Meeting the special requirements for on-line basis weight measurement of lightweight nonwoven fabrics

Paul A. Boeckerman

ABSTRACT: Fabric of lower thickness has reduced the cost per square meter of nonwoven roll goods while increasing the challenge to maintain fabric quality and performance. On-line basis weight measurement systems must meet special requirements for holding products and processes within tighter tolerances. This paper describes the specialized technology needed to make on-line basis weight measurements practical for the production of lightweight nonwoven fabrics.

KEYWORDS: Basis weight, fabric, nonwovens, on-line measurement, sensors, transmitters

On-line basis weight measurement systems, driven primarily by the paper and plastics industries, have evolved dramatically over the last 40 years. Using beta, gamma, X-ray, infrared, visible, capacitance, and microwave technologies, suppliers have continuously improved measurement accuracy and system reliability for a variety of applications. Broad acceptance and the use of such scanning on-line measurements has occurred throughout the nonwovens industry from felt and fiberglass mats through airlaid, chemibond, spunbond, meltblown, and spunlace fabric structures.

Special requirements, however, exist for the practical application of on-line basis weight measurements for lightweight nonwoven fabrics and lightweight sheets such as tissue paper and ultrathin plastic film. In these instances, difficult technical challenges have limited the number of suppliers providing successful sensor designs.

For instance a typical tolerance for a 500 g/m^2 sheet is only ± 0.2 %. The same error with a 50 g/m^2 sheet is ± 2.0%. For practical on-line basis weight measurement and control, the measurement accuracy tolerance must be small compared to the product's quality tolerance.

Therefore the error budget for designing and applying basis weight measurements must be continuously reduced for fabrics in the 5–50 g/m^2 range. A target error budget of ± 0.25% (or ± 0.05 g/m^2, whichever is greater) is needed to provide meaningful quality and control performance results.

Selecting the best sensor technology for lightweight nonwoven fabrics

Sensor technology selection focuses on two key issues: repeatability and sensitivity for low basis weights. Sensor design in terms of transmission versus reflection configurations has a major impact on measurement repeatability for any given source type. Source type selection has a major impact on basis weight sensitivity and composition insensitivity for any given sensor configuration.

Source type selection also affects the practical matter of costly developments for specific applications. Sensor refinements for on-line measurement of lightweight products such as nonwovens benefit from parallel developments for lightweight tissue and plastic film applications.

Transmission vs. reflection in sensor design

The sensor technologies mentioned above have been developed in both transmission and reflection configurations. When deciding which technology is best for lightweight nonwoven fabrics, the repeatability advantages of these two sensor configurations must be considered.

In transmission sensor designs, a source of radiation is located on one side of the fabric and a detector is located on the opposite side of the fab-

Boeckerman is marketing manager, nonwovens industry, for Measurex Corp., One Results Way, Cupertino, CA 95014.

I. Common source types and uses

Source type	*Radiation type*	*Basis sheet interaction*	*Most common use*	*Basis weight sensitivity*
Beta rays	Energetic electrons	Atomic absorption and scattering	Paper sheet and tissue Plastic sheet and film	Very good Low dependence on atomic number (composition)
Hard X rays (over 10keV, and gamma rays)	Energetic photons	Atomic absorption and scattering	Aluminum sheet and foil	High dependence on atomic number Poor for organic materials Very good for metals, inorganics
Soft X rays (below 10 keV and above 2.5 keV)	Energetic photons	Atomic absorption and scattering	Ash in paper Metallic oxide coatings Glass fiber	Very good Subject to variability of organic vs. inorganic composition High dependence on atomic number
Very soft X rays (below 2.5 keV)	Energetic photons	Atomic absorption and scattering	Not common	Highly absorbed by air
Infrared radiation	Photons	Molecular absorption by chemical bonds at specific wavelengths	Moisture Polymer concentrations	Good for water Good for pure polymers Some optical effects cause ambiguous readings
Visible light radiation	Photons	Optical density	Opacity, color	Optical effects may be ambiguous with basis weight effects
Capacitance and microwave	Electromagnetic field	Bulk dielectric properties	Moisture in presence of carbon black	Poor for basis weight of lightweight sheet Very sensitive to sheet structure, temperature, and humidity

ric. As the radiation interacts with the sheet, the detected radiation is reduced by absorption and scattering mechanisms. As basis weight decreases, the transmitted radiation increases.

In reflection sensor designs, the detector is located on the same side of the sheet as the source of radiation. As the radiation interacts with the sheet, a small portion of it is scattered backward toward the detector to carry information about the sheet. The majority of the radiation is either absorbed or scattered forward. As basis weight decreases, the reflected radiation decreases.

Comparisons between same source types such as high flux X-ray tubes or infrared lamps show that the basis weight repeatability of transmission sensors is much greater than the basis weight repeatability of reflection sensors. This effect corresponds to the relative ratio of transmitted to reflected radiation. The difference is even more pronounced for sensors using radioactive sources, since they have correspondingly lower flux levels.

Considering the need to meet an extremely tight error budget, the transmission sensor configuration is favored. The only loss in signal is from back scattering, and the amount of back scattering decreases as basis weight decreases.

Source type vs. sheet interaction

The issue of selecting the best source type for a nonwoven sheet depends on accurately separating the sheet from its environmental surroundings. Thus some property of the sheet must be selected for detection. This property must differ significantly from the other ambient conditions, and it must vary

according to the sheet's basis weight. **Table I** lists the commonly available choices and their typical uses.

By reviewing the source types and their basic sheet interactions, the number of viable alternatives can be considerably reduced.

The selection criteria for source types for lightweight nonwoven sheets must emphasize the ability to adequately separate the product from its surroundings. This test eliminates hard X rays, very soft X rays, visible light radiation and capacitance/microwave methods. The shortened list is then comprised of beta rays, soft X rays, and infrared radiation.

Both soft X rays and infrared radiation have been used successfully in certain paper and plastic applications. Where these techniques are successful, the sheet composition does not include additives, inorganic fillers, or other confounding constituents. Indeed soft X ray and infrared radiation are more frequently used to identify the concentrations of additives and fillers. Thus optimal designs using these technologies must be closely matched to the application, and the costs of developing optimal designs cannot be spread over significant numbers of users.

Fortunately, beta rays are not as composition-sensitive to additives and fillers. They are more sensitive to basis weight as a function of the total population of atoms they encounter rather than to the mixture of atom types in the composition. Furthermore, this source type has enjoyed a broadly supported development history. This has spread the costs of developing an optimal design over a very large number of thin film and tissue producers for suppliers specializing in these applications.

Optimizing the beta sensor error budget for lightweight nonwovens

The advantage of transmission beta sensor technology over the other sensor technologies shifts the focus to minimizing and managing the error budget for light basis weight measurements. To optimize the design and applications, the types and sources of errors shown in the upper portion of **Table II** should be considered.

The first division of error types separates random variability from nonrandom variability. A strict definition for random variability restricts its meaning to only those deviations which will always average to zero. Therefore, nonrandom errors are those deviations which may not average to zero unless special corrections and compensations are applied.

The consequence of this division of the error budget is that the accuracy of the basis weight measurement becomes two specifications: repeatability and dynamic verification accuracy.

The next partition of the error budget separates the nonrandom variability into two categories: systematic and environmental. Systematic errors stay the same even as the environment changes. Environmental errors arise from dynamic environmental conditions.

The strategies used to minimize the error budgets can now be better focused on the specific nature of each variability and error source. Random variabilities should be minimized and nonrandom variabilities need to be corrected or compensated to ensure that they average to zero.

Random variability has a strong impact on the ability to reduce accurately or eliminate nonrandom errors. Even though they will eventually average to zero, the repeatability performance must be excellent to implement steps to minimize the nonrandom errors.

Systematic variabilities such as X-Y head alignment and product structure/composition are repeatable and predictable. Therefore, these can be forced to average zero by using suitable techniques. For example, the offsets can be modeled and corrections applied through special sensor support software.

Environmental variabilities are the major source of concern for light basis weight measurements. Dynamic offsets are caused by unpredictable changes in temperatures and dirt accumulation. Such factors can be measured separately to make accurate, zero-offset corrections.

Improvements in repeatability performance

The variability tolerance for sensor repeatability should be no greater than ± 0.05 g/m^2 (2 sigma) for 5–50 g/m^2 sheets. This range limits the closed loop control performance for basis weight variations within a roll.

A single roll average basis weight value is comprised of a very large population of individual readings and thus may not be affected by a tight tolerance for repeatability. Instead, the repeatability range describes the limiting uncertainty of each new reading used for machine adjustments and measurement calibrations.

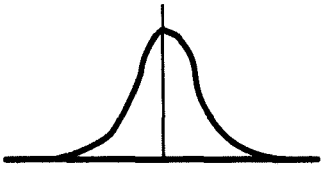
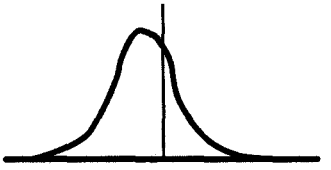
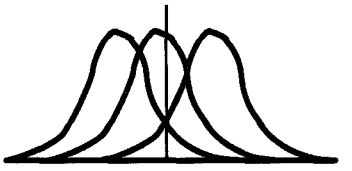
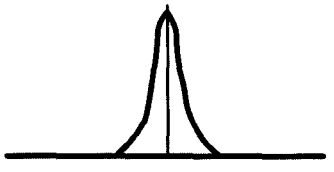
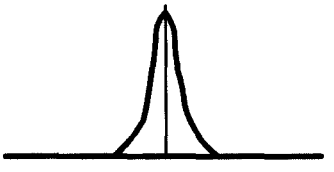
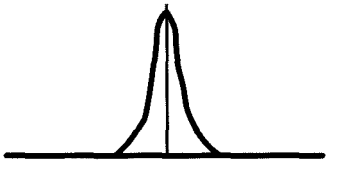
The primary source of sensor repeatability tolerance is the statistical nature of the radioactive decay which produces the beta rays. While no designer can change this physical phenomenon, efficient beam path design can improve the fundamental sensor repeatability.

The variability of the flux emanating from a Krypton 85 or Promethium 147 nuclear source is known to be proportional to one divided by the square root of the source activity. Thus a four-fold increase in the disintegrations per second (activity) will be required to reduce the flux variability to half.

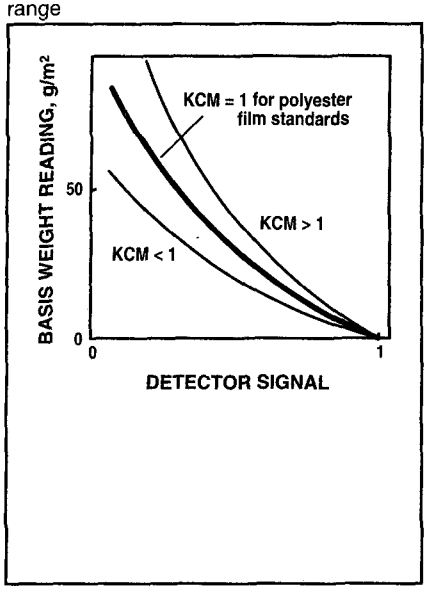
Once the source design is optimized for activity tradeoffs, the most fruitful path for repeatability improvements is optimizing the efficiency of the detection system. Successive design improvements over the last 20 years have continuously improved this efficiency.

First, the source capsule has been reduced in size which requires source enrichment for Krypton 85 gas. This design reduces the area of the capsule's metallic window which is also made as thin as possible while meeting strength requirements. Another benefit is the reduction of the total air mass between the source and receiver which can absorb the beam. In addition, the smaller footprint intersects smaller areas of

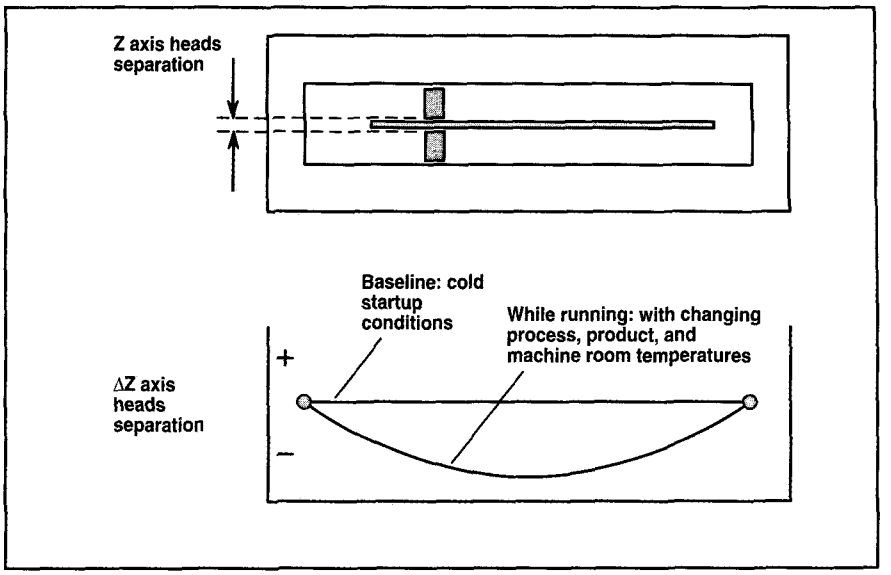
II. Typical categories of error types and optimization results targeted at the requirements of lightweight nonwovens

Random variability Always average to zero Repeatability specification	Nonrandom variability May average to nonzero values Dynamic accuracy specification	
 (-) (+) Random variability	 (-) (+) Systematic variability	 (-) (+) Environmental variability
Typical categories of error types		
Radioactive decay Sheet pass line effect (flutter)	Calibration for sheet structure and composition effects X-Y sensor heads Alignment for upscan/ downscan traverses	Air temperature (air mass) changes in the beam path Z axis (vertical separation of the sensor heads) changes air volume (air mass) in the beam path Dirt accumulation in the beam path
	Optimization results targeted at the requirements of lightweight nonwovens	
Optimized beam path design Size reductions	Enhanced higher order polynomial calibration models basis weight dependence of absorption coefficient Simplified KCM method for product calibrations Computer generated X-Y upscan and downscan profile correction	Real time air temperature measurements and basis weight corrections Real time Z axis measurements and basis weight corrections plus scanner thermal equalization technique Real time, basis weight driven dirt corrections based on three point standardization technique
 (-) (+) Always average to zero but within tighter band	 (-) (+)  (-) (+) Nonzero offsets minimized by additional systematic and environmental correctors	

1. A single parameter, KCM, calibrates the basis weight sensor for unique nonwovens structure and composition over a wide weight range



2. Differential thermal expansion changes the dimensions of the scanner



the sensor's protective plastic film windows. The result of these measures is a much "brighter" source to "shine" onto the sheet.

Next, the source body design has been made extremely compact so that the beta source can be located much closer to the sheet. The protective windows for both source and detector heads have also been made as thin as possible, and the source and receiver headers have been brought to within a 10-mm separation.

The detector design places an ion chamber as close as possible to the sheet with a minimum thickness window. Furthermore, the ion chamber diameter is several multiples of the source capsule diameter which ensures high detection efficiency.

The sheet pass line effect derives from the scattering of beta rays as they interact with the sheet. Proprietary beam path compensators have evolved to minimize this effect. As a result, sensors designed for lightweight nonwovens can restrict the pass line effect to magnitudes less than the sensor repeatability tolerance. The random position of the sheet within the sensor's gap indicates that no errors will persist.

Minimizing systematic errors for sheet structure and composition

Beer's Law approximates the absorption and scattering of the beta rays as they interact with a sheet as shown in Eq 1:

$$R = \frac{I\,sample}{I\,air} = e^{(-\mu BW)} \qquad (1)$$

where

R = detector signal

I sample = signal intensity for the sample

I air = signal intensity for no sample

μ = mass absorption coefficient of the sample

BW = basis weight of the sample.

The above resolves to Eq. 2:

$$BW = \frac{1}{\mu}(-\mathrm{Ln}\,R) \qquad (2)$$

For practical sensor designs, the relationship is actually more complex. The absorption coefficient, μ, is not constant but varies with basis weight. This additional aspect can be modeled by switching to a higher order polynomial equation, f(R), and introducing an alternate scaling factor, KCM, which does not depend on basis weight results as shown in Eq. 3:

$$BW = KCM \times f(R), \qquad (3)$$

where

KCM = a constant related to the sensor design and standard calibration material.

This improved equation yields a smaller error budget and leads to a single parameter calibration for individual product structures and compositions.

For lightweight nonwovens, the complexities modeled by this improved equation are important. The low basis weight region has the tightest tolerances for maintaining a small error budget, so even minor errors play a significant role.

The sensor is first calibrated using highly uniform polyester film to eliminate the effects of sheet structure and composition. This calibration can be viewed as setting the KCM for polyester film to a value of 1 as shown in **Fig. 1.**

The unique aspects of a nonwoven fabric's sheet structure and composition result in a change to KCM but not the fundamental sensor equation. Thus a single KCM models any given nonwoven's structure and composition over a very wide weight range.

This parameter is initially set by presenting a product sample to the sensor. It is subsequently refined by analyzing roll weight, width, and length checks to ensure adequately large sample populations from both the sensor and the product. Thus this systematic error is driven toward zero by routine verification programs on the line.

Minimizing systematic errors for X-Y head alignment

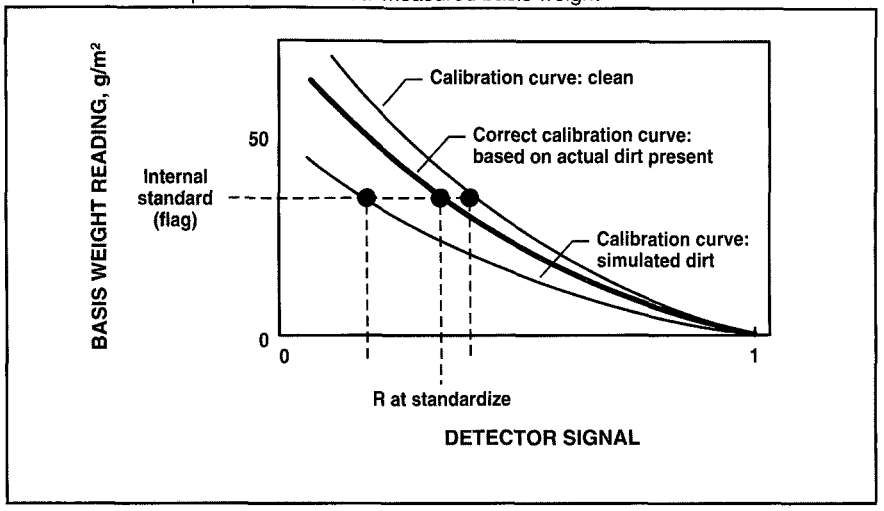
Measurement errors are caused by minor X-Y (machine and cross direction) misalignments between the sensor's upper and lower heads as they traverse. These typically small deviations derive from the scanner drive belt tensions and small anomalies in the alignment of the scanner's upper support beam with respect to the lower support beam. Although such errors are small, they persist. These measurement offsets can be eliminated.

Since these errors are repeatable, they can be corrected. The correction technique needed must operate continuously while scanning on-line. The errors it corrects, however, must be characterized when the line is down. The objective of this correction is to ensure that every measurement slice produces exactly the same reading during both upscans and downscans when a sample is fixed to the sensor.

To achieve this result, two correction arrays are established in the sensor support software. Each array has as many elements as there are measurement slices. The first array is used to correct upscans while the second corrects downscans. The arrays are automatically filled by scanning the sensor while the production line is down. Either an internal standard or a separate sample is inserted in the beam path. The software program accumulates the readings and automatically derives the correction factors for each array element.

Again the X-Y head alignment error approaches zero, and the required tolerances for a tight error budget are supported.

3. Dirt correction depends on the actual measured basis weight



Minimizing environment errors due to air column variations

The air column through which the sensor beam passes is the equivalent of 30–50 g/m² of basis weight depending on sensor design details. Lightweight nonwovens in the 5–50 g/m² range are indeed the needle in this air column haystack. Fortunately, proper compensation techniques can readily separate the nonwoven product from air column effects.

Two sources contribute to dynamic errors through changes in the air mass in the sensor's beam path. Air temperature changes affect the air density, and the vertical or Z axis separation of the source from the detector affects the volume of the air column. These variables function according to the Perfect Gas Law shown in Eq. 4:

$$PV = \frac{M}{r} kRT \qquad (4)$$

where

P = pressure

V = volume, proportional to Z

M = mass of air

r = density of air

k = a unit conversion factor

R = the perfect gas constant

T = absolute temperature.

Eq. 5 derives from this:

$$\Delta M = \frac{\Delta Z}{Z} M - \frac{\Delta T}{T} M \qquad (5)$$

This relationship indicates that the beta sensor acts as both a thermometer and a Z axis distance transducer! There are simple instruments, however, which make these measurements more accurately. These must be used to compensate the basis weight measurement to meet the tightest possible error budget.

The sensor air column is comprised of four parts: source to source window, source window to sheet, sheet to detector window, and detector window to detector. Thermistors are located to measure accurately the temperatures of each of these sections.

The compensations are based on comparing the four temperature readings made continuously while scanning to the four temperatures read during off sheet standardization (ΔT). This minimizes the magnitude of the corrections needed.

Thermistor temperature response is increased by the addition of tuned predictive circuits to overcome the thermal lag of the thermistor's thermal capacitance.

Finally air wipes are installed to break up the air flow near the sheet and vigorously mix the air in the sensor's gap. This ensures that the measurements accurately represent the tem-

perature of the air in the sensor's air column under all conditions.

Thus changes in air mass (ΔM) due to temperature changes (ΔT) can be precisely corrected for the basis weight readings.

The Z axis effect (ΔZ) derives from other temperature variation consequences. The local ambient temperature changes dynamically as the production line changes from cold startup to steady-state running conditions. Similarly, temperature transients occur as the plant buildings experience ventilation and weather changes. In addition, radiant heat transfers from the sheet to the scanner shift as run rates and operating conditions are adjusted.

Figure 2 indicates that thermal equalization of the structure and the real-time Z-axis measurements or both of these, as well as basis weight corrections, are critical for lightweight products.

When placed in this dynamic thermal environment, most scanner structures will undergo thermal expansions and contractions. These nonuniform stresses alter the distance between the supporting beams.

For any given air temperature, a 1-mm air column height change (ΔZ) is equivalent to 1.2 g/m² (ΔM). Typical dynamic Z-axis shifts vary according to scanner length, scanner construction, and the ambient conditions. For lightweight nonwovens, even a 0.1-mm shift would produce a 0.12-g/m² error which cannot meet the tight error budget.

Two patented solutions are available which can be used individually or together. In the first, the actual ΔZ can be directly measured by a magnetic reluctance proximity sensor. By continuously comparing the proximity readings to the reading made during the last standardization, every measurement can be corrected for the actual Z-axis changes while scanning. Thus changes in air mass (ΔM) due to source-to-detector separation changes (ΔZ) can be precisely corrected for basis weight readings.

In the second solution, a thermal equalization system continuously recirculates a heat transfer fluid in a loop consisting of two horizontal supporting beams. With the temperatures in equilibrium differential, thermal expansions of the scanner frame cannot contribute to dynamic Z-axis errors.

Minimizing environmental errors due to dirt accumulation

Dirt may accumulate in the beam path as the basis weight measurement system performs its duties around the clock. Lightweight nonwovens sometimes include binders, surfactants, and miscellaneous short fibers that fall out from the sheet. These and other debris cause shifts to the sensor's calibration.

Figure 3 shows two calibration curves for the same sensor. The first (clean) was established in the way described earlier. In the second (simulated dirt) curve, a separate sheet of polyester was introduced to simulate an arbitrary level of dirt, and the sensor was calibrated again.

The basis weight correction for a given level of dirt is not constant. Instead, it is shown to depend upon the actual basis weight being measured. Of course, the actual dirt present in the sensor varies over time.

For lightweight nonwovens, even a 0.05–0.10 g/m² error in dirt correction hurts the sensor's ability to meet a tight error budget. Fortunately, a proven method exists to overcome this problem.

A patented technique called three point standardization adds a third (flag) reading to the normal shutter open and shutter closed off sheet standardization points. A scalable dirt correction function is automatically generated by the computer based on the two calibrations: clean and simulated dirt.

The dirt correction is rescaled by the latest reading on the flag. Then the actual dirt correction is a direct result of the uncorrected basis weight readings while scanning and the properly scaled dirt correction. Thus the basis weight measurement errors caused by dirt accumulation can be precisely corrected.

Recapping the error budget

Recall that the target error budget was ± 0.25% or ± 0.05 g/m², whichever is greater. This tolerance was established without detailing any disciplined methods for quantitatively determining the actual size of any errors. Instead, this target was used as a reference point to better understand the size of random variabilities and nonrandom errors.

By optimizing sensor performance as summarized in the bottom portion of Table II, specialized technology has been applied which makes on-line basis weight measurements practical for lightweight nonwoven sheets. These techniques allow the on-line measurements to exceed the accuracy of off-line testing. Through closed loop basis weight control, the techniques ensure that the product stays within the tighter tolerances needed to maintain sheet quality and performance for less thick fabric weights. ■

Received for review Jan. 22, 1992

Accepted May 19, 1992.

Presented at the TAPPI 1992 Nonwovens Conference.