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Reviewing the concept of paper brightness

"Is the concept of standard brightness suitable today?" this question posed 1963 by J.A. van den Akken initiated a hot discussion with A.S. Stenius in Tappi Journal. Today, nearly 40 years later the situation has become even more obscure that before.

According to definition, brightness (in any of its variations i.e. Tappi, ISO, D_{65}, etc) is the property that corresponds to a number resulting from the application of a filter or a mathematical function, which has an effective wavelength of 457 nm and a width at half height of 44 nm. Strictly speaking it is a quantity related to the diffuse blue reflectance factor chosen on a more or less arbitrary basis, which was introduced as a visual aid for assessing the extension of bleaching during pulp cooking. It has definitely no connection with color perception and its action can be seen clearly on figure 1:

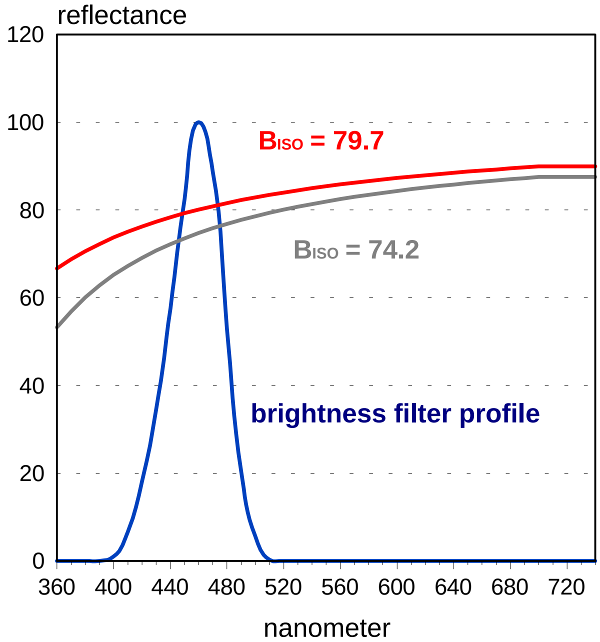

Fig. 1: Transmittance profile of the brightness filter compared to the reflectance of two pulp samples bleached to different extents.

The transmittance profile (denoted in the figure as ISO profile) indicates clearly that only light within the range of 457±44 nm (i.e. blue colored light) will be able to reach the detector; other wavelengths do not contribute to the observation. This was originally attained by observing the sample through a blue stained glass; in fact the color observed through the blue filter appears with increasing brightness as bleaching progresses, the method is then strictly valid within a process step (same process, same pulp, same conditions) and it is a measure (expressed as one number) that summarizes the action of the bleaching agent. The advantage in narrowing the observation region can be clearly seen by noticing that the changes in reflectance during bleaching are more pronounced in the short-wavelength region. The difference of the measured brightness values of the two samples of the figure is with a value of about 5.5 a large number in terms of bleaching process and readily noticed by using a blue filter.

The main point here is, however, that brightness, in spite of its widespread use does not have any connection with any color and in particular with the perceived whiteness as has been realized a long time ago and mentioned on repeated occasions.

Evolution of brightness: from visual assessment to instrumental measurement.

While quite rudimentary at the beginning of application in paper mills, an early step of automation in evaluating brightness was made by developing a photometric detector capable of measuring the light reflected by samples filtrated through a blue filter. As mentioned before, by selecting a blue filter the observer concentrates in the short-wavelength region and establishes the amount of "excess" of yellow color in the reflected light (one can also express it in a complementary way by establishing the "deficiency" of blue color). The reason for focusing on the blue-yellow axis lies in the evolution of the pulp color during the bleaching process: it starts with some dark brown color that dilutes to light brown, further to tan and to diluted yellow; further improvements towards colorless become more difficult to distinguish and to assess, due to the high luminosity level of yellow colors. With the advent of instruments capable to attribute a number to the visually assessed samples standardization of modes of observation, light distribution and nature of filter became necessary; these have been summarized into a norm that establishes exact conditions for measuring brightness:

- Filter characteristics are given as transmittance factors depending on to wavelength
- Lighting conditions correspond to that of an incandescent lamp. Light can be applied in a directional way (with 45° inclination) or using an Ullbricht sphere to achieve regular, diffuse illumination of the sample.
- Mode of observation is perpendicular to sample (0° observation)

The need to establish illumination conditions arises from the fact that at the end the instrumental assessment must correlate with the original visual observation (this does not ascribe brightness a color-related value).

First instruments like GE-Photovolt were designed as direct replacement of the observer; the instrument illuminated the sample with 45° inclination and the reflected light passed a blue filter before arriving at a detector that measured the integrated intensity. Certainly one of the biggest problems (even today) was the proper calibration to a 100 full-range scale; tablets made of Magnesium oxide or Barium sulphate were used for this purpose. The basic design has not changed much ever since, modern instruments use a spectrometer for the detection of light, the filter is not physically needed, but simulated by a standardized profile to convert the reflectance factors into brightness numbers (see figure 1). Because in absence of fluorescence, reflectance factors are independent of the light source at the moment of the measurement, the former existence of the incandescent light source is integrated into the numbers defining the profile of brightness filters and given within the norm.

The question of illumination however poses further problems: most materials are not isotropic i.e. optical properties show different numbers depending on the direction of observation. When using a 45°/0° geometry (illumination with 45° inclination and perpendicular observation of the sample) a plane is defined by the elements: light source, incidence point on the sample and detector. Remarkably, paper shows a large degree of anisotropy in its properties, also in the optical ones; this can be corrected by performing numerous observations while the sample is rotated around the observation axis. A different approach is to illuminate the sample from many directions simultaneously, eliminating the need for multiple directional measurements; this is done by placing the sample at the opening of an Ullbricht sphere that produces diffuse illumination. Geometries based on diffuse illumination are denoted as d/0°. Differences in norms lie normally on the different way of sample illumination:

Norms related to determination of brightness

Illumination mode	
45° / 0°	D / 0°
Tappi 452, Tappi 646, ASTM D-985	ISO 2470, Tappi 525, Tappi 534

Contributions from multiple reflections within the sphere and sample introduce unpredictable changes in the measurement that prevent a direct correlation between results obtained with d/0° and 45°/0°, one should not attempt to transform results in either way.

Depending on the geometry involved it is usual to talk about brightness Tappi (under 45°/0°) and brightness ISO (under d/0°).

The purpose of the measurement of brightness.

While, as stated before, brightness was introduced as a method to control the bleaching process, it evolved over the time as a number giving information about optical properties of pulp and later of paper: one of the most important numbers in the specification list for pulps is the brightness value, and this is also the case for paper.

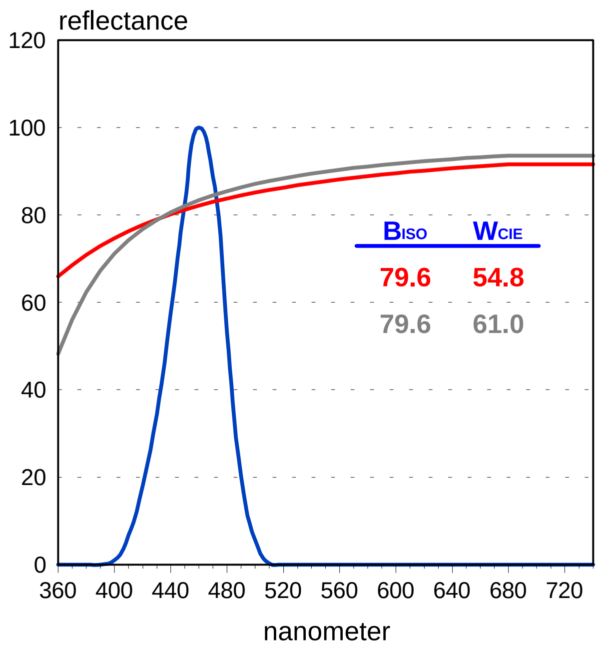

Fig 2. Different pulps may have similar brightness values but different whiteness

Following the issues reviewed in the last section, brightness cannot be seen as single number characterizing optical properties, because it focuses a too narrow part of the total visible spectrum. As a consequence of the purpose of brightness as measuring the "degree of bleaching", it became over the time a synonym of "how white the appearance of pulp (paper) is" or simply of whiteness. Whiteness is a visual perception that involves the whole spectrum from 380 to 780 nm and certainly there is no correlation between paper brightness and perceived whiteness. This is readily illustrated in figure 2, where two different pulps showing substantially different reflectance values appear to have the same brightness, but totally different whiteness (expressed as CIE values).

More striking is the fact that paper brightness fully ignores the overall spectral behavior, a point of high importance in today's papermaking.
Appearance of paper is one of its most important properties and characterization of appearance should be made as accurate as possible, in order to agree with final users; it is evident that in this respect brightness does not fulfill this demand.

Brightness and fluorescence

Today's white paper manufacturing includes the use of fluorescence to increase perceived whiteness through the application of Fluorescent Whitening Agents (FWA) as well as through the addition of small amounts of dyes known as shading agents. Their mechanisms of action are quite different from each other as well as the spectral region where they appear.

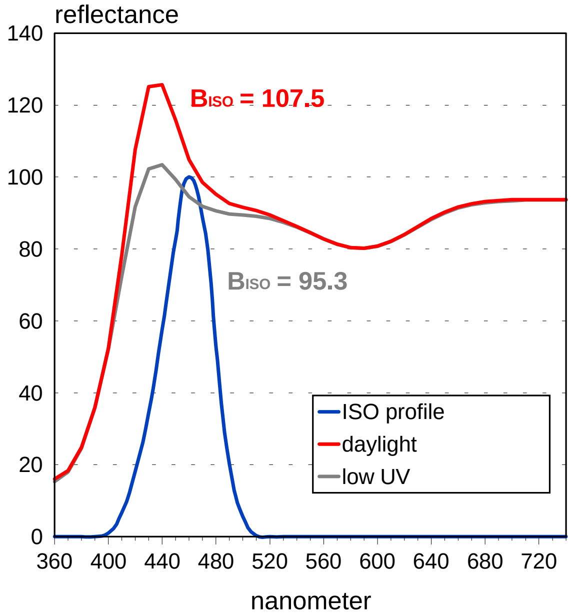

Figure 3. Spectra of a typical modern white paper showing the presence of fluorescence (peak at about 435 nm) and shading agents (absorption peak at about 570 nm).

A typical spectrum of white paper is shown in figure 3, notice the presence of strong fluorescence peaking at about 435 nm originating from the absorption of the FWA at about 360 nm, and the additional absorption at about 570 nm belonging to the shading dye.
Although there is strong overlap between the brightness profile function and fluorescence, the presence of shading dyes remains unnoticed i.e. their curves do not overlap. The consequence is that there is a dependence of paper brightness on the amount of fluorescence but none on the amount of shading dyes.
The amount of fluorescence depends on certain factors:

- Amount of FWA
- Nature of the substrate affects the efficiency of the FWA
- Amount of UV light in the environment

The third factor can be seen as a variable since its value depends on the given surrounding during observation; it follows that this is also a variable during measurement i.e. the value of the brightness depends on the amount of UV light present in the instrument at the moment of the measurement. This last fact poses an absolute demand for controlled conditions during the measurement process: the amount of UV coming from the light source of the instrument must be controlled and standardized. The effect of a deficiency in the UV amount is shown in the figure, the brightness value of the sample falls as the amount of UV decreases.

Standardization asks for observation under daylight conditions (CIE-illuminant D_{65}) in order to set the amount of UV falling onto the sample at a universal level. Discussions have arisen over the question whether the amount of UV in daylight is too high (referred to levels encountered in normal surroundings); since brightness is a technical number not related to the appearance of the sample, it is irrelevant to which level the values are based upon, as long as it is done the same way by everybody. From the point of view of fluorescence, a high content of UV produces higher levels of fluorescence allowing a better measurement and a better distinction of differences.

Fluorescence undoubtedly poses a problem for brightness measurement and interpretation; in order to distinguish brightness measured under UV-controlled conditions (implying also that the sample may show fluorescence) the term brightness D_{65} (or brightness ISO D_{65}) has been coined; this new defined brightness can take values well over the “natural” limit of 100 units.

Brightness and appearance

As stated in the last section the introduction of fluorescence poses serious difficulties for the interpretation of brightness values. The possibility of values over 100 units imply also the option of “improving” brightness values by “just adding fluorescence” during design and manufacturing of paper. This fact has led to attempts of recovering the “traditional” brightness now buried in fluorescence by eliminating the UV in the incoming light and thus eliminating the fluorescence. This is normally done by inserting UV filters with cut-off wavelengths of 400, 420 or 460 nm (see figure 4).

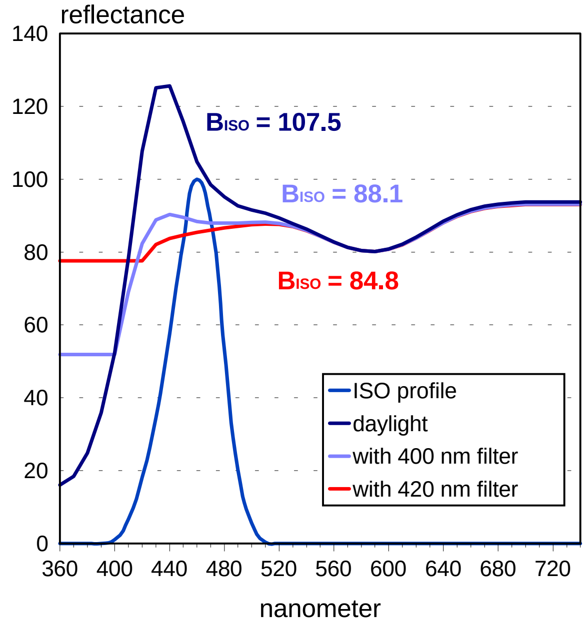

Figure 4. Reflectance values under different UV filters

Normally a 420 nm cut-off filter is used because the 400 nm is not able to effectively eliminate the fluorescence and the 460 nm filter eliminates too broad a range of the spectrum. However a problem arises from the fact that eliminated wavelengths do not produce measured reflectance values and a procedure must be found to handle these "missing" points; normally any of two procedures are applied depending on software/instrument manufacturer:

i) missing points are replaced by zero values: although many times suggested as a "good" method it has found application only in recent models; hesitation of its use is based on the fact that brightness values are going to be lower than the real ones and this induces a reluctance in their acceptance.

ii) missing points are replaced with values of the last point measured (see figure 4): this procedure has been quite popular with instrument manufacturers, however brightness values are higher than real ones because of overestimation of values in the short wavelength region.

It is clear then that no filter-assisted measurement procedure is able to produce reliable results and most reported values are results of extrapolations which have no much physical basis. Following the general working lines exposed above, "new" definitions of brightness have appeared to accommodate measurements using UV cut-off filters, like B^{+UV} and B^{-UV}, that are understood as values of brightness under full (i.e. not standardized) levels of UV and under restricted levels of UV (normally using the 420 nm UV filter). Reporting brightness values must indicate thus full experimental conditions and proper naming in order not to create (further) confusion.

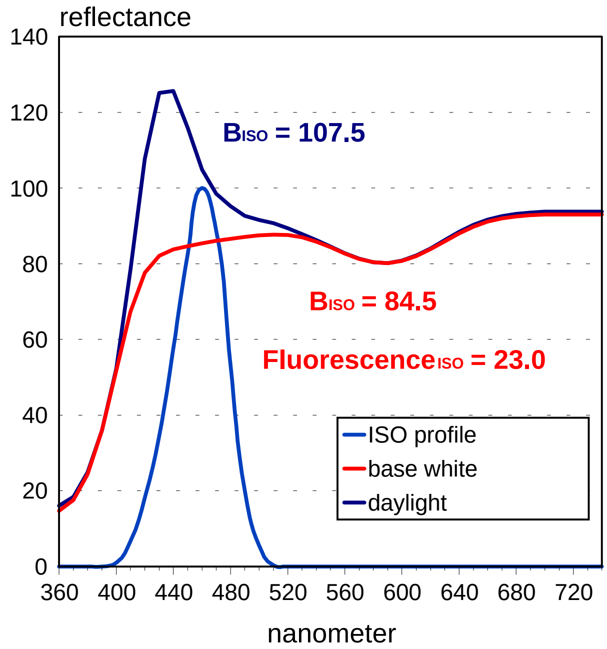

Figure 5. Separation of base white from total reflectance spectrum showing individual brightness contributions.

A different issue is the recent appearance of brightness under illuminant C, that tries to simulate brightness in an environment of reduced UV as supposed to be encountered in "normal office environments"; this is an oddity since brightness has no relationship to appearance or perceived color, as discussed above. Although illuminant C is neither a recommended illuminant of the CIE nor has its UV content been standardized, calibration samples are offered to help find the proper filter position.

A proper calculation of brightness values would involve a proper separation of fluorescence from substrate reflection in order to recover true optical values in the region of interest; this can be achieved today using instruments of the so-called "new-generation" that use a software-based "Numerical UV Control" to calculate reflectance values under different UV levels. The total separation of fluorescence assures the recovery of reflectance needed to calculate brightness values to be used in the classical sense (see figure 5); notice however that the profile of the brightness filter includes a region affected by the absorption of the FWA, a fact that leads to lower values of brightness than those supposedly shown by the original pulp substrate. This fact invalidates further use of the concept of brightness as a useful parameter for controlling appearance of manufactured paper.

A further point of application of brightness is the attempt to quantify fluorescence by defining brightness differences of those measurements performed "with" and "without" fluorescence, the latter measured using one of the procedures presented above; since the expression does not involve the substrate it can be seen as an estimation of the fluorescence present i.e. of the efficiency of the FWA present. The estimation is as good as the level of standardization of UV and the method used to "eliminate" fluorescence (see figure 4) that culminates in the determination of proper base white (see figure 5). The value receives different names as "Brightness Difference" or "ISO Fluorescence" and is regarded in general as a good piece of information about the fluorescence level of the sample. However its concept should not be over-stressed since its relationship with the amount of FWA is rather complicated; in fact, fluorescence levels are related to concentration of FWA but the amount of energy that is converted into fluorescence depends mainly on the amount of UV disposable for the FWA and its quantum efficiency, the latter being a complicated function of molecular dynamics in the substrate environment.

Thus one of the parameters, important for the energy at disposition to the FWA, is the level of substrate absorption in the UV area (most of FWA have an absorption maximum in the 350-360 nm region).

A critical examination of the significance of paper brightness

The need to control the bleaching process of pulp by measuring brightness has persisted until today, in fact most of specifications ask for a determined level of brightness as a criterion to stop this step; the value of brightness of pulp is still one of the most important characteristics and used as pass/fail criteria. The introduction of new bleaching processes and the emergence of different fiber types (derived in part from the effort to reduce the use of chlorine in the bleaching step) and the partial use of recycled fibers has resulted in a variety of reflectance spectra for "bleached pulp" that leads to situations as illustrated in figure 2. In fact the pulps presented on the figure would pass as "equal" through a Quality Assurance System with specifications based just on brightness (either ISO or Tappi); problems using both pulps of the example can be anticipated as follows:

- The pulp with the green curve has less whiteness because the relative amount of yellowness is higher; this will lead automatically to a higher demand of FWA to compensate the additional yellowness.
- The situation turns worse when looking at the 360 nm region, the pulp is not only yellower but has a higher absorption in the UV region; it follows that UV light for FWA (at the end also the amount of fluorescence) will be lower and the apparent efficiency of the FWA will automatically decrease, thus requiring a higher amount of FWA to achieve specified end brightness.
- Since final spectra will differ markedly, it follows that both samples will not appear the same (they never looked the same in the first place, see figure 2), even if the amount of FWA is drastically increased to raise whiteness.

The only way to save the situation presented here is by adding a small amount of a shading agent to the pulp of lower whiteness with the goal of raising it and match the whiteness of the other sample; while this could appear a feasible solution one should not forget that:

- The higher absorption in the UV region will lead to a still higher increase in the usage of FWA
- The new sample will contain different amounts of subtractive and additive whiteness components that will lead to an increased metameric effect of the samples (one should try here to use an invariant shading method); this results in different appearances upon changes in illumination during observation.
- Depending on the nature of shading applied, opacities of both samples may differ in such extent that both samples will not appear identical to the observer

The presence of shading agents does not affect the value of brightness in any manner, in other words, after brightness values for both samples match (notice that although fluorescence values will be comparable, the amounts of FWA used do not), any addition of shading dyes will affect whiteness to some extent, but brightness values will remain unchanged.

Conclusions

To summarize the points exposed above as:

- Brightness is not a parameter related to color of substrate; actually it is not even connected to its appearance. It is a number related to the color of substrate viewed under a blue stained glass.
- Brightness is related to reflectance values in a narrow region of the total visible spectra around 460 nm. Due to this limitation, values of brightness cannot be connected or correlated to (white) appearance of pulp or manufactured paper, not even in those cases where no FWAs are applied.
- The limited wavelength region described by brightness is also a limitation in any process that attempts to control modern bleaching processes. Since FWAs are used in following steps of paper manufacturing, total whiteness values and reflectance values in the UV region are of crucial importance to assure constant quality of white paper.

Considering these points is to conclude that brightness has become an obsolete parameter in modern paper manufacturing and its use should be dropped in favor of more informative parameters as given by modern formulas for whiteness (for white paper) and yellowness (for bleached pulp); control of white paper manufacturing should aim to separate the three components contributing to whiteness in order to allow a one-to-one control based on dosage of FWA, shading agents, etc. Control of bleaching units can be achieved effectively by on-line mo-nitoring of the UV region and con-trolling dosage pumps of chemicals directly to reach the bleaching levels required, a control system of this type aims directly at final paper quality rather than temporal appearance of bleached pulp.

References

J.-A. van den Akker, L.R. Dearth and W.-M. Shillcox
”Is the Concept of Standard Brightness Suitable Today?"
TAPPI 1963, 46(May), 202A-207A

A.-S. Stemius
”Is the Concept of Standard Brightness Suitable Today?"
TAPPI 1963, 46(November), 183A-187A

J.-A. van den Akker, L.R. Dearth and W.-M. Shillcox
”Is the Concept of Standard Brightness Suitable Today? Reply to Ake S:son Stenius"
TAPPI 1963, 46(November), 187A-190A

J.A. Bristow
“The Calibration of Instruments for the Measurement of Paper Whiteness”
Color Res. Appl. 1994, 19(6), 475-483

J.A. Bristow
“What is ISO Brightness?”
Tappi J. 1994, 77(May), 174-176