Quality of Process Control : As Good As The Measurement

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ABSTRACT

The first step in controlling any process is an accurrate measurement. That is why the most important part of any process control system is the sensor. Sensors are the eyes of the process control computer. If the sensors go "blind" or cross-eyed, or begin to see things that really are not there, the computer will act on this false information.

Sensor evolution, to a great extent, has been an evolution in application engineering. But measurement, interpreted as the combination of sensor and signal processing, has undergone a profound revolution as a result of striking advances in computer technology. The principles of measurement for basis weight, ash and moisture sensors are explained in this paper briefly. A few important design aspects are addressed here. A discussion on other sensors and an in-depth study of criterias to be met by today's sensor will be presented in a future paper.

1. BASIS WEIGHT

1.1 Measurement

The primary methods used for basis weight measurement are beta-gauge transmission techniques. The basic technology is illustrated in Figure 1. Beta particles are generated from a radio-active source and directed through the paper, where they are attenuated by the substance in the sheet. The transmitted radiation is detected by an ion chamber. The attenuation is nearly exponential and can be expressed by the following :

$$I/I_o = \exp(-\mu \rho t)$$

where :

I is the transmitted radiation intensity
I_o is the incident radiation intensity
μ is the mass attenuation coefficient
ρ is the density of the paper
t is the thickness

Unfortunately this equation does not allow a simple straight line conversion and various techniques are utilized to approximate a linear curve over the range of the product to be measured. Depending on the sophistication of the signal processing, and the power of the computer model used, this can be as simple as a series of two three straight line tables that are switched in and out depending on the grade of the paper or as versatile as a continuous multi-variable exponential equation with the terms in the equation generated by a factory calibration technique.

The strength of the signal produced from the ion chamber in a basis weight sensor is very small and is often in the same order of magnitude as the electronic noise in the associated electronics. In order to maximize the signal strength, it is important to ensure a large number of beta particles are absorbed by the ion chamber. The "shaping" of the particle beam and the sizing and design of the ion chamber is referred to as the measurement geometry. Some geometries are designed with a highly collimated "narrow" beam with the design philosophy that these will detect narrow streaks across the sheet. Unfortunately, as depicted by Figure 2, a "narrow" beam with a beam radius of r_n permits only a fraction of the emitted radiation to reach the detector. This is because beta sources emit radiation equally in all directions and shielding is required to absorb radiation emitted in directions other than that of the detector. In Figure 2, the fraction

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Figure 1 **Basic beta sensor configuration for basis weight measurement**

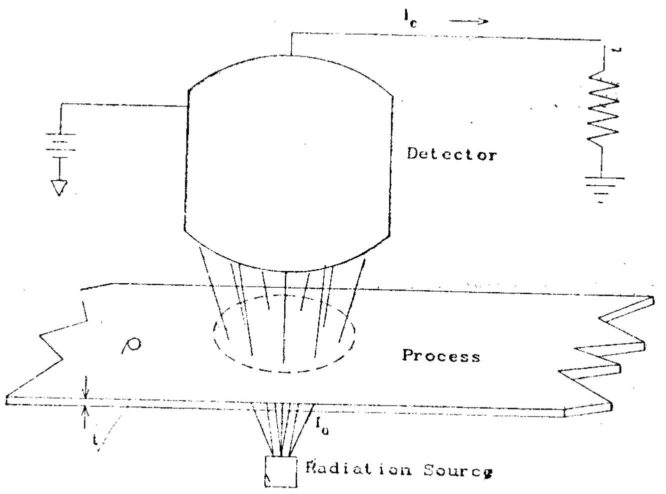
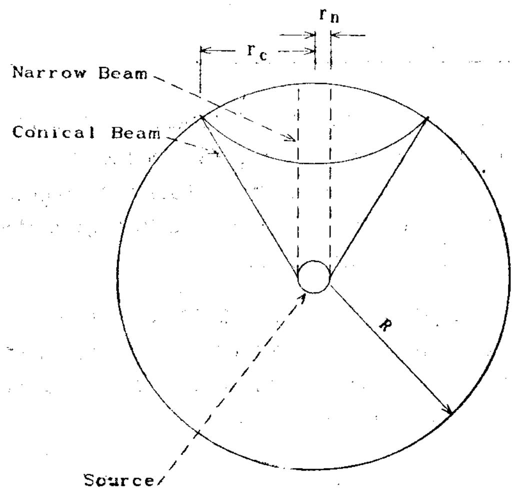


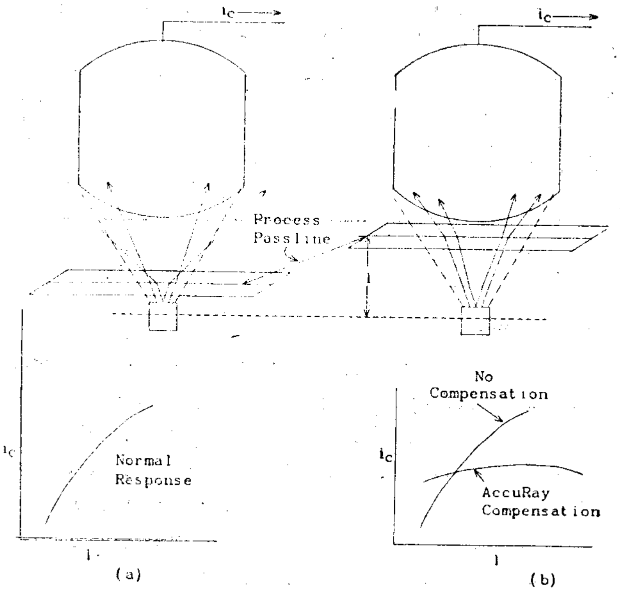
Figure 2 **Conical and narrow-beam radiation geometries**



of emitted radiation that reaches the detector is $\pi r_n^2/4\ \pi R^2$, were R is the distance from the source to the detector. Another type of measurement geometry can be characterized by a "conical" beam shape. A "conical beam" of radius r_0 at the detector permits a greater fraction of the radiation, $\pi r_0^2/4\ \pi R^2$, to reach the detector. Thus, the intensity developed is much greater for conical beam geometries than from narrow-beam geometries, and the resultant signal-to-noise ratio is proportionately greater.

The interaction of beta radiation with the sheet is not strictly an absorption interaction. It is also a scattering interaction and it is therefore not always possible to apply a complete mathematical description even with the sophisticated computer programmes of today. One of the sources of this phenomena is illustrated in Figure 3, where the attenuation of radiation is dependent on the location, or "flutter" of the paper in the gap between source and detector. Through extensive research and development, compensation of this effect has been accomplished with "beam shaping" methods. These consist of collimation and attenuation structures integral to the geometry which "tune" the compensation. In Figure 3b, the flat region of the flutter curve indicates that the measurement is independent of sheet position.

Figure 3 **Flutter Effects**



A similar complication occurs when attempts are made to compensate for misalignment characteristics of online applications, where source and detector heads are mounted on scanning frames. One design philosophy is to accept that there will be relative movement of the heads in the vertical direction and to use an additional sensor to measure the distance apart of the source and detector and compensate for this in the signal processing. Obviously this technique relies on the accuracy of two sensors : the basis weight sensor and the sensor used to measure the distance apart of the heads. Another design philosophy is to minimize the deflections caused by the scanning frame by designing a solid platform for the sensors to scan across the sheet and then "tuning" the sensor geometry to minimize the small residual error.

Recent global economic forces have raised the cost of pulp, causing widespread use of recycled paper and high proportions of clay fillers. Since the exact composition of these papers is generally unknown, the need has arisen for the beta gauge to be insensitive to furnish changes. Furthermore, the trend towards lighter weight papers has stretched the limits of the Kr_{85} source material and recent developments have made available a source based on Promethium that provides a much greater sensitivity at the lower basis weights. Extremely demanding applications (such as creped tissue) characterized by extreme dust and accuracy requirements, have also been satisfied with specific geometries. Details of these state-of-the-art gauge measurements will be presented in a subsequent paper.

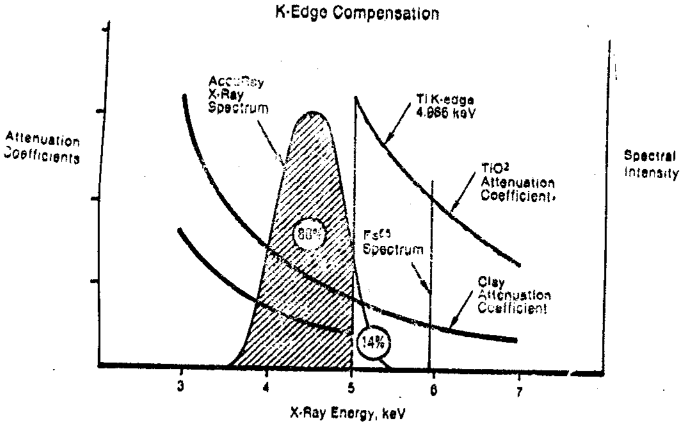
2 ASH

2.1 Measurement :

For the measurement of ash in paper, low-energy X-ray measurement techniques are used. The basic mechanism is the attenuation of low-energy X-rays by typical ash minerals. In contrast of the beta gauge attenuation mechanism (scattering), the X-ray attenuation mechanism is absorption. whereby X-rays interact with an atom by causing ionization. The X-ray simultaneously transfers its energy to an atomic electron and ceases to exist. Since electrons in different orbital shells are bound in the atom with different and quantified energies, the attenuation coefficient exhibits discontinuities at the specific energy levels required to ionize electrons in different orbital shells.

The spectral output of an X-ray tube is bell-shaped, bounded at the high-energy side by the anode voltage, and limited at the low-energy side by absorption of the tube window. Adjustment of the anode high voltage cause the spectrum to shift correspondingly. The ash measurement takes advantage of this spectral adjustability to provide a measurement independent of two constituent mixture ratios by "straddling" the K-edge of the highest atomic number element in the ash (titanium for titanium/clay mixtures, and calcium for chalk/clay mixtures) to render equal effective attenuation coefficients of the ash constituents. This composition insensitivity is fundamental to the X-ray measurement and is illustrated in Figure 4.

FIGURE 4



COMPOSITION SENSITIVITY

K-Edge Compensation

$$\mu_{Ti} \doteq 0.857 \times 0.5\,\mu_{clay} + 0.143 \times 4\,\mu_{clay} = \mu_{clay}$$

The major challenge in recent years in the measurement of the ash content of papers has been with those applications where there is not a clearly defined constituent ratio in the additives, or the grades of paper changed to include a different constituent. In these cases where an ash sensor may have been supplied to measure chalk/clay and the grade structure has changed to include TiO_2 as a constituent, there will be an error in the measurement of the true ash content. Only very recently has a sensor become available that allows the measurement of any ratio of the basic components irrespective of their composition. This has been achieved by spcetrally tuning the X-ray tube and the anode voltage to effectively provide a series of bell-shaped responses that straddle all the constituents.

3 MOISTURE

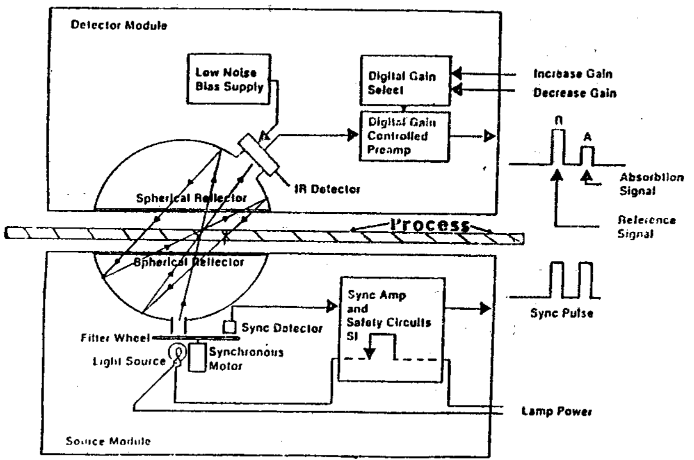
3.1 Measurement :

Several different technologies are available for the measurements of moisture. The most widely recognised technique that provides the accuracy needed for today's requirements, utilizes infrared technology. For applications where the infrared energy may be insufficient to penetrate the sheet or broad band absorbers such as carbon black (present in recycled papers) cause undesirable attenuation of the infrared signals, microwave techniques are applied.

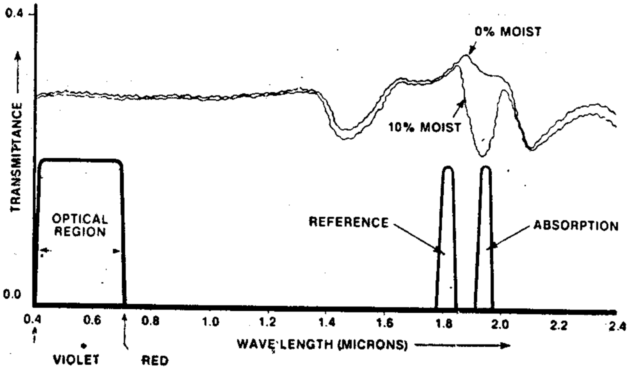
Infrared absorption, which causes vibrational resonances of water molecules, occurs for frequencies around 10^{10} Hz. Dipole orientation, basis of the dielectric properties of water, is significant over a broad range of frequencies up to the microwave region. A combination of charge transport and dipole orientation mechanisms provide macroscopic polarisation in a medium with definite interfaces (as in paper, with its cellulosic fibre structure).

A typical configuration for paper moisture measurement with infrared radiation is shown in Figure 5. This figure shows the essential elements of the sensor; an infrared source, a semi-conductor detector, and filters to pass specific bands of radiation into the sheet. Figure 6 illustrates the two centre wavelengths are normaly provided : an absoorption wavelength at about 1.95 microns wavelength, that is strongly absorbed by water in the sheet, and a reference wavelength at about 1.8 microns that is nearly independent of the sheet moisture content. Moisture information is contained in the ratio of signal levels at the two wavelengths. The signal at the reference wavelength provides normalization for source intensity and detector gain drifts, and coarse compensation for variation in the sheet weight and scattering coefficient.

FIGURE 5 IR MOISTURE



Infrared Spectrum FIGURE 6



Due to the fact that optical radiation can be easily refracted and reflected, infrared measurements are relatively insensitive to geometry misalignment effects characteristic of scanning-measurement systems. However, rendering the measurement insensitive to composition influences has presented a substantial challenge. The infrared absorption phenomenon, basic to the measurement in paper, is secondary to complex scattering interactions provided by the fibre interfaces within a sheet. Due to these interactions, the ultimate effect of variations in the scattering coefficients and basis weight of the paper is a change in the path length of radiation (per unit basic weight) and, consequentially, a change in the measurement sensitivity (probability of absorption interaction per unit basis weight) to water.

Compensation for variations in the infrared path length per unit basis weight is provided in principle in redirecting an appropriate portion of the out-scattered and/or trasmitted radiation back into the sheet. Some design philosophies achieve partial compensation by the incorporation of partially reflecting/partially transmitting windows in the geometries. However, such implementations are effective only over a limited range of applications, and by their nature, cause unsatisfactory attenuation of light such that heavy sheets can not be measured. A more satisfactory solution is to provide compensation by a series of geometries which incorporate hemispherical mirrors. With these geometries, multiple passages of light through the sheet is provided for relatively translucent sheets to compensate for inherently low path length per unit basis weight, and the signal-to-noise ratio is optimized for heavy sheets.

It has been generally proven that infrared technology provides the most accurate method for determining the moisture content of the sheet. However, when the sheet contains a broad band absorber such as carbon black, the accuracy suffers in conventional two-wavelength technology. The reason for this is that at the reference wavelength, the broad band absorber attenuates the reference signal in a unpredictable manner causing an apparent change in the moisture content as the amount of carbon black varies with the type and quantity of recycle used in the furnish. Similar effects occur when the furnish changes and has been traditionally compensated by generating correction factors in the software with lengthy and tedious sampling and testing procedures. Recently, multiple wavelegth technology has been introduced where more spectral information is provided by analyzing more of the infrared spectrum. With this information, it is now possible to measure all grades of paper accurately with minimal calibration sampling and testing. This had initial application in those mills using recycle in their furnish but the absolute success of this sensor has made it the standard in developing countries where the type of furnish is highly variable.

In summary, today's papermaker has a choice of sensor designs. The critical decision is to choose the correct sensor geometry for a particular operation. To conclude, the performance and quality of sensors should be evaluated based on measurement accuracy and insensitivity to sheet composition and process dynamics.