Large Account (>150 films/day)	X 0.9 .

The resultant replenishment rates should give results equivalent to the "effective" value chosen from Figures 1, 2, and 3.

For example: An Account is using Type R in a chest changer-with-processor and is doing 200 films per day --

The recommended replenishment rate is:

$$60 \times 1.2 \times 0.9 = 65 \text{ cc}/14\text{X}17$$

or

For example: An Account is using Type XD in a 10X12 AOT, processing is done in an exclusive processor at an average rate of 100 films/day.

The recommended replenishment rate is:

$$60 \times 0.75 \times 0.8 = 36 \text{ cc}/14\text{X}17 .$$

Using the calculated rates, further steering can be done using the graphs of Figures 1, 2, and 3 where the calculated rate replaces the "effective" value and the other indicated rates are proportionate.

For examples:

Using the 36 cc/14X17 which was calculated above, the values of 109, 69, 51, 40 and 33 listed in Figures 1, 2, and 3 become 66, 41, 31, 26, and 20 respectively in the above example.

As mentioned in Section G2 and shown in Figures 1, 2, and 3 the effects of going above 70 cc are minimal. For Type XD one would infer from the example above that the effect of going above 53 cc/14X17 would be minimal. This is verified by reference to Figure 4 where one can see that the speed changes very little at rates over 51 cc/14X17.

I. Processor Steering

If an adjustment is made in replenishment, the chemistry will begin to equilibrate to a new stable value. The number of films (under normal running condition) which are required to move 90% of way to the new value can be calculated by the formula:

$$N(90\%) = \frac{8700 \times V_T}{r}$$

where V_T is the volume of the working tank in gallons and r is the new replenishment rate in cc/14X17.

For example: To obtain 90% of equilibrium in a 5 gallon tank with a replenishment rate of 60 cc/14X17 requires:

$$\frac{8700 \times 6}{60} = 870 \text{ films.}$$

A 2 gallon tank (Independent I) will require 290 films.

Obtaining 99% of equilibrium requires twice the number of films as 90%.

$$\text{Thus } N(99\%) = 2N(90\%)$$

or in the above example of the 6 gallon tank

$$N(99\%) = 1740 \text{ films.}$$

The process can be speeded up considerably by replacing part of the working solution or by running Dmax films.

If the replenishment rate is being raised the new equilibrium value can be approximated by removing working strength developer and replacing it with replenisher according to the following formula.

$$V_R = V_T \times \left(1 - \frac{r_{\text{old}}}{r_{\text{new}}} \right)$$

Where V_R is the volume (in gallons) to be replaced and r_{old} and r_{new} are the old and new replenishment rates in cc/14X17.

For example: You determine that an Account has been running at 40 cc/14X17. The new steady state condition at 60 cc/14X17 can be approximated by replacing

$$\frac{V_R}{V_T} = 1 - \frac{40}{60} = 1/3$$

the volume of the working solution with replenisher.

If the replenishment rate is being lowered, the new equilibrium value can be approximated by processing Dmax 14X17 at zero replenishment according to the following formula,

$$N = 38 \left(\frac{1}{r_{\text{new}}} - \frac{1}{r_{\text{old}}} \right) \alpha V_T$$

where N is the number of 14X17 Dmax sheets to be run and a is the percentage exposure (normally 35) of the film normally run in the particular processor.

NOTE: These sheets are to be run with no replenishment.

For example: In a processor with a developer volume of 3 gallons you wish to lower the replenishment rate from 70 cc to 50 cc. Assume 35% exposure. Run

$$N = 38 \times \frac{1}{50} - \frac{1}{70} \times 35 \times 3 = 23.$$

Dmax 14X17 sheets a zero replenishment.

Caution: N is number of sheets of Type R, HL or XM to be run. If Type XD Dmax sheets are to be used, the value of N will have to be increased by 30%.

J. Summary

All too often x-ray processors are controlled by trial and error with no real understanding of the mechanisms involved. In applying the principles which have been outlined here, there are several important factors to remember:

- 1) Given good chemistry, the system can be made to do what is wanted.
- 2) Certain low activity chemistries may not be capable of providing and/or maintaining high speed and contrast. In order to maintain an acceptable contrast and speed, it is necessary to replenish at a higher rate and to operate at a higher temperature even though the fresh chemistry may yield excessive fog, speed and contrast. If such a chemistry provides a just-acceptable contrast when fresh, it will fall off severely when seasoned.
- 3) Understand the system - the film is not simply being acted upon by the developer but is an integral part of the developer itself.
- 4) If questions arise, submit documented samples to the St. Paul Laboratories for analysis.
- 5) Do not forget that this is a set of general guidelines rather than specific temperature - replenishment recommendations.
- 6) The charts are based on Kodak X-Omat developer, but other chemistries will show similar temperature replenishment relationships. Other chemistries may not give equal sensitometry but will respond similarly to changes in temperature and/or replenishment.
- 7) Nothing has been said about fixer replenishment rates but a value of twice the developer rate will usually be adequate.

- 8) This discussion does not consider other outside factors such as contamination, thermometer miscalibration, mixing errors, storage conditions, water conditions, air-locked lines, faulty recirculation, malfunctioning replenisher switches, sticking check valves, etc. Controlling a processor without an awareness of the extraneous factors is touchy!

TEMPERATURE AND REPLENISHMENT RATES RECOMMENDATIONS

<u>FILM</u>	<u>DEV. REPL. RATE</u>	<u>90 SEC. TEMP.</u>	<u>3-1/2 MIN TEMP</u>
Type R/HL	60-70	91-93	85-87
Type XM	50-70	91-93	85-87
Type XD/XDL/XUD	50-60	93-95	87-89

These are guidelines only, if you have any problems consult the previous section.

Fix rates should be double the developer rate. Low replenishment rates will lower contrast and speed.

Fresh chemistry will produce high speed and contrast and higher fog sensitivity.

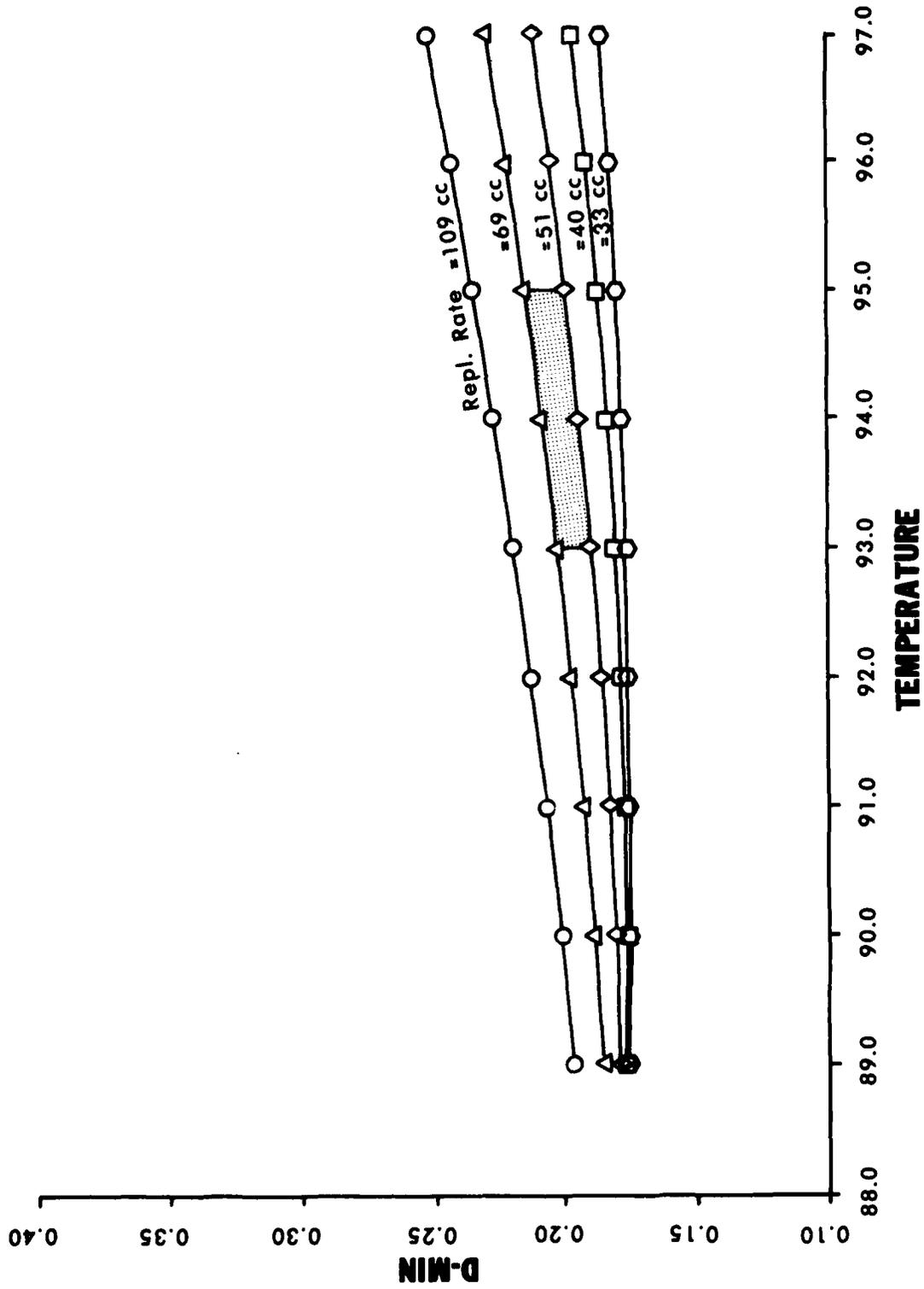


Figure A-1. Effect of Temperature and Replenishment Rate on Type R and XM D-min

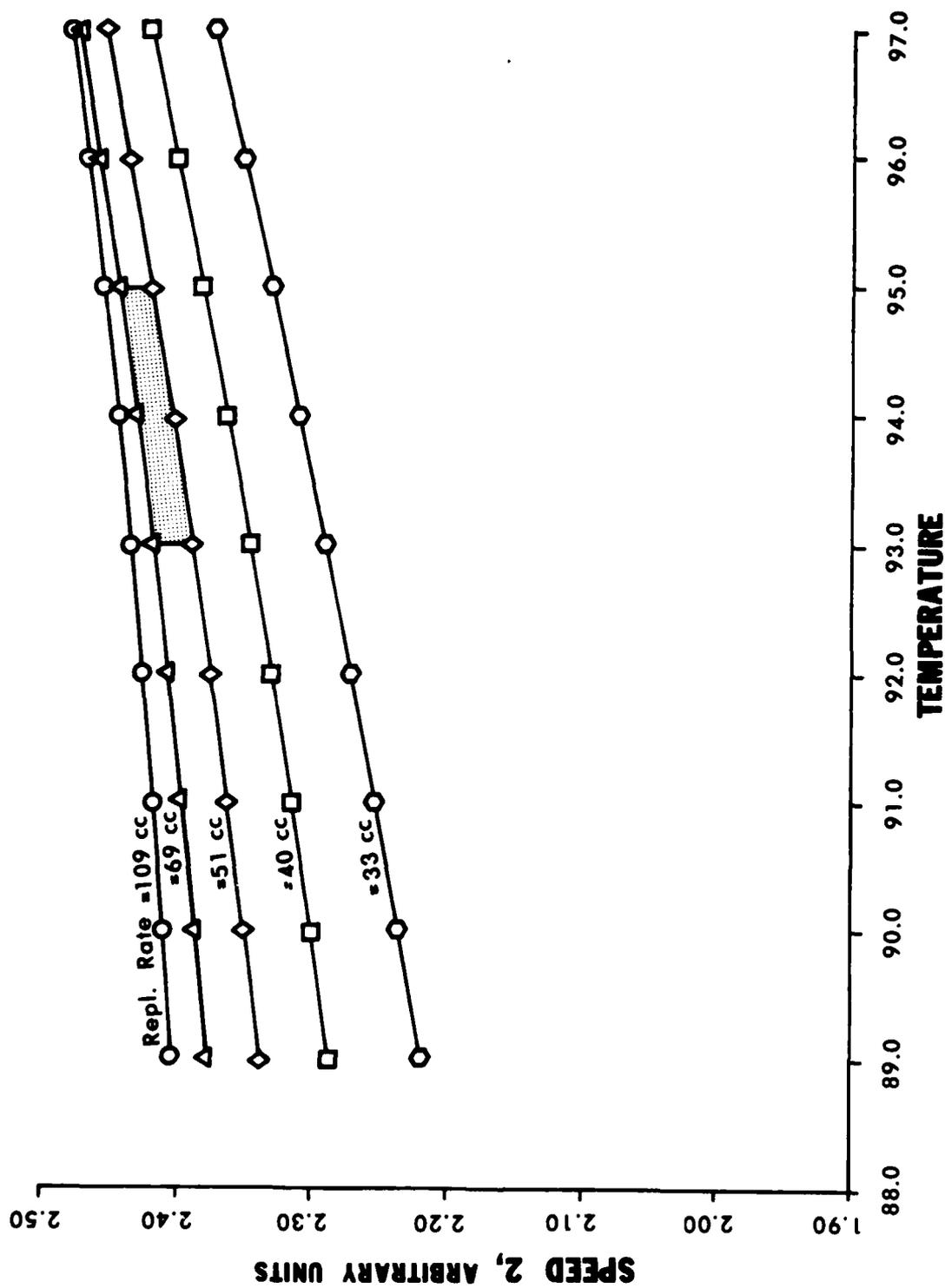


Figure A-2. Effect of Temperature and Replenishment Rate on Type R and XM Speed

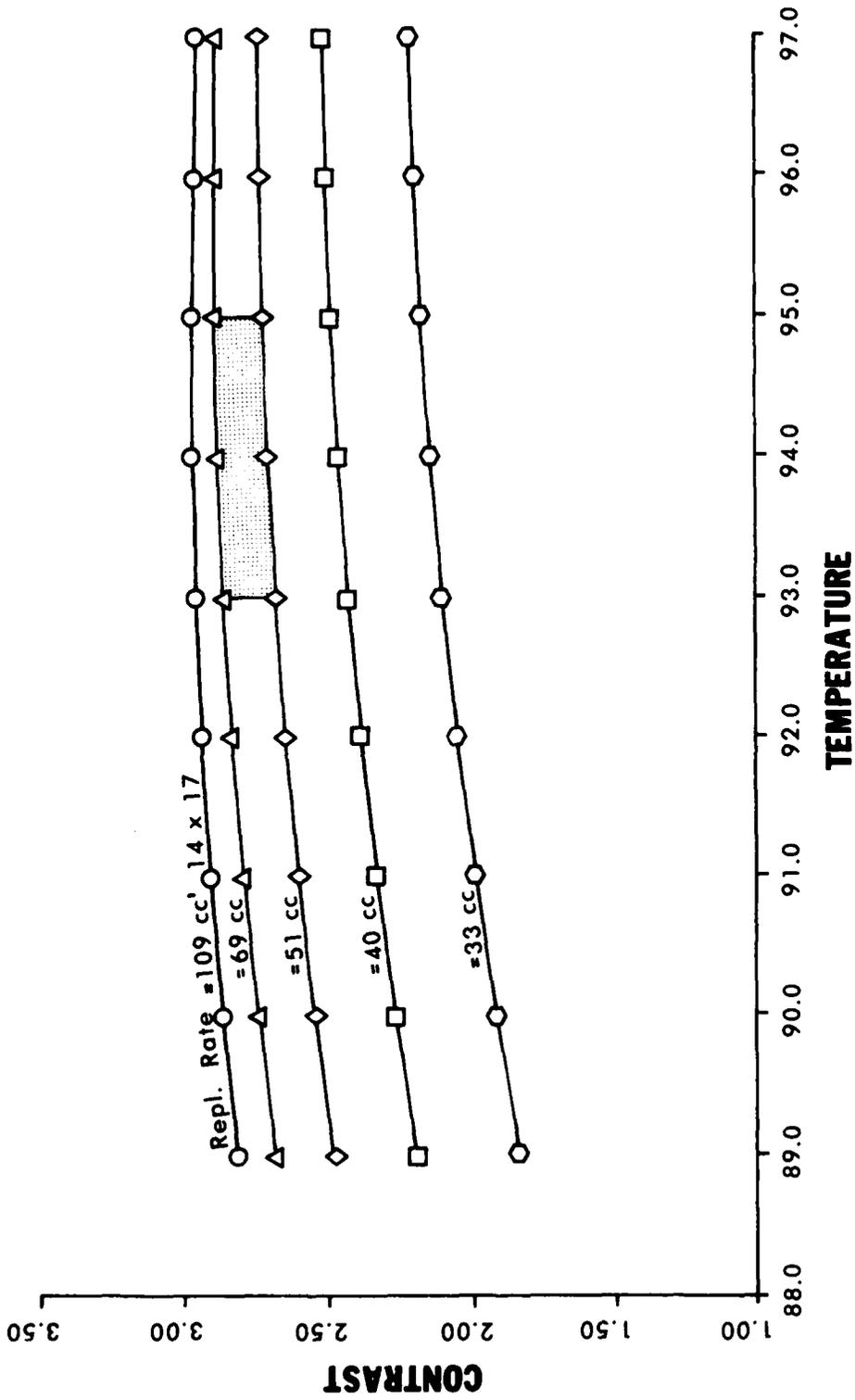


Figure A-3. Effect of Temperature and Replenishment Rate on Type R and XM Contrast

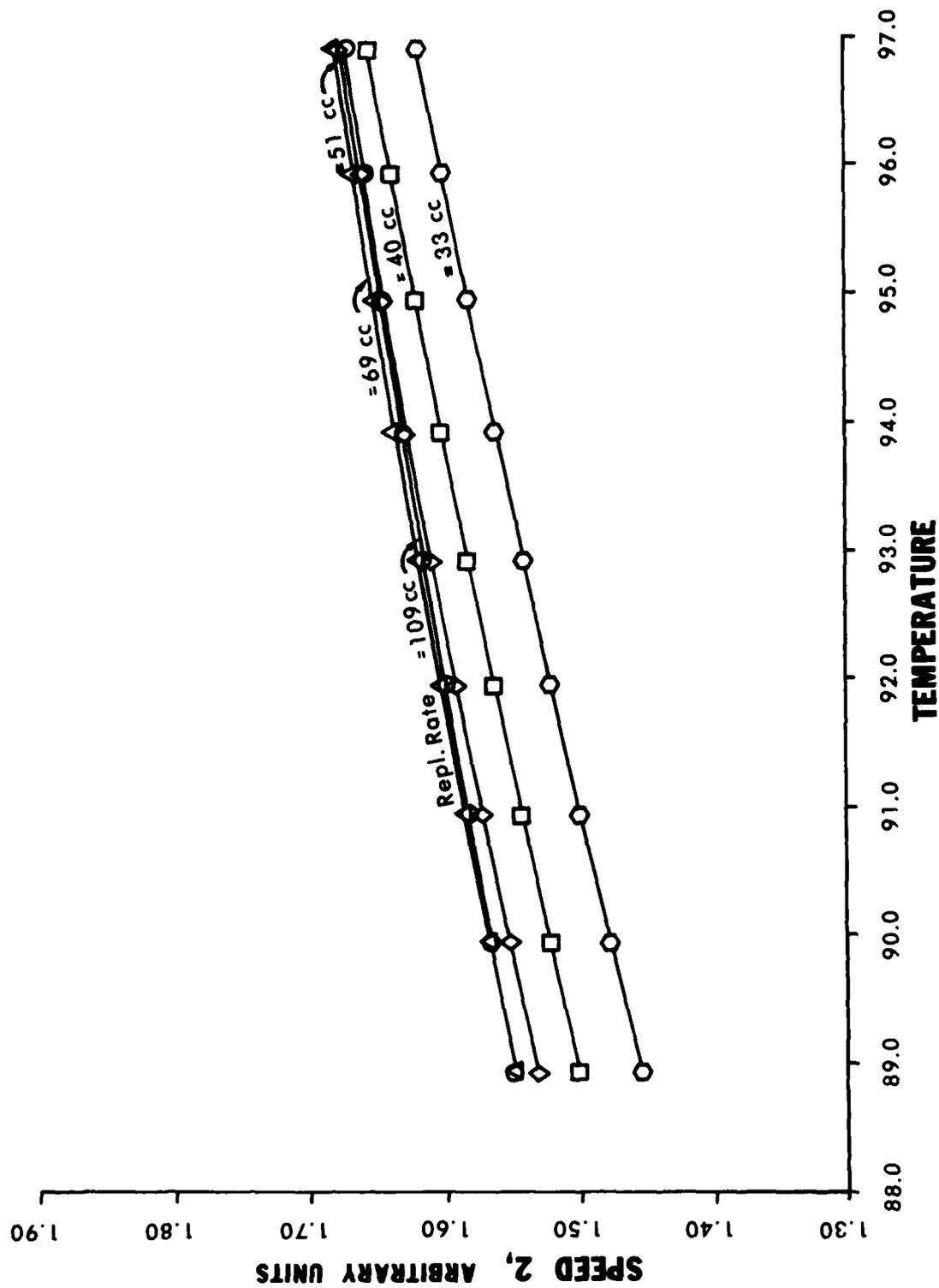


Figure A-4. Effect of Temperature and Replenishment Rate on Type XD Speed

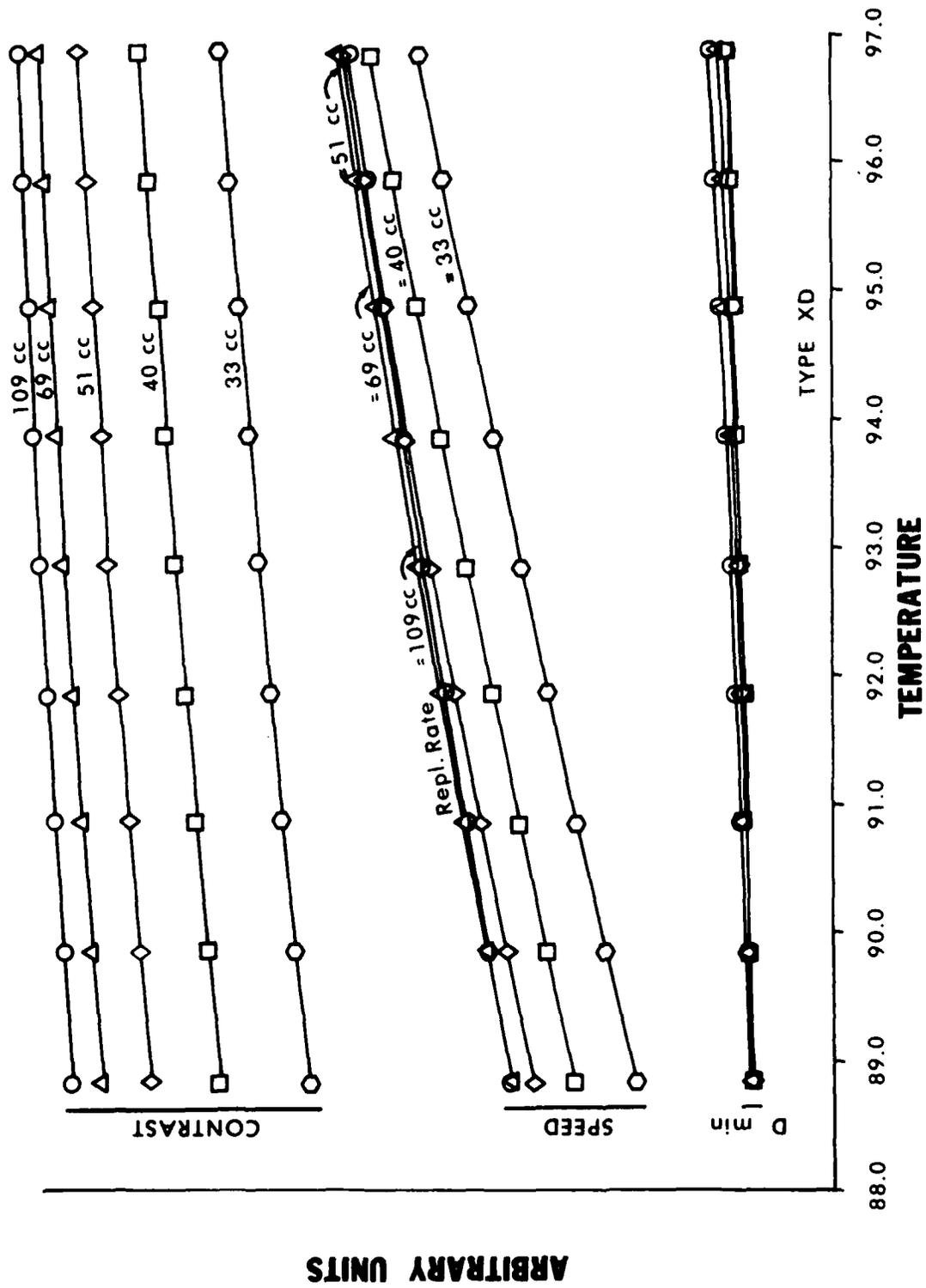


Figure A-5. Effect of Temperature and Replenishment Rate on Type XD D-min, Speed and Contrast

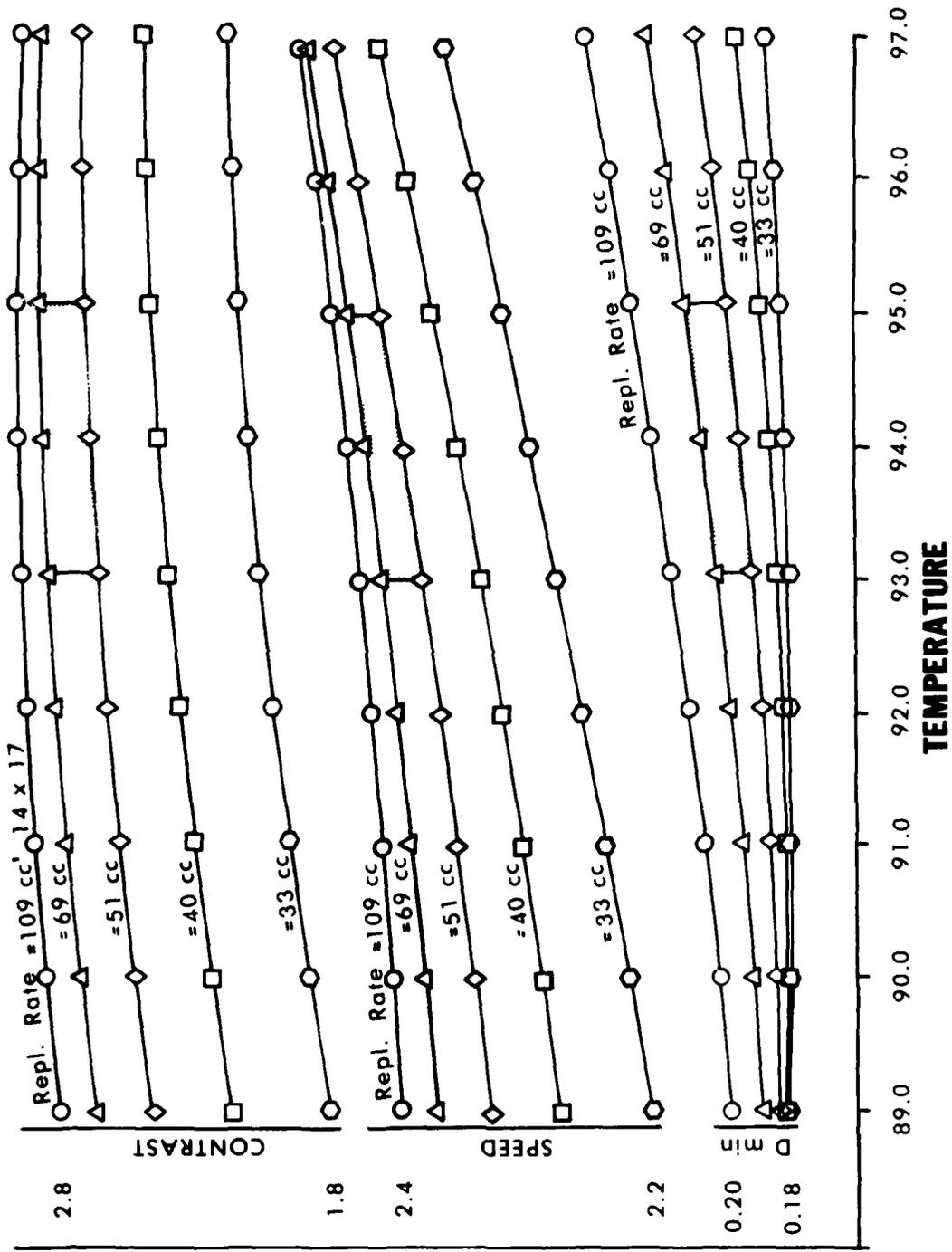


Figure A-6. Effect of Temperature and Replenishment Rate on Type R and XM D-min, Speed and Contrast

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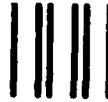
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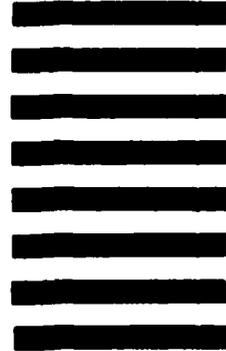
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