# Characterization of paper formation

## Part 1: sensing paper formation

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**ABSTRACT** *A two-stage technique for sensing paper formation is introduced. Video-beta radiography (VBR), a system that combines beta radiography and video-image processing, can accurately measure the distribution of mass density in a paper sample. Maximum resolution over a broad range of basis weights is obtained by optimizing system parameters. This article shows how beta-radiographic parameters (film type, exposure time, developing time, temperature, and developer concentration) and video image-processing parameters (light intensity and lens aperture) can be optimized.*

**KEYWORDS**
Basis weight
Beta gauges
Calibration
Density measurement
Formation testers
Paper properties
Photometry
Radiography
X-ray film

Paper formation is typically evaluated by "look through." This operator-dependent procedure is subjective and thus prone to human error and interpretation. Formation is commonly described using terms such as "blotchy," "flocced," "cloudy," "uneven," "well-closed," "uniform," or "even." These terms strive to characterize the uniformity of the fibrous network by relating the visual perception of light transmission to paper structure.

If the visual evaluation by an experienced operator is adequate to monitor the quality of the paper, the researcher needs a more objective way to characterize formation. The researcher's interest is in the true knowledge of the planar variations of mass within the sheet. Variations in sheet opacity are often used to approximate mass variations. The property sought is commonly known as the distribution of optical density (DOD).

Formation meters that measure optical density have been around since 1935, when Davis *et al.* (*1, 2*) introduced the first scanning device based on the transmission of light through a rotating disc of paper. Many variations of this original design have been proposed. Among the most important are the Thwing-Albert (*3, 4*) and the Quebec North Shore Mead (QNSM) (*5*) testers. The QNSM tester, which uses a cylindrical configuration and provides useful information on floc size and intensity, has been further developed by Kallmes (*6*). Descriptions and evaluations of these and other formation meters can be found in the reviews of Gorres (*7*) and Corte (*8*).

Human perception of paper uniformity is a key factor in evaluating quality. Nonetheless, selection of a formation meter should not be based on its correlation with rankings provided by human observers. There are at least two good reasons for this:

1. Human visual perception is highly subjective.
2. While good fiber distribution is a prerequisite for a good DOD, a good DOD does not necessarily imply good fiber distribution. This is especially true in filled papers, which scatter light effectively.

Light transmission in paper is affected by many factors, including the degree of bonding and pressing as well as the presence of light-scattering fillers (*9–11*). It is better to describe the fiber distribution within the sheet

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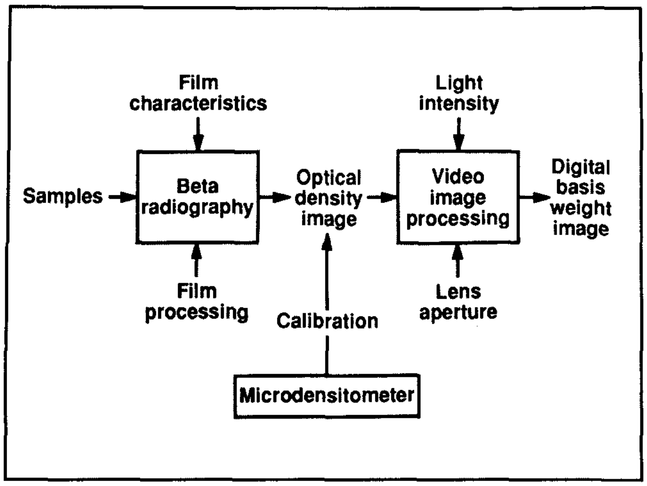
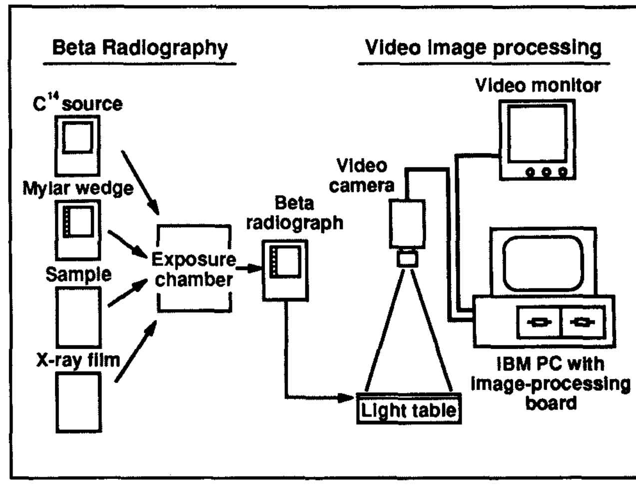
1. Block diagram of VBR system




2. VBR system




using methods that assess mass variation rather than opacity variation. In the early 1960s, Herdman and Corte (*12, 13*) introduced the distribution of mass density (DMD) in contrast to the DOD. This method relies on beta radiation instead of visible light. Beta rays are attenuated and absorbed in matter, with their absorption related to the amount of mass being traversed. The DMD is therefore a true basis-weight representation.

The ongoing controversy over whether formation should be measured with light or with beta radiation has been around for many years. Corte has strongly influenced the paper research community toward the preferential use of beta-ray techniques. However, recent authors such as Komppa (*10*), Kropholler (*14*), Sara (*9*), Demeyer (*15*), and Kallmes (*6*) have given a new emphasis to light-transmission techniques. Komppa (*10*) studied the correlation between light and beta rays by performing simultaneous measurements at the same location. For most papers, the correlation between optical formation and mass formation was good. However, in the presence of fillers, heavy pressing, or calendering, the correlation was very poor. Demeyer (*15*) used stepping motors to position a light and a beta-ray source at the same location. The correlation between light and beta-ray measurement was fair for newsprint samples.

## Purpose

Evaluation of paper formation with beta radiography is often based on film images that have been developed under unspecified conditions. The images obtained by beta radiography depend not only on the film but also the developing conditions. We systematically evaluated how these conditions influence the film density and, ultimately, formation measurement.

The information in a beta radiograph must be digitized for use in assessing paper formation. This can be done using either a microdensitometer (with a basis-weight-calibrated gray scale) or a drum scanner. Each is time consuming or requires special handling techniques. We were interested in developing an automatic system for rapid image analysis using a video camera as a real-time-image input device.

## Experimental

A formation-monitoring system was designed with the following criteria: (a) The system should measure the distribution of mass density of paper; (b) the system should supply the information as a digital image in a format compatible with our statistical analysis system and simulation system. (Details about the analysis and simulation systems will be published later.)

The formation-monitoring system, known as video beta radiography (VBR), combines beta radiography and digital image processing within a single instrument. The system has two principal advantages:

1. Direct interpretation of the beta radiograph
2. Automatic basis-weight calibration.

Moreover, the developed basis-weight image is made directly available to the computer for further processing, analysis, or comparison with simulated images.

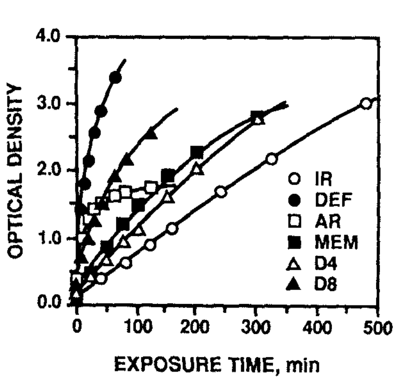
The system has two main parts, as shown in **Fig. 1**.

1. The beta radiography of the sample, which transforms the sample into a radiographic image
2. The image processing of the developed beta radiograph. This includes scanning of the radiograph, acquisition of a digital image, and calibration.

The schematics of the VBR are presented in **Fig. 2**. In the first stage, a $C^{14}$ plastic film (102 mm × 102 mm × 1 mm, 6.17$\mu$Ci) is placed against the sample and an X-ray film. The $C^{14}$ film was chosen for its stability (long half-life) and its low energy. The beta rays that traverse the sample are absorbed by the photographic emulsion of the X-ray film to create the DMD image. This stage is carried out in an aluminum container specifically designed for this purpose. Two foam pads press the source–sample–film sandwich to ensure close contact between all components. Two vacuum nozzles evacuate air from the container.

A wedge of Mylar film (basis weight up to 87 g/m²) is always exposed with the sample. The densities of this

3. Optical density as a function of exposure time for six X-ray films. Film abbreviations are identified in Table I.




I. Values of coefficient n and mass absorption coefficient for various X-ray films

| Film | Abbre-viation | Coefficient for film sensitivity, n | Mass absorption coefficient ($\mu$), cm²/g | | | |
|---|---|---|---|---|---|---|
| | | | Mylar film | | Paper | |
| | | | Before correction | After correction | Before correction | After correction |
| Kodak Industrex-R | IR | 1.049 | 346 | 330 | 304 | 290 |
| Kodak DEF | DEF | 0.631 | 235 | 372 | 207 | 327 |
| Kodak X-Omat AR | AR | 0.398 | 149 | 374 | 131 | 329 |
| Mitsubishi MEM | MEM | 0.749 | 242 | 323 | 212 | 284 |
| Agfa Structurix D4 | D4 | 0.856 | 273 | 319 | 240 | 281 |
| Agfa Structurix D8 | D8 | 0.700 | 215 | 307 | 189 | 270 |

wedge are used to fit a calibration curve. The curve is then used to interpret the density of the sample and convert optical densities into local basis-weight variations. This method has been used with success in many instances (*7, 9, 11, 12, 16–21*).

Exposure time can vary from 1 h to 24 h or more, depending on the sensitivity of the film used and the basis weight of the sample. After exposure, the radiograph is developed according to a standard procedure. The absolute optical-density values of the film are measured manually with a MacBeth TD-504 microdensitometer.

In the second stage, the radiograph is placed on a light table and scanned by a video camera connected to a Coreco Oculus 200 image-processing board. The board is hosted by an IBM PC and performs the data acquisition of the radiographic image. It also performs the basis-weight calibration of the image by monitoring the optical densities of a Mylar film wedge exposed with the sample. Following these two operations, an image of the basis-weight distribution is obtained in the memory of the image-processing system.

The variables affecting the beta radiography (film type, exposure time, developing time, temperature, and developer concentration) were studied separately from those affecting the video image processing (light intensity and video-camera lens aperture). This was done because of the dual nature of the VBR system. The overall accuracy of the system can be predicted from the knowledge of the accuracy of both components.

## Results and discussion

### Influence of beta-radiographic parameters

Many factors can affect the output of the radiographic process. First, it is necessary to maintain all radiographic parameters constant to obtain good reproducibility. It is also important to know the relative influence of each parameter. This study focuses on the influence of those parameters considered important and likely to vary from one experiment to another.

**Film type.** If the film has linear characteristics, the relationship between the logarithm of film optical density and basis weight is ideally linear. This is true because of the exponential relationship of beta-ray absorption in matter, which is expressed in Eq. 1.

$$I = I_0 \cdot e^{-\mu w} \qquad (1)$$

where

$I$ = attenuated beta-ray intensity

$I_0$ = incident beta-ray intensity

$\mu$ = mass absorption coefficient

$w$ = basis weight of the sample

Unfortunately, no film has truly linear characteristics. As a result, the influence of film characteristics on its absorption needs to be studied. For example, suppose that Eq. 2 describes the relationship between optical density $A$ and exposure $E$ for an X-ray film. ($E$ is the product of intensity of the source $I$ and exposure time $t$.)

$$A = A_\infty + \mathrm{k}\, E^n \qquad (2)$$

where

$A_\infty$ = optical density of the background

k = constant

$n$ = coefficient for film sensitivity

The relationship in Eq. 3 is obtained from Eqs. 1 and 2.

$$A = A_\infty + ct^n e^{-n\mu w} \qquad (3)$$

where

$$\mathrm{c\ (time\ constant)} = \mathrm{k} \cdot I_0^n$$

If the exposure time is constant, Eq. 3 can be transformed to Eq. 4.

$$w = [1/(n\mu)]\,[\ln(A_0 - A_\infty) - \ln(A - A_\infty)] \qquad (4)$$

where

$A_0$ = optical density of the blank exposure ($w = 0$ g/m²)

Equation 4 shows that the film's coefficient of sensitivity, $n$, affects the basis-weight calibration. Several X-ray films with different characteristics were chosen to assess how variation in $n$ affected the results. **Figure 3** shows the characteristic curves of the films. The values of the coefficient $n$ are listed in **Table I.**

Table I shows that the coefficient $n$ varies considerably during the basis-weight calibration. Thus the correction for the coefficient should be performed in the calibration process. The correction is done by plotting the logarithm of optical density vs. basis weight for each film. The slope is then divided by the film's sensitivity coefficient. The values after the correction are fairly consistent and acceptable.

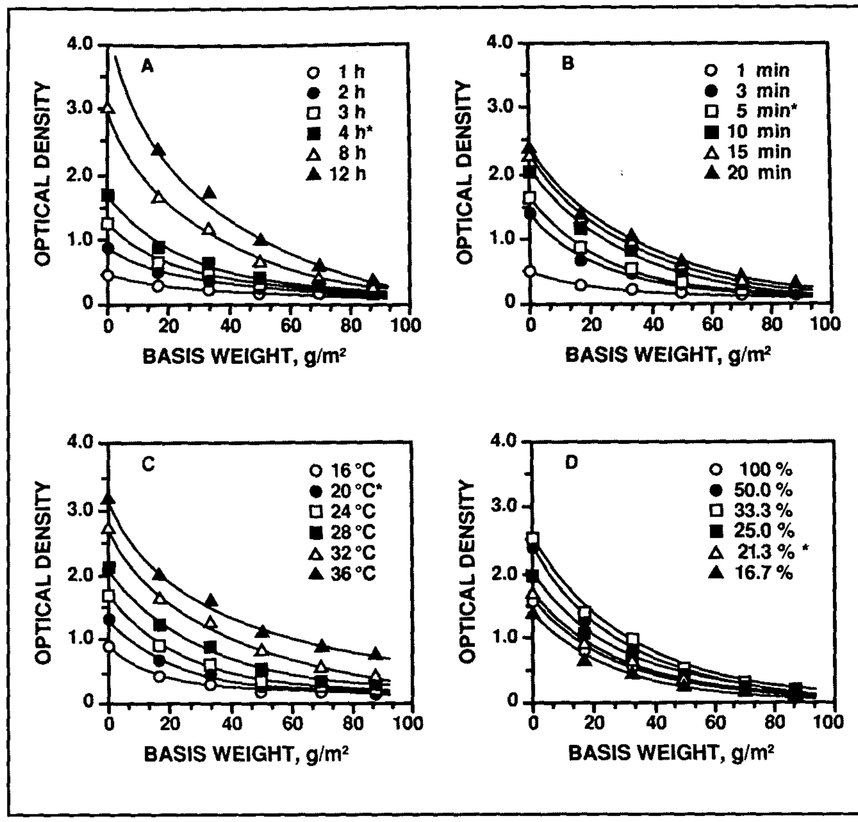
The mass absorption coefficient for paper obtained with Industrex-R film was 290 $cm^2/g$. Norman (*11*) obtained 320 $cm^2/g$; Bergh (*21*) obtained 350 $cm^2/g$; and Murata (*16*) obtained 298 $cm^2/g$. These variations can be explained by the difference in the coefficient *n* of the films used. Based on these results, Kodak Industrex-R (IR) film was used in the following study because of its linearity over a wide range of exposures.

**Exposure time. Figure 4A** shows the influence of exposure time on Film IR. Variation in exposure time resulted in large differences in optical density. Long exposure times (>12 h) yielded high optical densities, causing saturation in the calibration. Short exposure times (<2 h) resulted in low optical densities and underexposure of the film. The over- and underexposure effects cause the relationship between the logarithm of optical density and basis weight to be nonlinear.

**Developing time, temperature, and developer concentration. Figures 4B-4D** show the influence of developing time, temperature, and developer concentration, respectively. Variation in these parameters caused small variations compared with that of exposure time. The deviations are larger at low basis weights, except for high developing temperatures, where the curve is shifted toward higher densities. This translates into an increase in developing activity, which in turn causes a higher background density.

Time constants and mass absorption coefficients of Film IR were determined for all conditions and are shown in **Figs. 5A-5D**. The time constant, which is a characteristic of the radiographic process, varied with the process parameters as expected. However, it was surprising to find that the absorption coefficient also depended on these parameters. This can be explained by the change in the shape of the film-characteristic curves. The strong dependence of the absorption coefficient calls for caution in the use of the beta-radiography technique. All parameters must be accurately monitored and kept constant.

**4.** Optical density as a function of basis weight for various (a) exposure times, (b) developing times, (c) developing temperatures, and (d) developer concentrations. (Each figure presents results obtained by varying a single parameter. The other three parameters were held constant. Base conditions are marked with an asterisk: 4-h exposure time; 5-min developing time; 20°C developing temperature; 21.3% developer concentration. Film type IR was used.)




Based on these results, the standard conditions used in the subsequent experiments were as follows:

- Film: Kodak Industrex-R
- Exposure time: 8 h
- Developing time: 5 min
- Developing temperature: 22°C
- Developer concentration: 21.3%.

All further experiments were made on a JOBO CPP-2 automatic rotary film processor.

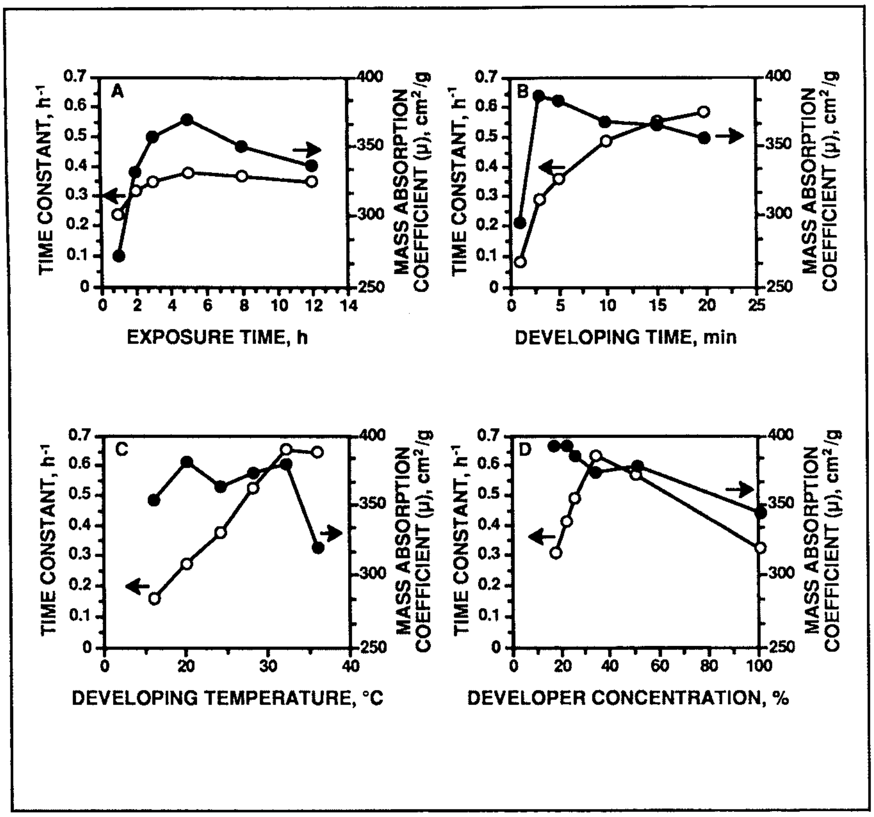
### Influence of video image-processing parameters

After optimizing the beta-radiography parameters, we focused on the VBR system's image-processing parameters. Data acquisition is the function of the video image-processing system, which consists of a light table, a video camera, and an image-processing circuit board.

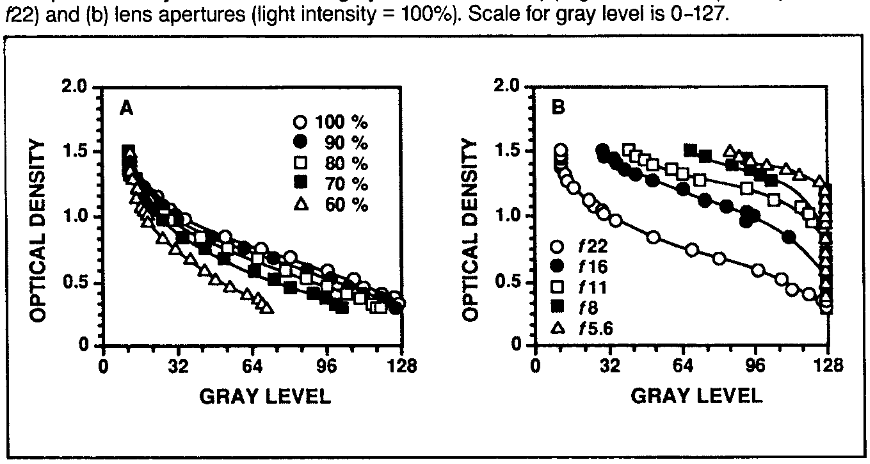
Since no light table can be considered totally uniform, it is necessary to perform background corrections to obtain correct optical-density variations. This is generally done by one of three methods. One method uses a point-to-point subtraction of the background image (image of light table with no film). Another technique removes the background pattern by Fourier filtering. A third procedure fits the background light intensity image to a two-dimensional quadratic map, which is then subtracted from the images. We used the latter technique because it provided a smooth background removal in a reasonable amount of time. The first technique requires a considerable memory and sometimes overcompensates. The second technique, used with success by Farrington (*22*) for removing the "heel effect" in X-radiographs of paper, requires extensive computations and is time consuming.

The absolute film optical densities are registered by the image-processing board as relative densities or gray levels. The accuracy of the data

5. Time constants and mass absorption coefficients as a function of (a) exposure time, (b) developing time, (c) developing temperature, and (d) developer concentration. Base conditions are the same as in Fig. 4.




6. Optical density as a function of gray level at various (a) light intensities (lens aperture = f22) and (b) lens apertures (light intensity = 100%). Scale for gray level is 0-127.




acquisition is measured by a curve relating image gray level to film optical density. This curve is called the video image-processing calibration curve.

There are two video image-processing parameters that strongly influence the calibration curve: the intensity of the illuminating light source and the aperture of the camera lens. Each parameter was varied independently. Gray levels corresponding to a series of 25 optical-density steps ranging from 0.3 D to 1.5 D were measured. The optical-density wedge was obtained by beta radiography of a Mylar wedge ranging from 0 to 150 g/m².

**Light intensity. Figure 6A** shows the influence of light intensity on the optical-density to gray-level transfer. Light intensity was controlled by changing the input voltage. Decreasing the light intensity caused a drop in gray-level range, which in turn caused a drop in contrast and accuracy.

**Video-camera lens aperture. Figure 6B** shows the influence of the video-camera lens aperture on the optical-density to gray-level transfer. Decreasing the *f* stop caused a decrease in optical-density and gray-level ranges. (A decrease in *f* stop corresponds to an increase in lens opening.)

Optimal conditions were encountered for a high *f* stop (small aperture) and a medium-to-high light intensity (70–100% of nominal intensity). This configuration limits video-image saturation and gives the largest ranges for optical density and gray level.

## Basis-weight calibration of the VBR

The basis-weight calibration of the process is the combination of two successive calibrations: the beta-radiographic calibration (film optical density vs. sample basis weight) and the video image-processing calibration (gray level vs. film optical density). Both calibrations are made against an absolute optical-density scale measured with a MacBeth TD-504 microdensitometer.

**Figure 7** shows how the basis-weight calibration is automatically performed. The curve on the upper left is the video image-processing calibration curve; the curve on the upper right is the beta-radiographic calibration curve. The basis-weight calibration curve is constructed by eliminating the optical-density variable and combining the two other curves.

This process gives an S-shaped curve with a linear basis-weight range of 30-90 g/m². The calibration is affected by all the parameters that influence the two calibration curves from which it is constructed. For instance, the influences of light intensity and lens aperture are shown in **Figs. 8A and 8B**, respectively. Reducing the light intensity increases the basis-weight range while decreasing the accuracy of the basis-weight measurement. (Basis weight is measured in units of grams per square meter interpolated from gray-level units.) On the other hand, changes in lens aperture drastically reduce the basis-weight range while increasing the accuracy of the measurement within that limited range of basis weights.

**Figure 9** plots the basis-weight-to-gray-level ratio vs. the basis-weight range for various sets of video image-processing conditions. This curve shows that:

- The basis-weight range cannot be maximized without sacrificing basis-weight accuracy.
- The lens aperture should be near *f*22.
- The light intensity should be between 80% and 100% of the nominal intensity.

## Conclusion

Paper formation can be evaluated by measuring the distribution of mass density (DMD) in paper. Video beta radiography (VBR) measures DMD by combining beta-radiographic and video image-processing technologies.

Mass density of a paper sample is recorded on a beta radiograph. This image is then analyzed and calibrated by a video system. A calibration curve for the VBR system links the image's gray level to sample basis weight. The system curve is obtained by merging the calibration curves of the two subsystems, each of which is affected by processing parameters. The beta-radiography curve is influenced by film type, exposure time, developing time and temperature, and developer concentration. The video-image curve is affected by light intensity and lens aperture. However, these processing parameters can be optimized to maximize the range and resolution of basis-weight measurements.

The final video image is a true representation of the sample's DMD. The image's format is compatible with our Statistical Analysis System and Simulation System, which will be described in an upcoming article.□

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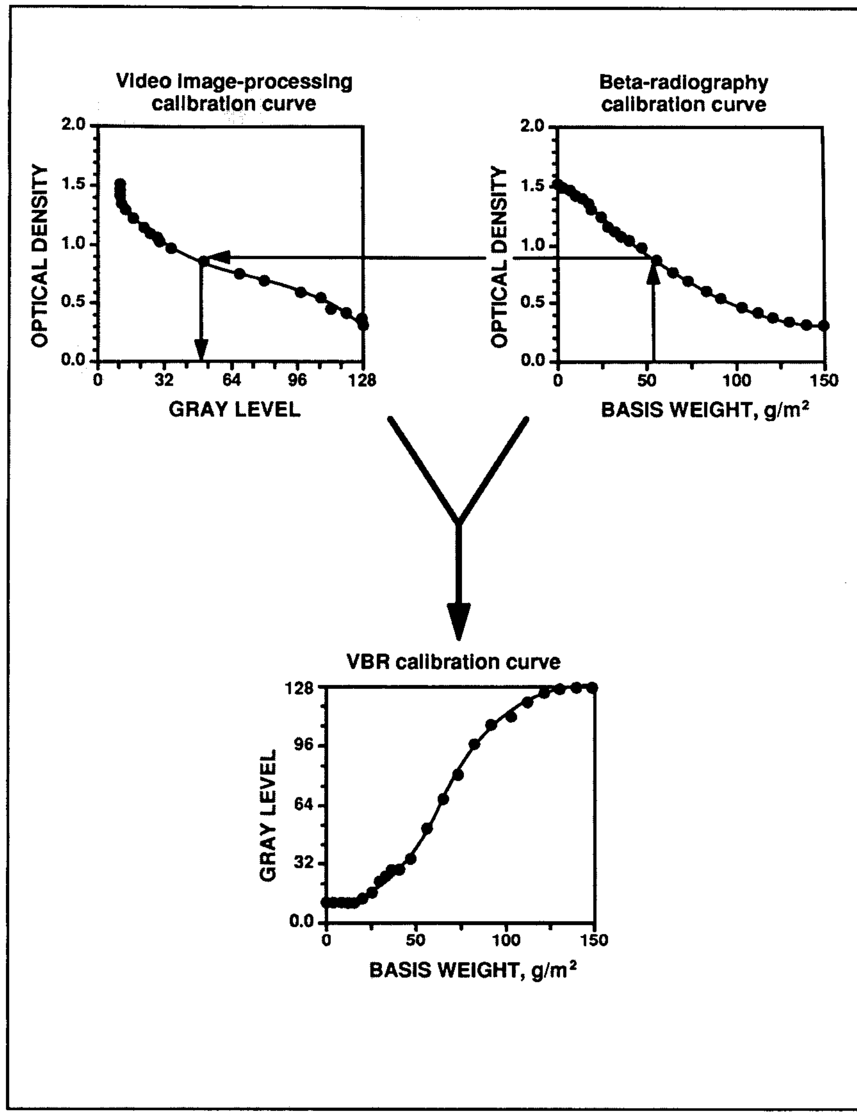
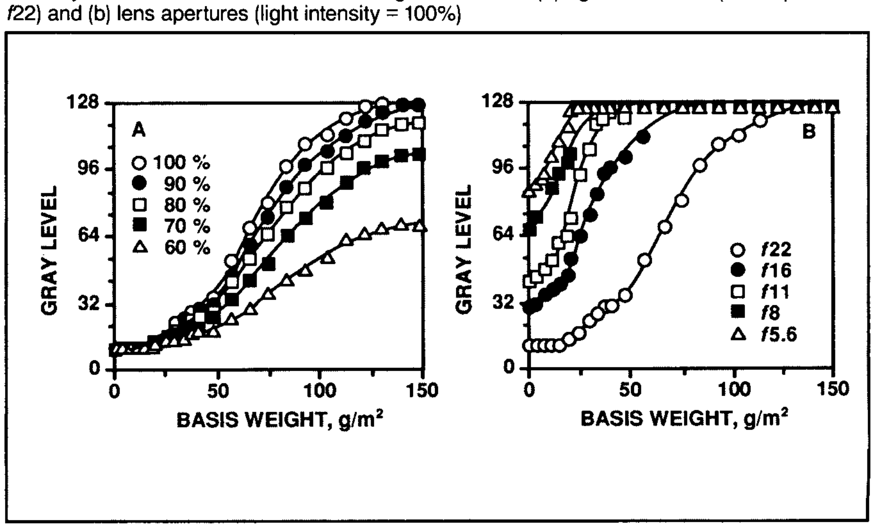
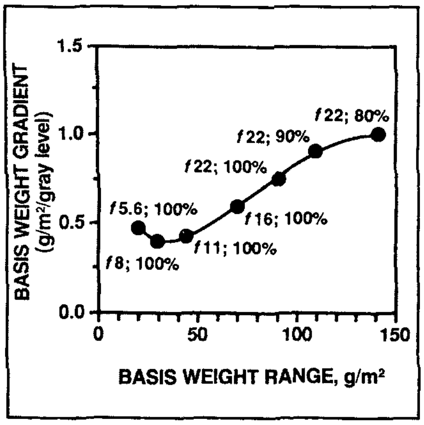
**7.** Construction of the VBR calibration curve. The image-processing and radiography curves are combined by eliminating the optical-density variable.




**8.** Gray level as a function of basis weight at various (a) light intensities (lens aperture = *f*22) and (b) lens apertures (light intensity = 100%)



**9.** Basis-weight gradient vs. basis-weight range for various combinations of aperture and light intensity

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