Having confidence in on-line instruments

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The instrument will gain the confidence of the user when it is stable, reproducible, and free of static and dynamic calibration shifts.

On-line instruments for measuring basis weight, caliper, moisture, and ash have improved over the last decade to the point where they rival the standard laboratory tests for these parameters. Since the on-line instruments will examine a much larger fraction of the product than the quality control laboratory, the measurement system can be allowed to characterize the product quality.

Before the instruments can be relied on to such an extent, the personnel must have confidence in the measurement system. What are the factors, then, that influence user confidence?

Here, we will look at an installation for measuring basis weight and moisture on a machine producing fine paper. We will evaluate a Promethium 147 isotope beta-gauge instrument for measuring basis weight and a multi-frequency infrared (IR) instrument for measuring moisture. The same principles in effect on these systems will apply for other instruments as well.

Various instrument suppliers, instrument users, and technical associations have different definitions of terms used to describe instrument performance. We will use a standard established by the International Electrotechnical Commission (IEC) (*1*). This standard characterizes ionizing radiation measurement systems with analog or digital signal processing for thickness measurements (based on area weight). However, the terms are useful in describing on-line instruments in general.

The confidence program

A program to build on-site confidence has evolved at our company. This program consists of two phases. The first phase is a rigorous test period intended to build initial confidence. This phase will be conducted either at the vendor factory before shipping or after installation in the mill. The second phase is one of continuing verification, intended to keep confidence high. These less rigorous tests involve the user in basic statistical quality control charts to monitor the "health" of the instrument system.

This two-phase program approach allows the user to separate "common" causes of variation from "specific" or chance cause of variation (*2*). Common causes of variation relate to specific vendor equipment design and should be tested against the vendor's specifications. Common causes are usually remedied by management action. Specific or assignable causes of variation can often be remedied by the user. Examples are dirty instrument windows, faulty wiring, failing components, or instrument misalignment.

The user's primary interest is the elusive sensor property called "accuracy." It is difficult to devise a simple test that will verify instrument accuracy under all conditions. We can test and verify certain instrument characteristics that, when taken together, will give the user confidence that the instrument is operating accurately.

Stability, reproducibility, and "influence quantities" are the three major criteria we will evaluate. The influence quantities include process flutter, instrument deflections, process composition, and ambient or process temperatures.

Stability

Good stability is the most important instrument parameter. Without stability, calibration or verification work is meaningless. Most computer-based instrument systems report electrical and radiometric instability.

There are two IEC definitions for instability. First, electrical instability is the variation of the output signal under reference conditions, while all influence quantities are held constant and the detector is not irradiated. Second, overall radiometric instability is the variation of the output signal under reference conditions while all influence quantities are held constant and the detector is irradiated.

Beta-gauge stability

Over any 2-h period, the instrument should maintain an effective air gap (zero basis weight) signal within the vendor's stated limits. To maintain reference conditions, it is necessary to allow all components to come up to stable temperatures. An overnight test should be set up with the instrument system reporting average signals and noise at least every 10 min. The test results should be plotted to verify stated stability limits. Using standard $\bar{X}$ (called "X-bar") and R charts, as shown in **Fig. 1**, the result of this controlled test can be evaluated and compared to vendor specifications.

The continuing verification test should be a periodic recording of the raw air gap signal. The variation in this signal will be greater than the controlled stability test, since it is affected by dirt on sensor windows, source decay,

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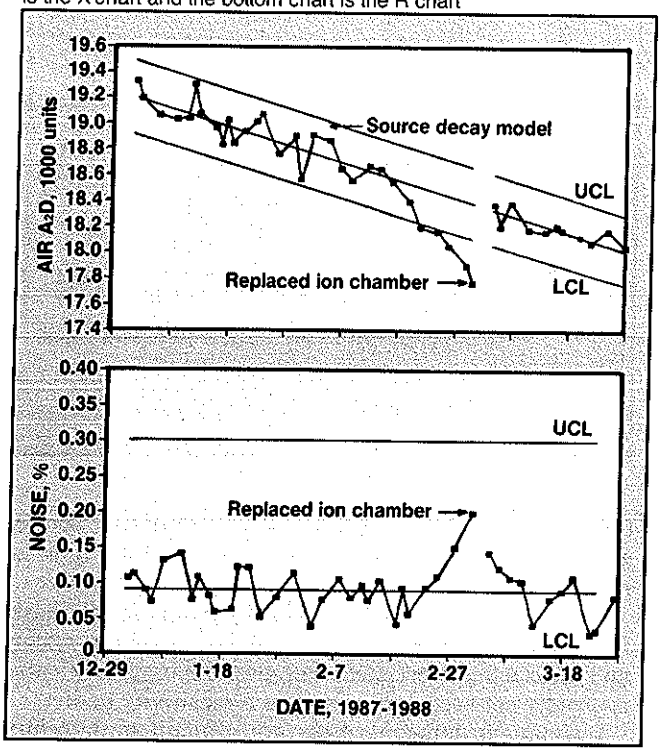
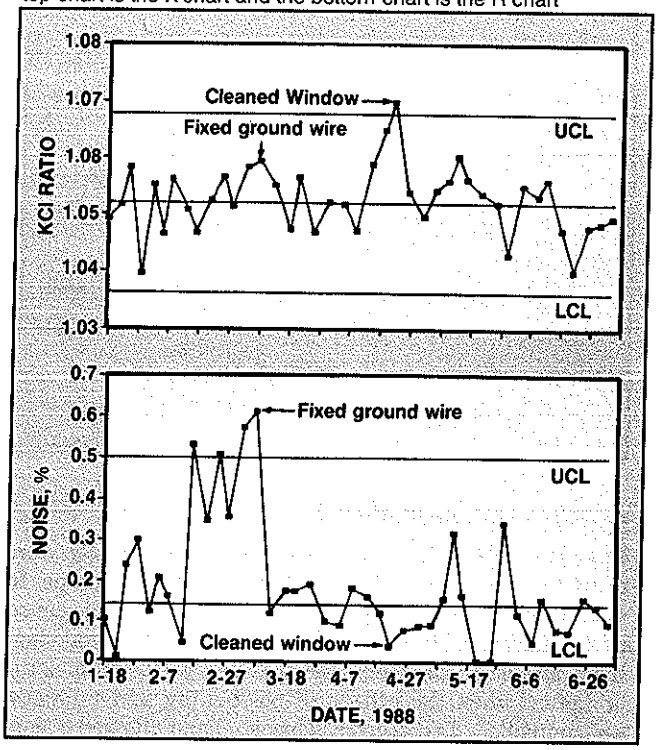
1. Control charts for beta-gauge air gap stability, where the top chart is the X chart and the bottom chart is the R chart



2. Control charts for the moisture sensor air gap ratio, where the top chart is the X̄ chart and the bottom chart is the R chart



frame deflections, and air pressure changes. Acceptability is based on standard statistical procedures of establishing the $\bar{X}$ and the standard deviations for upper and lower control limits (UCL and LCL, respectively).

The control limits are established during an initial stage of careful monitoring of both the process and the instrument performance. The example of a control chart for the beta-gauge instrument in the $\bar{X}$ chart in **Fig. 1** is somewhat unusual, since it incorporates a model of source decay. Removing this predictable bias allows much closer tracking of the signals.

Using the control chart, problems can be detected early, such as excess dirt on sensor windows, broken windows, or the defective ion chambers indicated on March 1, 1988, in Fig. 1. One control chart alone may not catch problems. The defective ion chamber did not cause a problem on the "R" chart, for instance.

IR sensor stability

Since IR instruments measure the ratio of two or more frequencies, the absolute stability of the IR source or detector (in single detector systems) is not important. What is important is the ability of the measurement system to accurately measure this ratio. The stability of this ratio will typically be better than 0.1% of the ratio per hour. This value may be recorded and compared to vendor specifications at the same time the basis weight stability data are recorded.

The upper and lower control limits for the air gap ratio, during the continuing verification test, will be wider than those in the controlled test because of dirt buildup or electronic drifts. The standardization cycle removes these effects over a given range. As indicated in **Fig. 2**, problems can be caught early and accuracy can be kept under control by using the $\bar{X}$ and R charts.

It takes both charts to find the two problems indicated. The ground wire problem in February and the window cleaning problem in late April show up on different charts.

Reproducibility

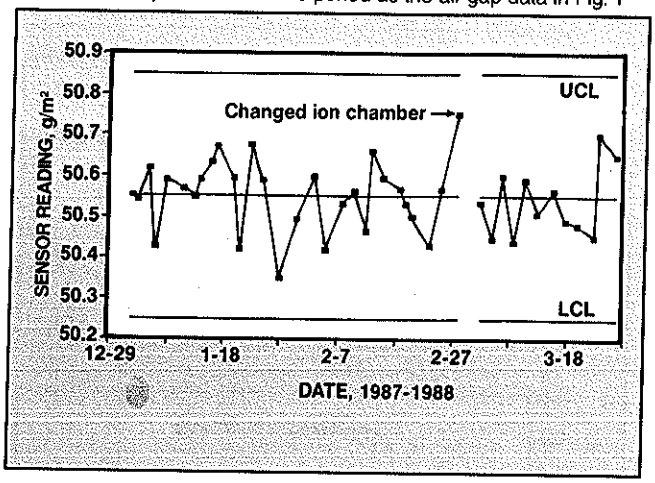
Reproducibility is the closeness of agreement in values of consecutive measurements of the output signal. Reproducibility combines the effects of "noise" and stability.

Beta-gauge reproducibility tests

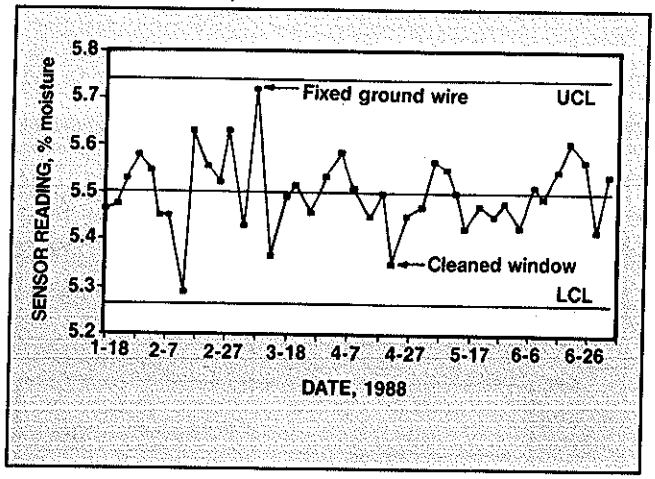
This specification is proved using stable check samples. It is more difficult to achieve good static reproducibility than on-line accuracy since the tests may introduce errors that do not influence on-line accuracy. Factors that may influence the reading include (a) repositioning the check sample accurately, (b) check sample durability, (c) sensor package deflection in the off-sheet position, and (d) gap temperature influences caused by the check sample hardware.

Taking extraordinary care to control the factors mentioned, the check samples can be used to establish reproducibility to the vendor's specified accuracies. For continuing verification, the upper and lower control limits will be greater than the specified accuracies. These limits must be established using standard statistical quality control techniques. **Figure 3** represents the $\bar{X}$ control chart for check sample readings taken over the same period as the air gap data in Fig. 1. This chart is particularly useful in catching problems related to improperly entered sensor calibration constants or source and detector modules that have become misaligned.

3. Check samples for the same period as the air gap data in Fig. 1



4. IR gauge check samples



IR sensor reproducibility tests

Reproducibility of static check samples is usually worse than on-line accuracy. An additional influence for moisture samples is migration in the check sample caused by temperature gradients during the test. Typical short-term precision for check samples can be 0.05% moisture or better when the effects of positioning and migration are controlled. The sample is inserted and allowed to come to equilibrium for 5–10 min. With the sample in place, from 7 to 10 sample readings are taken. Typically, two standard deviations are less than 0.05% moisture, which should be the basis for the initial $\bar{X}$ and R charts.

The continuing verification of precision consists of a number of short-term tests over many months, as shown in **Fig. 4**. We have found that variations of the $\bar{X}$ readings of less than ±0.20% moisture indicates good performance. Note that fixing the ground wire problem indicated by the "R" chart in Fig. 2 helped reduce the variations in the check sample readings.

Influence quantities

Influence quantities include any quantity, generally external to the apparatus, which may effect its performance. These quantities are typically specific to particular instruments and applications. Typical quantities are sensor deflection, process flutter, dirt buildup, sheet composition changes, and process or ambient temperature effects.

Influence quantities cause the instrument to suffer shifts in calibration, static or dynamic. It is desirable to remove these affects through design, but sometimes secondary measurements are required. When secondary sensors are required, consideration must be given to the influence effects that may cause uncertainty in those measurements.

Tests for beta-gauge influence quantities

Sensor and process deflections are often causes for on-line errors that do not show up in off-line static testing. Samples that span the process range should be measured in the instrument at various passlines, or the planes across which measurements are taken. Because of positioning problems, data from several samples should be averaged. Typical effects of passline flutter for a 50 g/m² sample are less than ± 0.18 g/m² for ± 6.4 mm of process flutter. As long as the instrument is stable and reproducible, it is not necessary to test flutter for ongoing verification.

Tests for dirt buildup are made by taping a thin plastic film over the sensor window, standardizing the system, and measuring a few check samples. Ongoing verification is usually not necessary to ensure insensitivity to dirt.

Instrument deflection tests are difficult to determine while the instrument is installed in a scanner. These tests are best demonstrated on a special test stand at the vendor's factory. Since the source of misalignment is the scanner, we may test the instrument with a stable check sample in place while scanning. The beta-gauge instrument we tested had less than ± 0.25 g/m² error for scanner misalignment of 1.2 mm in any direction.

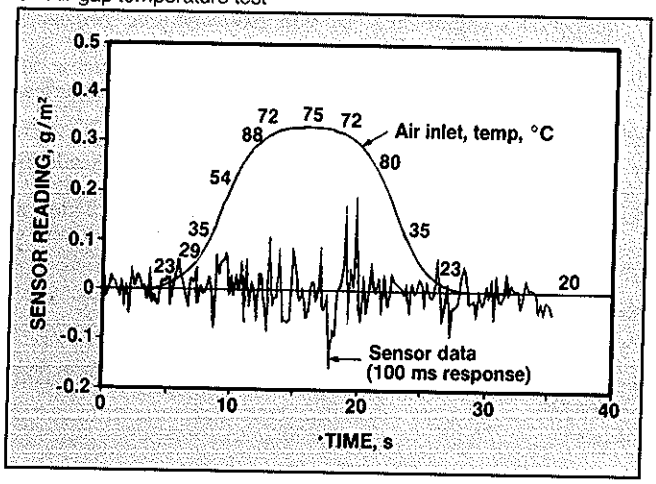
If scanner deflections are present that do not change with temperature, then profile compensations can be stored in the system memory to keep the on-line measurements accurate until scanner alignment can be performed. Current advanced scanner designs allow maximum deflections of less than 1 mm over a broad range of process temperatures. This range allows the sensor geometry to be designed to be insensitive to deflections without using external measurements for compensation. Periodic verification tests should be made when the sheet is not in operation by scanning a check sample to be certain that deflections are not a problem.

The source of composition errors for beta-gauges are subtle scattering changes that occur as the average atomic number of the process varies (*3*). Today's beta-gauges use beam shaping and secondary scattering components to compensate for atomic composition variations.

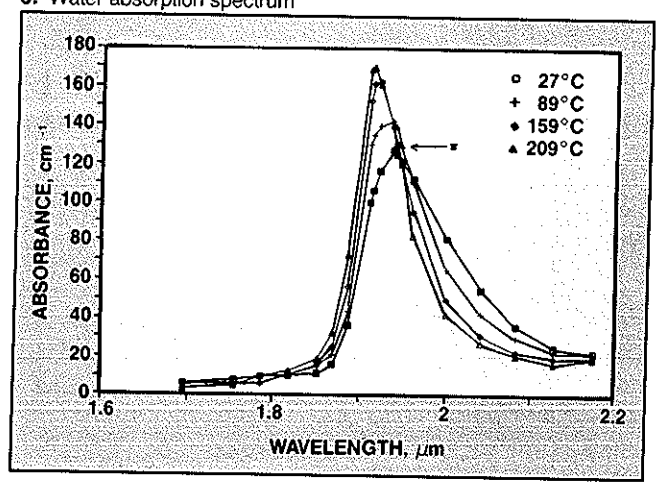
The primary indicator of insensitivity to composition is that the product uses the same calibration regardless of the amount of clay filler or coating. Extreme tests can be made by comparing calibration curves on aluminum samples with the curves for polyester samples. There is no need for ongoing tests to verify composition insensitivity as long as the instruments are stable and the measurements are reproducible.

The effect of air temperature in the measurement gap can be a significant problem. The mass of air in a 13-mm gap at standard temperature is about 13 g/m². That mass will change inversely with the absolute temperature. A

5. Air gap temperature test



6. Water absorption spectrum



40°C increase in temperature will change the air mass by 1.7 g/m², or 10% of a tissue weight or 3.4% of newsprint. The effect of gap temperature must be accounted for on lightweight sheets to maintain instrument accuracy. A combination of air gap temperature control and gap temperature measurement can provide excellent results.

The performance of these gap conditioners can be tested. Heated air can be blown into the measuring gap. The temperature can be modulated by adjusting the distance between the gap and the heat gun. **Figure 5** is a plot of the results of such a test. Ongoing verification of these gap conditioners is maintained by checking the electrical indications at the frame junction box to be sure that the conditioners are functional.

IR sensor influence quantities

Process flutter effects can be measured off-sheet using check samples or bagged process samples. Several measurements will be required to average out the effects of sample positioning. In general, flutter errors will be less than 0.1% moisture for ± 6.4 mm of process movement.

Instrument package deflections are more difficult to measure when the package is installed in the scanner. A check sample should be scanned to verify that frame deflections will not cause significant errors. The multi-frequency moisture sensor will have less than ± 0.1% moisture error for scanner deflections greater than 10 mm in any direction.

A quick test for dirt can be made by taping a piece of lightweight paper over the instrument window, standardizing on the paper, and rereading the check samples. Allow the paper to equilibrate in the gap before doing the tests, or its changing moisture content will cause the tests to be invalid.

IR instruments may experience composition sensitivity if additives are used that have absorption bands coincident with those used by the instrument, or if there are gross changes in the optical properties of the sheet. Except for the addition of urea in large amounts, we have not experienced composition sensitivity from chemical additives. The optical properties of the sheet characterized by the scattering coefficient and absorption coefficient are much more variable. Tests have shown how IR instruments are influenced by these variables (*4*).

The multi-frequency IR moisture instrument is designed to nearly eliminate calibration variation caused by changes in the specific scattering coefficient or the broadband absorption coefficient of the sheet. By measuring the optical properties of the sheet using several frequencies, these deleterious effects can be removed (*5*).

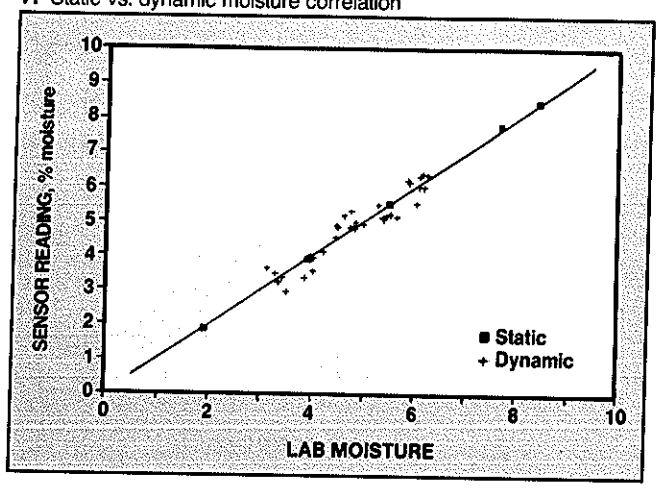
Tests to identify effects of composition sensitivity are difficult on an installed system. A good indicator is to compare the calibration coefficients required for specific products. Large grade-to-grade variation in the coefficients is an indicator of composition sensitivity. The actual determinations of the paper grade's variation in IR specific scattering coefficient or absorption coefficient is best left to a well-equipped laboratory. If large in-grade variations in optical properties are expected, a careful analysis may explain erratic instrument performance on certain grades.

Since the IR instrument does not "see" air or water vapor in the measurement gap, the temperature of the air in the gap is not important. The process temperature is a different matter. The shape and intensity of IR absorption bands are not always independent of the process temperature, especially with substances involving hydrogen bonding and surface absorption. Hydroxyl stretching vibrations can shift with surface absorption (*6*).

Figure 6 shows a near IR absorption spectrum of liquid water at several different temperatures (*7*). The 1.9-μm combination band narrows, increases in intensity, and shifts to the short wavelength as temperature increases. To compensate for this effect, some vendors use on-line sheet temperature measurements for compensation. The surface temperature of the sheet is not indicative of the true internal sheet temperature, especially on linerboard machines. The top and bottom of the sheet may differ by as much as 20-30°C.

By careful selection of band pass filters in conjunction with a proprietary technique for fine tuning the center frequency, the measurement frequency can be positioned in the area marked on Fig. 6. This positioning has the desirable effect of making the measurement insensitive to sheet temperature, which can be verified by heating and reading the check samples. A small oven brought out to the scanner heats the sample to about 60°C. The sample is inserted, and a number of sample checks are quickly started.

7. Static vs. dynamic moisture correlation



An alternative method for evaluating static and dynamic shifts is by comparing a static calibration to on-line dynamic sampling. As shown in **Fig. 7**, the data from on-line sampling should agree with the static calibration. These tests were run using procedures outlined in TAPPI TIS 018-6, approved by the Quality Control Committee of the TAPPI Process and Product Quality Division.

Conclusions

The current degree of refinement of on-line instruments justifies their use in judging the final production quality on a roll of paper. It is not reasonable to expect a user to have this confidence until it is demonstrated that the instrument will be stable and reproducible and that it will not suffer static or dynamic calibration shifts.

By conducting some initial verification tests on-site or in the vendor's factory, the user can begin to gain confidence in the instruments. The successful implementation of a "ship by the gauge" program must include ongoing systematic tests of the "health" of the instruments. Using standard statistical quality control techniques, the user will become familiar with parameters that influence the on-line instruments. Using these charts, problems can be avoided before any bad paper is produced. If a problem is expected, a more in-depth analysis may be required. The instrument engineer must have a knowledge of the basic principles to effectively accomplish this analysis.

The economics of a "ship by the gauge" program are obvious. The amount of material examined by the on-line instruments far exceeds that examined by the quality control laboratory. People involved in the mundane tasks of continuous weighing, measuring, and drying can be involved in more challenging positions. Without proper planning, training, and continuing verification, the implementation of such a program will ultimately fail and lead to loss of confidence in the measurement system.

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