Computerized tomography of a paper roll

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ABSTRACT *Paper rolls were analyzed nondestructively by a computerized tomographic (CT) system. The images of cross sections of paper rolls were shown as faithfully as if they were observed by cutting them. The tomographic image density (CT value) of a cut paper sheet bundle was proportional to its sheet paper density.*

In CD profiles of CT values of paper rolls, each roll had a different CD profile. A paper roll wound at higher tension had a poor CD profile of CT values, which indicated internal stress concentrated locally in the roll. The macroscale MD profile of CT values coincided well with the basis weight profile. The long-range MD profile of CT values decreased gradually from a surface to a core of a paper roll, which indicated that internal stress decreased from the core to the surface.

KEYWORDS
Basis weight
Rolls
Sensors
Winders
X-ray analysis

How well a paper roll runs on a printing press is influenced by various paper roll qualities. Important among them is the homogeneity of roll compaction and tightness. Studies to measure paper roll hardness nondestructively have been made over the past decades (*1-5*). However, these studies were based on the assumption that paper qualities such as basis weight, moisture, thickness, and density were constant—and that only winder operations determined the quality of the roll. Therefore, the variation of local compaction and tightness in a roll were not studied.

With the introduction of a high-resolution, X-ray, industrial, computerized tomography (CT) scanner, the tomographic images of cross sections of papers rolls were shown. This technique successfully demonstrated the variation of local roll tightness.

Industrial X-ray CT scanner

The industrial X-ray CT scanner is used to inspect such materials as ceramics, plastics, rubber, and aluminum nondestructively. Studies to measure the tomogram of annual rings of living trees have also been reported (*6, 7*).

As for the equipment, there are already several models available as commercial products. The one we used has a high resolution, an emission energy capacity of 140 kv, a 300-mA X-ray tube, and a 512-channel, xenon gas detector. A diagram of this system is shown in **Fig. 1**.

A sample (**Fig. 2**) is placed on either of the two tables located between the X-ray tube and the detector. The sample is exposed to pulsed X rays while the table is rotated. The X rays which pass through the sample are detected by the detector. The data are sent from the data acquisition system (DAS) to the first reconstruction unit (FRU), where they are preprocessed.

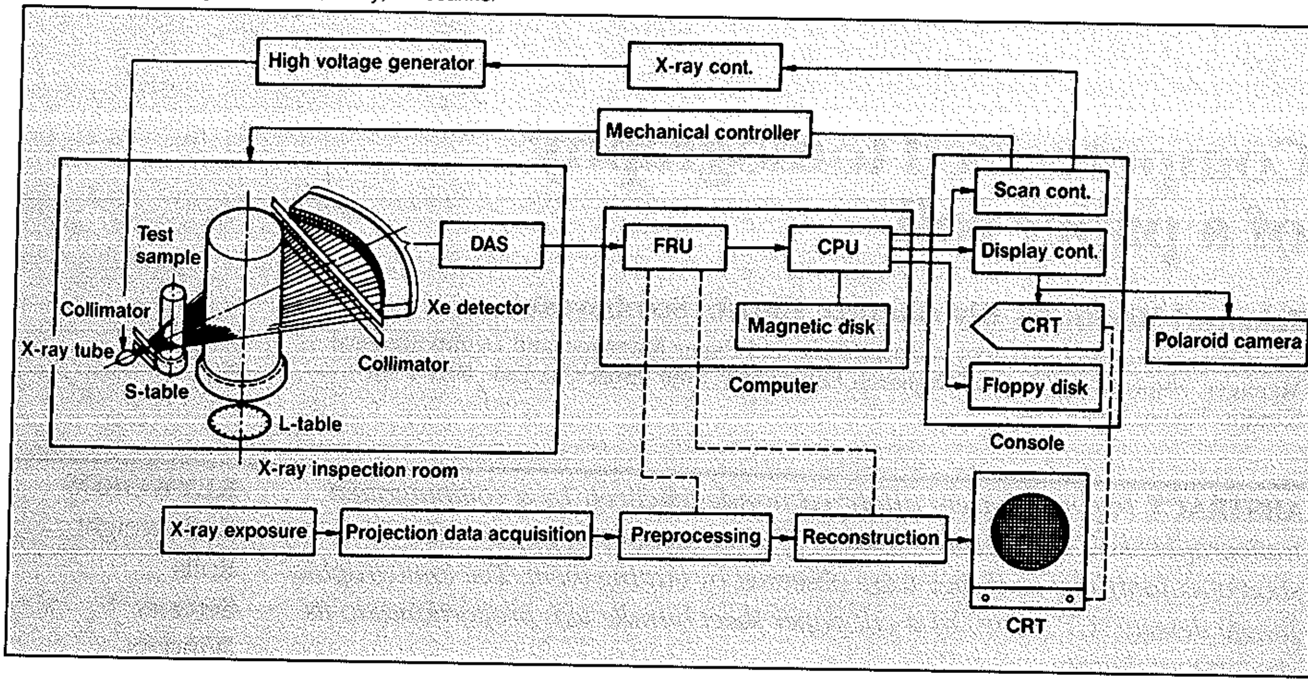
The results are sent to the computer (CPU) and are stored on a magnetic disk. These data are also fed back from the CPU to the FRU for image reconstruction. The FRU provides pipeline processing of the data so that it takes only 15 s to give an image display. The reconstructed tomogram is displayed on the CRT in a resolution of 320 × 320 pixels.

Every material has its own absorption coefficient, which corresponds to its specific tomographic image-density value (CT value), with water and air serving as arbitrary standards in **Table I**. Few materials with CT values lower than that of water have been measured so far, and it was not known whether a paper roll could be tomographed.

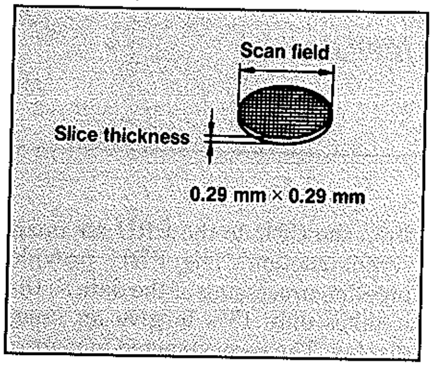
Preliminary measurement with cut sheet bundles

For a preliminary test, bundles of cut paper sheets were scanned by the system, because they could be prepared as specimens more easily than rolls. Three grades of papers of different sheet density were selected, as

1. Diagram of a high-resolution, X-ray, CT scanner



2. When the tomogram is scanned with X rays, the matrix resolves to a picture image of 320 × 320 pixels.



I. CT values of materials

Material	Absorption coefficient: Mass, μ	Absorption coefficient: Linear, ($\mu \times \rho$)	CT value
Air	0.155	0.0000279	-1000
Water	0.171	0.171	0
Concrete	0.169	0.389	1275
Aluminum	0.169	0.455	1661
Iron	0.370	2.908	16006
Copper	0.490	4.045	22655
Selenium	1.650	12.012	69246
Lead	5.460	61.916	361082

CT values of air and water are defined as standard.

listed in **Table II**. Three hundred sheets for each grade, 210 mm wide and 297 mm long, were loosely bundled with an adhesive tape. Each bundle was placed one on top of the other with Sample 1 at the left-hand side, Sample 2 in the center, and Sample 3 at the right-hand side.

The cross-sectional (vertical) tomographic image was constructed by the system, as illustrated in **Fig. 3A**. The cross-sectional CT image of Sample 2, which had the highest sheet density of the three, was the brightest of all. The average CT values of the encircled areas of the three grades in **Fig. 3B** were calculated by the system. The average CT value of a sheet bundle was proportional to its sheet density (**Fig. 4**).

II. Sheet samples for the preliminary test

No.	Sample name	Basis weight, g/m²	Thickness, µm	Density, g/cm³
1	Xerography	67.3	87	0.77
1	Newsprint	47.8	77	0.62
3	Magazine	68.1	86	0.79

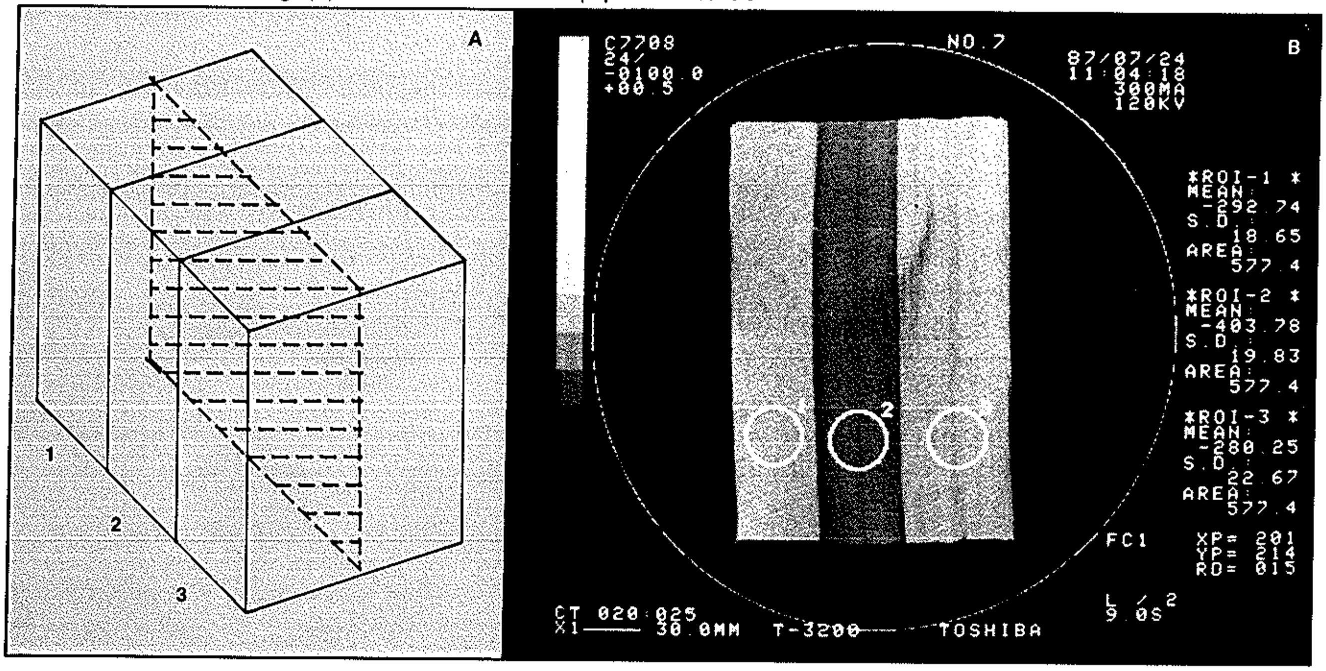
Tomographic analysis of paper rolls

As a result of sheet measurements, sheet density could be measured as a CT value. Six paper rolls were collected next for tomographic analysis.

Preparation of the tomograms

Five rolls, from Sample No. 1 to No. 5, are of different grades. Rolls 5 and 6 are of the same paper grade but were wound at different tensions. Roll No. 5 was wound at 2.0 N/cm (1.1 pli), and No. 6 was wound at 9.8 N/cm (5.5 pli). As shown in **Fig. 5**, each roll had a diameter of 300 mm. Small samples were peeled off from each roll, and basis weight and paper thickness were measured with normal testing procedures. Sheet density was calculated from these two measurements

3. Diagram (A) and the image (B) of a cross-section of a cut paper sheet bundle



III. Paper roll samples of different paper grades

No.	Sample name	Basis weight, g/m²	Thickness, µm	Density, g/cm³	Width, mm
1	Newsprint	47.8	77	0.62	300
2	Magazine No. 1	67.9	106	0.64	300
3	Magazine No. 2	68.1	86	0.79	300
4	Base paper of coated grade	8.34	96	0.87	300
5	Magazine, rough, No. 1	87.6	172	0.51	500
6	Magazine, rough, No. 2	87.6	172	0.51	500

(Table III).

Because the system can produce a complete three-dimensional tomogram, a CT value image of any cross section, horizontal or vertical, can be displayed on a screen. To study a tomogram in radial direction, CT images of several cross-sections perpendicular to the CD axis were reconstructed. For the Rolls 1-4, this reconstruction involved three cross sections with reasonable intervals along the CD axis for each roll, while five cross sections were used for Rolls 5 and 6 (Fig. 5). The average CT value of each cross-section was calculated, by which the variation of CT value in the CD axis or CD profile could be figured.

Average CT value of paper rolls

First, the image of a cross-section perpendicular to the CD axis at the center position was prepared for each roll, as shown in **Fig. 6**. The image of a high-density roll was brighter than the image of a low-density roll. In the preliminary test with sheet samples, we found that the average CT value was proportional to its sheet density (Fig. 4). However, linearity between the CT value and sheet density was not as good with roll samples as it was with sheets (**Fig. 7**).

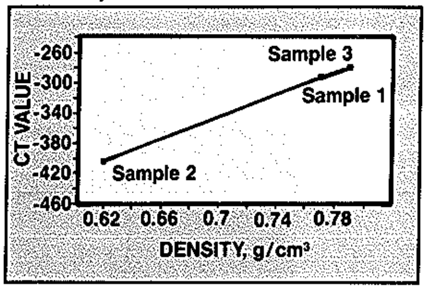
This difference implied that there must be another parameter influencing the CT value besides the original paper density measured in a free condition. The effect of winding tension became obvious. Roll 6 had higher CT value than Roll 5, which was the same grade wound at lower tension (**Fig. 8**). When observed carefully, images of each roll were not uniform, and some mottle was noticed. Roll 3 had especially severe mottling, like annual rings of a tree (Fig. 6).

CD profile of the CT value of paper rolls

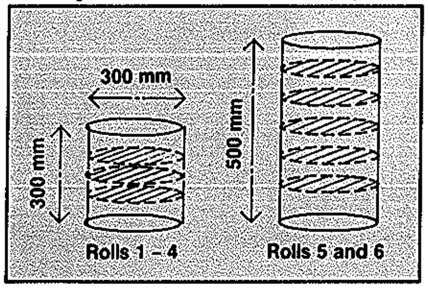
Each paper roll had its own CD profile of CT values. In Roll 1, the CT values at the back side were lower than those at the front and the center position (**Fig. 9**). The CT value of the center position was lower than those values at the front and the back side in Rolls 2 and 3 (**Fig. 10**). The CT value decreased almost linearly from the back side to the front side in Roll No. 4 (**Fig. 11**).

The effects of winding tension were observed when the profiles of Rolls 5 and 6 were compared (**Fig. 12**). Roll 5 had a relatively flat profile, while Roll 6 had a poorer CD profile. The CT value between the front and the center position was lower for Roll 6 than for Roll 5, and the CT value at the center position was higher than that of Roll 5. This difference indicated that the higher winding tension would cause less even internal stress distribution in the cross direction.

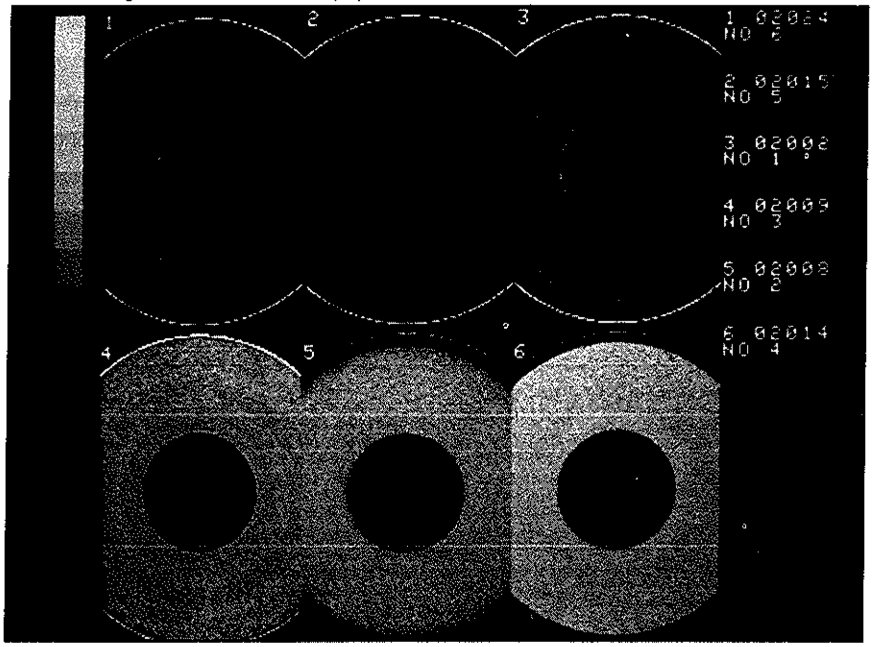
4. Density vs. CT values of cut sheets



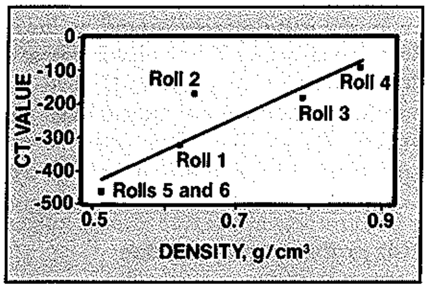
5. Diagram of the cross sections of paper rolls



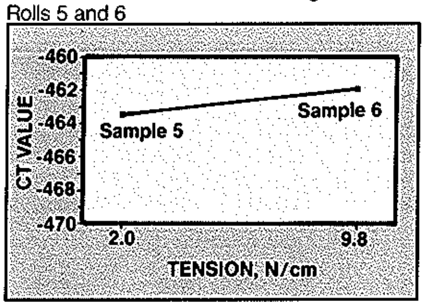
6. The image of cross sections of paper rolls



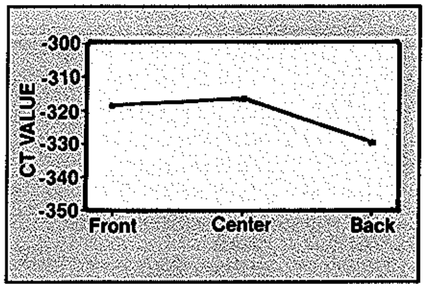
7. The CT value vs. the density of paper rolls



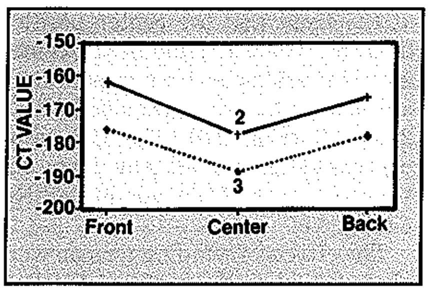
8. The CT value vs. the winding tension of Rolls 5 and 6



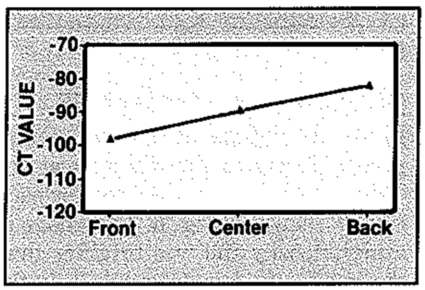
9. The CD profile of CT values of Roll 1



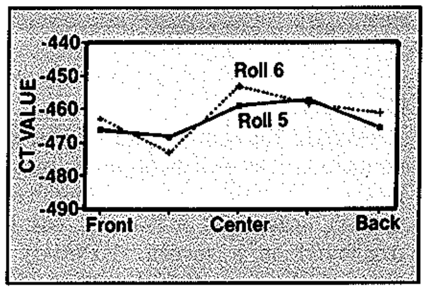
10. The CD profile of CT values of Rolls 2 and 3



11. The CD profile of CT values of Roll 4



12. The CD profile of CT values of Rolls 5 and 6



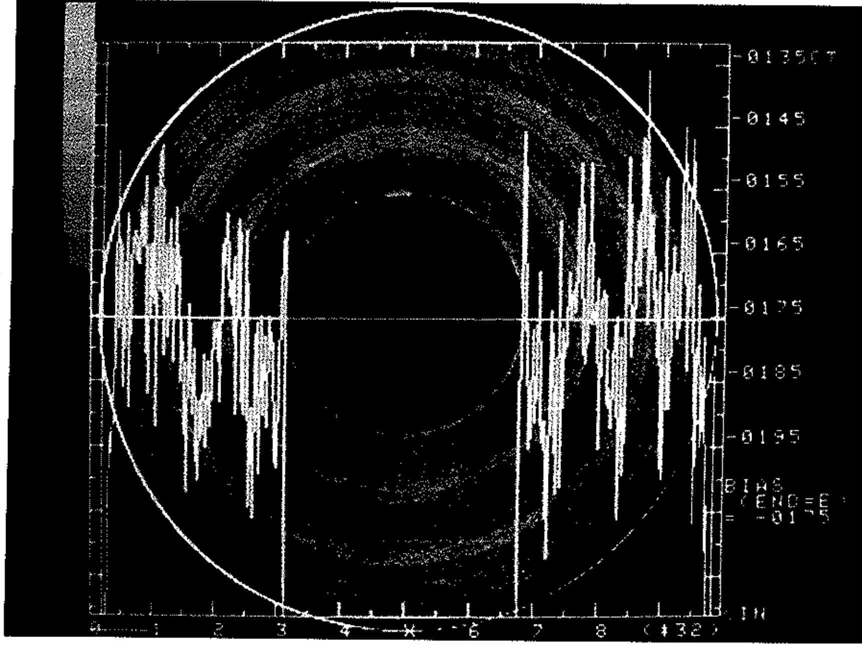
MD profile of CT value of paper rolls

As mentioned, the image of cross sections of Roll 3 was quite erratic, and we decided to study this roll in more detail. By using image analysis functions, the CT value profile was superimposed on the image. The CT value profile was obtained by numerically converting the image density profile along the radial direction of the roll.

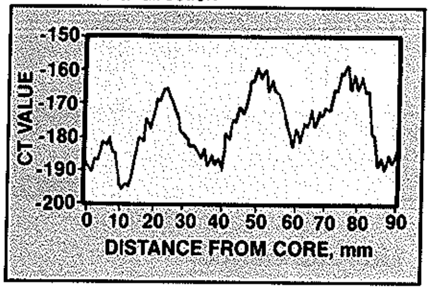
Some fluctuation of the CT value was observed but was not large enough for data analysis, so the contrast of images displayed on the computer screen was increased. Mottlings like annual rings of a tree were enhanced and became more visible. Next, a binary image was created, and four white rings appeared more vividly. Finally, the slit of the X-ray beam aperture was opened from 3 mm to 5 mm, and Roll No. 3 was irradiated again to get a sharper image.

The signal to noise ratio was increased by integrating images five times. High-contrast treatment was performed, and the CT value profile in the radial direction was created from this image, as shown in **Fig. 13.**

13. The enhanced image and CT profile of Roll 3 in the radial direction



14. The moving average of CT profile of Roll 3 in the radial direction



This profile was transferred from a CT system to a microcomputer, and the moving average was calculated. Four peaks appeared in the profile along the radial direction (**Fig. 14**).

Basis weight and moisture measurement of paper rolls with an on-line sensor

To study what the CT value profile in a radial direction of a roll meant, the basis weight and moisture content of all six paper rolls were measured by an on-line basis weight and moisture sensor. This on-line sensor is an effective tool for paper quality analysis, and almost all modern paper machines are equipped with one. However, a modern paper machine runs so fast that the data logging interval is not short enough to get continuous MD profiles. Fortunately, a new pilot coater that could run both at a high speed and at a low speed with an on-line sensor had recently been constructed in our company's R&D division.

Measurement conditions were as follows. A coater speed was set at 60 m/min, and signals from the on-line sensor were transferred every 0.15 s to a microcomputer. In other words, basis weight and moisture were measured every 15 cm. Charts connected to the on-line sensor showed that moisture decreased gradually but steadily from the periphery of the rolls to their core. Therefore, we concluded that moisture was not responsible for fluctuations in radial CT values in these rolls.

On the other hand, the basis weight recorded in the chart varied so much that more detailed analysis became necessary, using data transferred to a microcomputer. These data were retrieved and processed to show the MD profile for each roll. The actual linear paper length from the periphery of the roll, which was measured in units of time from the start of rewinding, was correlated to a position in a radial direction of the roll. This position was represented in a horizontal axis, where $x = 0$ at the surface of a core. An average basis weight was set to the zero position of the vertical axis, where the deviation represented a fluctuation of basis weight.

Studying these figures, three modes of fluctuations were recognized, which were defined as follows:

1. Microscale fluctuation was defined as fluctuation which appeared at the interval of several millimeters in the radial direction
2. Macroscale fluctuation was defined as fluctuation at the interval of 10–30 mm in the radial direction
3. Long-range fluctuation was defined as a constant trend of change from the periphery to the core.

The magnitude of microscale fluctuations of basis weight were observed as follows. The fluctuations for magazine-grade Roll 2 were greater than for newsprint (Roll 1), which were greater than those for magazine grade Rolls 3, 5, and 6, which in turn were greater than fluctuations in base paper for coated paper (Roll 4).

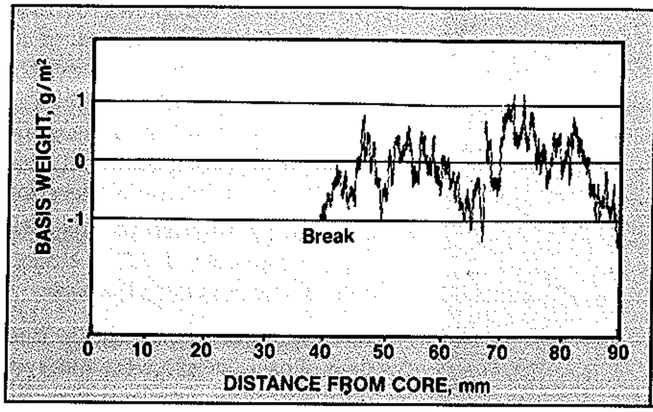
Macroscale and long-range fluctuation gave interesting results. Rolls 1 and 2 had almost even profiles from their peripheries to their cores. Basis weight gradually increased from periphery to core in Roll 5. In Roll 6, sheet basis weight decreased from the periphery to a position of 65 mm in a radial direction and then increased to the core. Because Rolls 5 and 6 were made from the same jumbo roll, this paper was estimated to fluctuate at long intervals.

Roll 3 had quite a noticeable profile, compared with the other five rolls. In addition to microscale fluctuations, macroscale cyclic fluctuations appeared, and two large peaks were observed, as shown in **Fig. 15**. While Roll 3 was running at the pilot coater, the paper chanced to break, and only data from the periphery to the 40-mm position were collected. The remaining data were missed. This accident was an indication that macroscale cyclic fluctuations of basis weight could damage paper runnability.

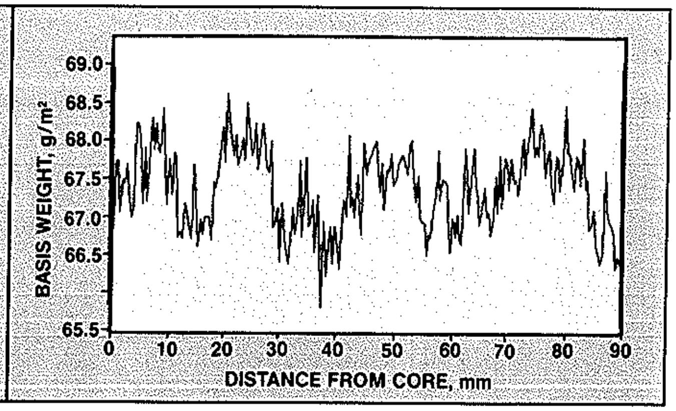
The measurement of rolls by hand

After measurement with an on-line sensor, Roll 3 was cut by a knife, and basis weight and paper thickness were measured every 5 plies. The objectives of this experiment were to (a) supplement missed basis weight data, (b) compare the basis weight taken with an on-line sensor with that of data collected by manual methods, and (c) measure paper thickness.

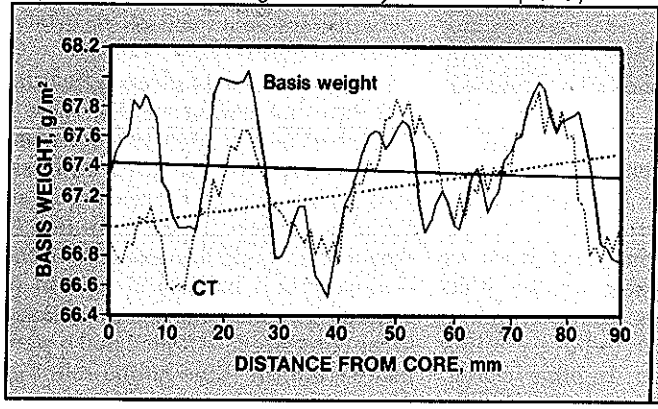
15. Basis weight profile of Roll 3 in the radial direction, as measured by an on-line sensor



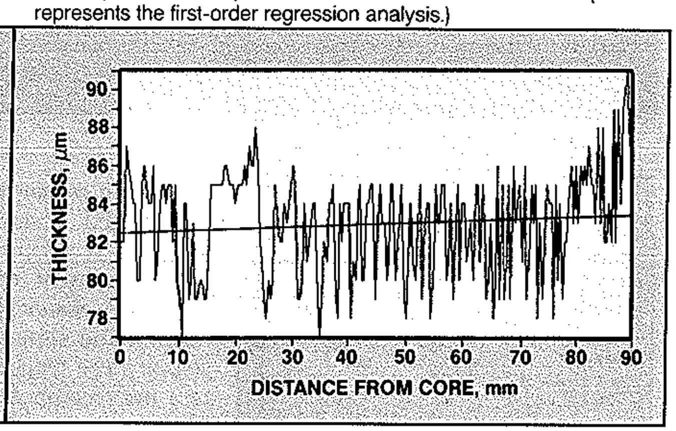
16. Basis weight profile of Roll 3 in the radial direction, as measured by hand



17. Basis weight and CT profile of Roll 3 in the radial direction. (Lines represent the first-order regression analysis from each profile.)



18. Paper thickness profile of Roll 3 in the radial direction. (The line represents the first-order regression analysis.)



The data collected through manual methods (**Fig. 16**) coincided well with those of an on-line sensor, and the validity of both measurements was proven.

To complete the measurement of the macroscale profile, the moving average of the data collected manually was calculated and displayed. By superimposing this basis weight profile with the CT profile (Fig. 14), we found that both of the macroscale profiles matched (**Fig. 17**).

On the other hand, the long-range profile of basis weight was different from the profile of CT values. Basis weight was almost constant, while CT values decreased gradually from the surface to the core. Sheet thicknesses of the same samples used for basis weight measurement were measured by hand. Microscale fluctuation was observed, but it could be regarded as constant from a long-range point of view (**Fig. 18**). Therefore, in Roll 3, the basis weight profile was regarded as a sheet density profile.

There was a good relationship between CT value and sheet density with cut sheet bundles and a less favorable one with rolls. Therefore, the CT value, which seems to be equivalent to local apparent bulk density, will be affected by winding tension or internal stress as well as by sheet density. The gradual decrease in CT value with constant basis weight, which was equivalent to constant sheet density in the case of roll No. 3, suggested that Roll 3 was wound loosely near the core and tightly at the periphery. This difference in winding tension might result in uneven internal stress distribution in the radial direction of the roll.

Conclusions

Paper rolls were nondestructively tomographed with an industrial X-ray CT scanner. Local compaction and tightness of the roll were affected by qualities such as basis weight, sheet density, and internal stress created by winding tension.

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