

Photoyellowing of mechanical pulps

Part 2: Activation spectra for light-induced yellowing of newsprint paper by polychromatic radiation

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ABSTRACT: *An exposure technique using cut-on filters to define the effect of different spectral regions determined the activation spectra for solar-simulated UV radiation-induced yellowing and brightness reversion of newsprint. Wavelengths between 335–380 nm caused the maximum yellowing and brightness reversion. Wavelengths transmitted through window glass therefore cause much of the photodegradation from solar radiation. There were changes in pH of water extracts of samples exposed to UV and visible radiation. Under polychromatic radiation in the visible region, the UV absorption peak decreases and the pH increases with wavelength.*

KEYWORDS: *Brightness, color reversion, mechanical pulps, newsprint, spectra, ultraviolet radiation, wave lengths, yellowing.*

Light-induced yellowing and brightness reversion of mechanical pulps is a common phenomenon that limits wider use of these more economical pulps in a variety of consumer products. The detailed mechanism of photoyellowing remains unclear despite recent research. A better understanding of the wavelengths responsible for yellowing and the brightness reversion process could obviously aid the development of techniques to control the phenomenon.

Lignin is 29–33% by weight of softwood mechanical pulps (1). It contains many chromophores and is a very efficient absorber of UV radiation and visible light. While holocellulose does absorb UV radiation, 80–95% of the absorption coefficient of wood is due to the lignin fraction (2). Hon and Glasser (3) compiled a list of potential chromophoric entities present in lignin.

Absorbed light energy starts a complex series of reactions that lead

to readily observable changes in lignin. These include cleavage of methoxy groups and formation of low molecular weight decomposition products of lignin. Electron spin resonance studies (4, 5) suggest that reactions of irradiated lignin and amorphous cellulose fractions of wood involve free radicals. A lignin fraction undergoing photodegradation (3) produces compounds such as quinones, quinone methides, and stilbenes. These impart a yellow color to pulp (6, 7). Carbonyl functional compounds like the β -aryl ether materials commonly found in lignin (8) are efficient chromophores.

Arylglycerol- β -aryl ether units abundantly present in softwood lignin might oxidize or photoconvert to carbonyl structures that are also efficient light absorbers. Gierer and Lin (9) proposed that excitation of these carbonyls causes the formation of substituted phenoxy radicals and an α -ketone or α -ketol through hydrogen abstraction. Phenoxy radicals may oxidize into *o*- and *p*-quinones (10). These are colored compounds. An excited carbonyl group may also yield singlet oxygen during energy transfer. This may directly oxidize substituted phenols into quinones (6). Alkylation of pulp (11) to block the phenolic hydrogen content and borohydride reduction to reduce the ketone group content (11, 12) both result in a decrease in the light-induced yellowing of mechanical pulps. Heitner (13) recently reviewed and summarized the vari-

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I. Activation spectrum of newsprint paper using increase in yellowness by xenon-arc radiation through cut-on filters

Cut-on filter no.	5% trans. wavelength, nm	Increase in yellowness*	Filter pair	Band pass at 20% trans., nm	Change in yellowness	Normalized YI change
00	238.2	25.75	00-2	258–282.5	0	0
2	262.5	25.75				
3	280.2	25.71	2-3	273.5–294	0	0
4	295.0	25.51	3-4	287.5–305.5	0.20	0.20
5	303.5	25.07	4-5	300–320	0.44	0.40
6A	313.2	25.14	5- 6A	308.5–327	0.93	0.93
6B	318.0	22.70	6A-7	319–339.5	1.47	1.38
7	322.5	-	6B-8	324–344	0.75	0.71
8	328.1	21.95				
9	337.7	18.67	8-9	334–354.5	3.28	3.08
10	339.7	19.11				
11	352.4	16.52	10-11	346.5–365	2.59	2.82
12	359.1	13.26	11-13	359–381.5	2.99	2.78
13	360.5	13.53	12-14	367.5–387	1.25	1.45
14	367.5	12.01				
15	373.0	10.80	14-15	379–403	1.21	1.23

*Change in YI after exposure for 13.8 h

ous reaction pathways involved. While cellulose also can photoyellow, the discoloration of the lignin component in mechanical pulps occurs more rapidly. It is the predominant factor causing light-induced yellowing.

Light-induced reactions of synthetic polymers depend on wavelength. Energetically shorter wavelength radiation causes faster photoyellowing and other photo damage (14). This is also true of lignin-containing pulps where UV radiation commonly causes the most damage (15). Andrady *et al.* reported in the first part of this paper on the wavelength sensitivity of yellowing in newsprint exposed to monochromatic

radiation (16). Yellowing occurred with exposure to radiation of wavelengths between 280–340 nm. The efficiency of yellowing—change in yellowness index (YI) per available photon—decreased logarithmically with increase in wavelength of irradiation. Other investigations also report such a logarithmic relationship for several synthetic polymers (14, 17) and provide a quantitative description of wavelength dependence of the yellowing of newsprint paper by monochromatic light. In addition, exposure of paper samples to wavelengths of 400 nm, 500 nm, and 600 nm resulted in photobleaching—a reduction in the YI of the paper.

A study of jute containing 13% lignin using a narrow band filter technique showed maximum photoyellowing in the interval of 330–370 nm (18). Forsskåhl *et al.* (19) recently reported the activation spectra for yellowing of several bleached and unbleached chemimechanical refiner pulps exposed to monochromatic radiation. Photo-yellowing was most extensive in the wavelength interval 310–320 nm. Photobleaching by longer wavelengths of radiation is interesting from a practical standpoint. Sunlight contains both UV radiation causing yellowing and longer wavelength light that causes bleaching. The yellowing process observed on exposure of newsprint paper to

II. Activation spectrum of newsprint paper using decrease in brightness by xenon-arc radiation through cut-on filters

<i>Cut-on filter no.</i>	<i>5% trans. wavelength, nm</i>	<i>Decrease in brightness[*]</i>	<i>Filter pair</i>	<i>Band pass at 20% trans., nm</i>	<i>Change in brightness</i>	<i>Normalized brightness change</i>
00	238.2	-11.41				
2	262.5	-11.46	00-2	258–282.5	0	0
3	280.2	-11.20	2-3	273.5–294	0.26	0.29
4	295.0	-11.24	3-4	287.5–305.5	0	0
5	303.5	-11.05	4-5	300–320	0.19	0.17
6A	313.2	-10.31	5-6A	308.5–327	0.74	0.74
6B	318.0	-9.01	6A-7	319–339.5	1.22	1.15
7	322.5	-9.09	6B-8	324–344	0.75	0.71
8	328.1	-8.26				
9	337.7	-5.90	8-9	334–354.5	2.36	2.22
10	339.7	-5.42				3.08
11	352.4	-4.43	10-11	346.5–365	0.99	1.08
12	359.1	-1.91	11-13	359–381.5	2.77	2.58
13	360.5	-1.66	12-14	367.5–387	1.16	1.35
14	367.5	-0.7				
15	373.0	0.07 ^{**}	14-15	379–403	0.82	0.84
16	406.7	2.35 ^{**}				
17	420.3	2.37 ^{**}				

^{*}Change in brightness after 13.8 h exposure
^{**}Increase in brightness

sunlight is therefore the net result of competing yellowing and bleaching processes.

An activation spectrum best describes the relative effectiveness of different parts of the spectrum emitted by a specific light source such as sunlight in causing discoloration of a substrate. The aim of the present study was to generate the activation spectrum of newsprint paper to photoyellowing and brightness reversion by polychromatic radiation. There would also be a comparison to findings from a previously reported study (16) on exposure to monochromatic radiation.

Activation spectra

An activation spectrum is a plot of the relative extent of photoconversion—yellowing or brightness reversion—resulting from different spectral regions of the source spectrum. It varies with the type of light source and the nature of photoconversion studied. The data in this paper pertains only to the UV wavelengths in filtered xenon-source radiation.

A series of sharp cut-on filters determined the relative effects of narrow bands measuring 20 nm of UV radiation from a borosilicate-filtered, xenon-arc source. A separate sample of the same test material undergoes

exposure to the light source behind each filter simultaneously for the same time. Determination of the YI, the brightness, or both for each sample was made before and after exposure. The difference in degradation of two samples exposed behind a pair of adjacent filters in the set was the incremental change in properties caused by each added spectral portion. Normalization of the incremental degradation gave equal spectral increments of radiation to plot against the spectral band pass of the pairs of filters to obtain the activation spectrum. The relative extent of degradation by different spectral regions depends on two factors. One is the wavelength sensitivity of

III. Contribution of heat radiation to change in yellowness and brightness of newsprint paper exposed behind cut-on filters

Cut-on filter no.	5% trans, wavelength, nm	Hours exposed	Front of sample		Back of sample	
			YI change	Brightness change	YI change	Brightness change
2540	870	3.4	+1.6	-1.4	-	-
		14.1	+1.6	-1.2	+1.3	-1.0
2418	600	3.4	+3.9	-1.4	-	-
		14.1	+7.3	-1.9	+6.5	-1.7
3384	496	3.4	+5.5	-1.1	-	-
		14.1	+9.3	-0.5	+9.3	-1.2

the material, and the other is the intensity of radiation—the relative number of photons in the different spectral regions. The spectral irradiance distribution of the source spectrum gives the latter.

Determination of the wavelength sensitivity ideally comes from experiments involving exposures to equal intensities of monochromatic radiation. Alternatively, there can be adjustment to normalize the degradation data coming from exposure to radiation of different intensities to the effect of equal intensities. A plot of the relationship obtained between wavelength of exposure and efficiency of degradation is the action spectrum. Using this with the spectral power distribution of the light source provides a calculation of the activation spectrum. The degradation measured is assumed to be linearly dependent on the intensity of the light. Neither synergism nor antagonistic effects by multiple wavelengths are also assumed.

Experimental

Paper samples

The study used sheets of newsprint paper with basis weight of 48 g/m² made from unbleached loblolly pine

IV. Change in pH and UV absorbance at 277–279 nm of paper samples exposed to different spectral regions

Monochromatic radiation			Xenon-arc radiation through cut-on filters		
Wavelength, nm	pH	Absorbance	Wavelength*, nm	pH	Absorbance
control	5.48	0.43			
280	4.66	1.57	>303.5	4.5	0.787
300	4.67	1.33	>322.5	4.12	0.728
320	4.75	1.14	>339.7	4.24	0.632
340	4.83	1.01	>360.5	4.87	0.492
400	4.89	1.01	>406.7	5.23	0.306
500	4.83	0.48	>492.4	5.35	0.213
600	4.94	0.48	>600.3	5.44	0.242

*The 5% transmission of the cut-on filter used (sample exposure to all wavelengths longer than the wavelength shown)

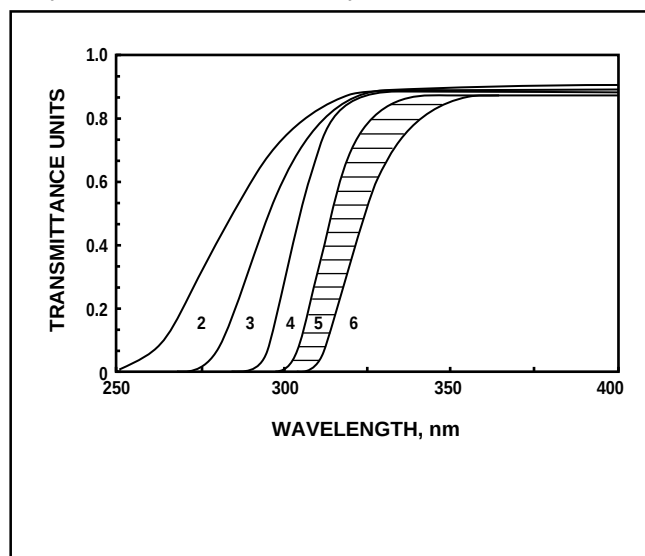
(*Pinus taeda*) TMP pulp. Samples came from a commercial supplier of newsprint paper.

Exposure to light

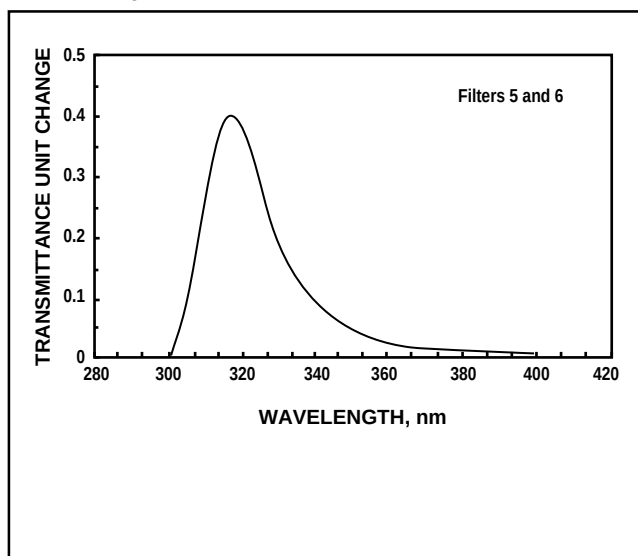
Sheets of newsprint paper measuring 2.5 in. x 2.5 in. underwent exposure behind different cut-on filters to a double borosilicate-filtered, xenon-light source of 6500 W in a commercial unit. The set of 16 cut-on filters covered the wavelength range of 238–373 nm at the 5% transmis-

sion wavelength. **Table I** identifies the different filters by a code number and by the wavelength at 5% transmission. **Figure 1** shows the UV transmission spectra of filters 2–6A, and **Fig. 2** illustrates the spectral band obtained by subtracting the transmittance of filter 6A from that of filter 5. The band passes at 20% transmittance are the spectral regions used for the activation spectra.

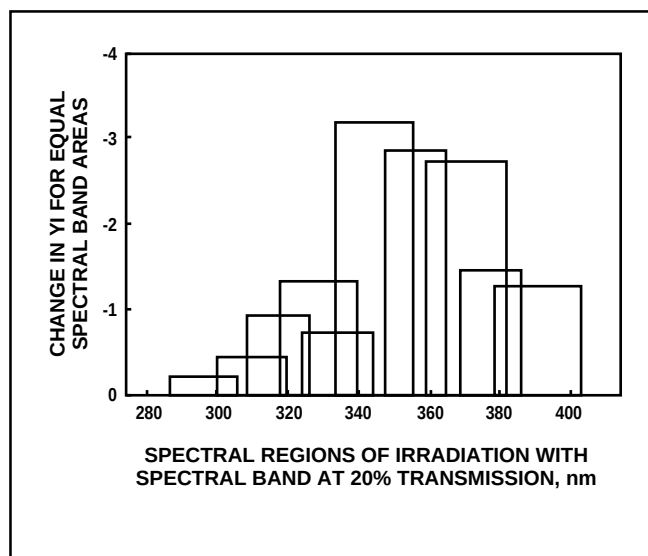
1. Transmittance characteristics of five cut-on filters used in the study with filter code from Table I by the curves



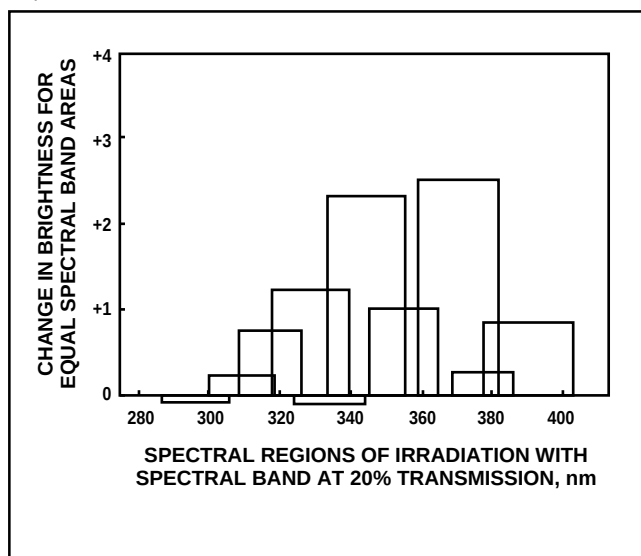
2. Difference in transmittance between filters 5 and 6A, i.e., the area shaded in Fig. 1



3. Activation spectra for yellowing of newsprint paper exposed to borosilicate-filtered, xenon-arc radiation for 13.8 h



4. Activation spectra for brightness reversion of newsprint paper exposed to borosilicate-filtered, xenon-arc radiation for 13.8 h



Yellowness and brightness measurements

A commercial colorimeter with an integrating sphere determined YI according to American Society for Testing and Materials D 1925-70 by reflectance measurements. The specimens had a backing of white-ceramic, standard-reference tile. The measurement included the UV component of the incident light and ex-

cluded the spectral component of the reflected light. YI used commercial standard observer viewing. This came from the tristimulus values X, Y, and Z using the following equation:

$$YI = [100(1.28X - 1.06Z)]/Y \quad (1)$$

ASTM D 1925 describes the procedure more completely, and ISO 2470-1973 describes the brightness measurements.

Determinations of sample pH and UV absorbance of extractives

Testing involved cutting a 1.00 g sample of paper into approximately 5 mm squares and placing them in 70 mL of distilled water. After maceration and allowing the sample to stand covered for 3 h, a laboratory pH meter measured the pH of the water. TAPPI Test Method T 410 om-88 describes the test procedure. Absorbance measurement used the

Photodegradation

same solution with a commercial spectrophotometer.

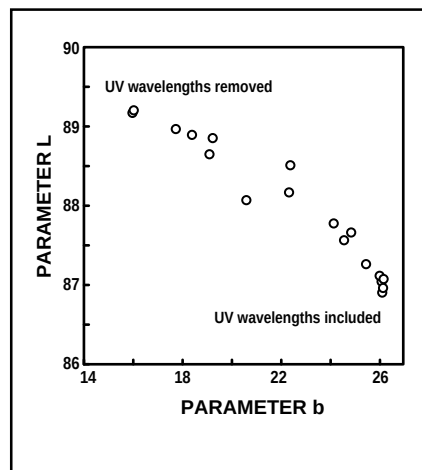
Results and discussion

Activation spectra for yellowing and brightness

In a previous study (15), exposure of newsprint paper to monochromatic light caused yellowing in the wavelength range of 280–340 nm. The change in yellowing per available photon was logarithmically dependent upon the wavelength of irradiation. Higher-energy, shorter wavelengths caused more yellowing. This logarithmic dependence results from the different energies of photons of varying wavelengths and the wavelength dependence of light absorbance by paper.

Figure 3 shows the activation spectrum for yellowing by borosilicate-filtered, xenon-arc radiation for 13.8 h at 69°C. The wavelength region of 335–380 nm caused the maximum change in YI. The photon energy at these wavelengths is much less than at shorter wavelengths such as 280 nm. The much larger numbers of longer wavelength photons in the filtered xenon-arc source more than compensate for this. A second activation spectrum for yellowing at the same temperature for 3.5 h exposure (not shown) had the same general features and the maximum yellowing in the same spectral interval. Table I gives the data for the YI, and **Table II** gives the data for brightness of samples exposed behind different cut-on filters. **Figure 4** shows the corresponding activation spectrum for change in brightness of newsprint samples. Since activation spectra are source-dependent, it is only possible to compare the data here to data generated using a similar source. Holmbom and Gratzl (20) reported changes in brightness of CTMP exposed behind a series of cut-on filters with spectral range of 294–524 nm to filtered xenon-arc radiation. While there was no determination of activation spec-

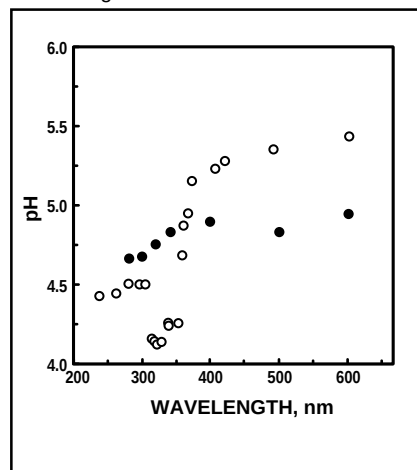
5. Parameters L and b from tristimulus measurements for samples exposed behind cut-on filters with each data point representing a filter in Table I



tra, the results indicate that yellowing occurred with filters that allowed radiation of wavelength greater than 396 nm to reach the sample. At longer wavelengths of 396–420 nm, photobleaching predominated. This agrees qualitatively with previous work (15). The slight increase in brightness in the interval 370–420 nm in this study is consistent with observation of photobleaching in these references.

This study compared the yellowing per photon values obtained using polychromatic radiation to that from previously published monochromatic exposure results. Using estimates of irradiance (W/m^2) for the borosilicate-filtered, xenon-arc source in the commercial unit from its manufacturer, it is possible to calculate the number of photons of a given wavelength received at the sample location over 13.8 h. Change in YI per available photon reported by Andradý (15) provides the change in yellowing expected from exposure to that photon flux. This was only possible for the specific wavelengths in the previous study. One cannot compare the size of these calculated or expected changes in yellowness directly to the measured data because of the different techniques and exposure conditions in the two studies. There was good agreement, how-

6. Change in pH of paper samples exposed to monochromatic radiation (closed circles) and to borosilicate-filtered, xenon-arc radiation through different cut-on filters



ever, for the general features of wavelength dependence. Using the calculated yellowing obtained at 340 nm as unity, the calculated data gives relative yellowing values of 0.60 at 320 nm, 0.14 at 300 nm, and 0.02 at 280 nm. The relative values of yellowing from the experimental data for activation spectrum in Fig. 3 using the 319–340 nm band as one are 0.67 for 309–327 nm, 0.14 for 287–305 nm, and 0 for 273–294 nm. Such agreement would occur only if the degradation is a linear function of intensity. The agreement also suggests that the role of photobleaching by longer wavelengths of radiation minimally affects yellowing of a sample.

YI is a composite index that quantifies the visual degree of yellowness but not necessarily the change in pure yellow hue due to photodegradation. Such details are better understood in terms of the Commission Internationale de l'Eclairage (CIE) parameters L, a, and b calculated from the measured tristimulus values. In discussing yellow hue, the b dimension measuring yellowness is the most important consideration. Large positive values of b signify deeper yellow hues. Large negative values associate with blue. The value of L varies from 0 (black) to 100 (white) and is a scale for lightness of

the material. An L vs. b plot such as **Fig. 5** best illustrates changes in whiteness of paper. Each data point represents the measurement relating to paper exposed under a filter listed in Table I. The filter with the shortest wavelength cut-on is at the right, lower end of the figure. As the filters progressively allow less UV radiation in white light to pass, the data points shift in a direction of higher L (increased lightness) and lower b (decreased yellowness) values for the same duration of exposure.

Thermal component of yellowing

Thermally-induced yellowing (21) occurs in mechanical pulps and in bleached paper containing only a trace of lignin. The light exposures of this study were carried out at 67°C. While the cut-on characteristics of the filters should not greatly affect their transmittance in the visible and infrared region of the spectrum, small differences in temperature of samples under different filters is possible. It was therefore of interest to determine the component of yellowing obtained assignable to thermal effects.

An attempt to do this involved exposing newsprint-paper samples to filtered xenon-arc radiation behind four additional cut-on filters for 3.4 h and 14.1 h. These are equivalent to 3.9 kJ/m² at 340 nm and 15.4 kJ/m² at 340 nm, respectively. **Table III** shows the data.

Filters 2540 and 2418 are long-wavelength, cut-on filters that transmit the infrared (IR) part of the white light spectrum and block all of the UV and most of the visible light. Note that samples exposed behind these filters underwent a change of about 1.5 to 7 YI units, respectively, during 14 h of exposure. The change of about 1.6 units with Filter 2540 is significant (measurement of YI has a precision of ± 0.5 units) and indicates a measurable effect of thermal yellowing under the present exposure conditions. Allowing light of

wavelength above 600 nm to reach the paper enhances the yellowing process considerably. This is not surprising considering that the present newsprint-paper samples reflected less than 70% of the incident light between 600–700 nm. They therefore absorb a considerable amount of this long-wavelength radiation. Chromophores absorbing in the red region of the spectrum can apparently promote thermal yellowing or contribute to photoyellowing. Using Filter 3384 to allow more visible radiation to interact with the paper further increases the yellowing.

The percentage of yellowing assigned to thermal mechanisms depends upon the filter used. Assuming all the yellowing obtained with Filter 2540 is solely due to the effect of heat, the following approximate fractional contributions of thermal effect come from the other two filters:

- Filter 2418: 40% at 3.4 h and 22% at 14.1 h
- Filter 3384: 28% at 3.4 h and 17% at 14.1 h.

All filters in Table I have cut-on wavelengths shorter than 496 nm. The fraction of thermal yellowing from them must therefore be considerably less than 17%. YI of the reverse side of the newsprint-paper samples show that discoloration occurred to the same extent on both sides of the paper when using all three filters. This is consistent with the conclusion that the yellowing is due to heat or wavelengths of light or both that can penetrate the low basis weight sheet. In all instances, increases in yellowness affected the brightness of the papers. The two measurements do not relate simply or directly, however. While the brightness decrease was greater with Filter 2418 compared with Filter 2540, adding additional visible light with Filter 3384 reduced the effect on brightness. In contrast, the yellowness increased further.

Changes accompanying yellowing

Light-induced yellowing of wood and pulp generates chromophoric materials that absorb in the UV and visible regions of the spectrum (3, 22, 23). Acidic products are also produced (24). Measure of these provides another means of following the light-induced degradation of the samples. Accordingly, there was a comparison of the UV absorption and pH measurements of the paper extracts with the colorimetric data for YI to determine the relationship between these processes.

Table IV shows the changes in pH and UV absorbance at the absorbance maximum of 277–279 nm for the water extracts of the paper samples exposed to monochromatic radiation in a previous study (15) and those listed in Table I. **Figure 6** is a plot of the changes in pH. The wavelength in the figure is 5% transmission of filter. Under exposure to monochromatic radiation, visible and UV wavelengths reduce pH with UV causing a larger change. Exposure behind cut-on filters results in a smaller change by visible radiation and a progressively larger change as the cut-on wavelengths shift to shorter wavelengths. The decrease in pH with decreasing wavelength parallels the wavelength sensitivity of the yellowing process. This suggests that the primary photochemical reactions that cause yellowing also lead to the formation of acidic, water-extractable products.

It appears that the monochromatic wavelengths of 500 nm and 600 nm that caused bleaching rather than yellowing gave a significant decrease in the pH of the paper. The data on pH is not sufficient to conclude unambiguously that the photobleaching process involves the acid-producing photoreactions. This is a possibility, however.

The UV absorption band of the water extract increases rapidly with decrease in wavelength of irradiation. In the visible region, the polychromatic radiation causes a decrease in the peak absorbance.

Photodegradation

This is an unexplained phenomenon that could account for the smaller effect by polychromatic radiation.

Conclusions

The most significant conclusion from the study is that the amount of photoyellowing or brightness reversion for newsprint paper exposed to polychromatic radiation (similar to terrestrial sunlight) varies with the spectral region of exposure. The 330–385 nm region of the sunlight spectrum or UV-A region causes the largest amount of yellowing. Window glass that filters most UV-B radiation in sunlight can therefore still transmit wavelengths that can cause considerable amounts of yellowing or brightness reversion in newsprint paper. The spectral characteristics of display and indoor lighting conditions will also affect the lifetime of historic documents and printed matter displayed under library or museum conditions. Minimizing UV light with wavelengths less than 385 nm reaching the paper will ensure much slower discoloration.

In the UV region, decrease in brightness parallels increase in yellowing of paper samples. Both become progressively larger as the cut-on wavelength of the filters shifts to shorter wavelengths. Under visible radiation, however, loss in brightness does not correlate with the increase in yellowing. While visible polychromatic radiation (particularly the wavelength interval 370–420 nm) produces significant

increase in yellowing, it causes an increase rather than a decrease in brightness.

The UV absorption peak at 277–279 nm of the aqueous extract of paper increases progressively with decrease in wavelength of exposure to UV radiation. Exposure to polychromatic visible radiation, however, reduces the absorbance of the aqueous extract of the unexposed paper samples. The photobleaching detected by exposure to monochromatic light in the visible region was not evident on exposure to polychromatic light.

The acidification of paper that accompanies photodegradation contributes to reduced permanence of mechanical pulps. An interesting conclusion of this study is that acidic reaction products form not only during yellowing of paper but also to a reduced extent during photobleaching of paper by monochromatic radiation in the visible region. ■

Literature cited

1. Timell, T. E., *Wood Sci. Tech.* 1(1):45(1967).
2. Norrstrom, H. *Svensk Papperstidn.* 72(2): 25(1969).
3. Hon, D. N.-S. and Glasser, W., *Plast. Tech. Eng.* 12(2): 159(1979).
4. Hon, D. N.-S. and Feist, W. C., *Wood and Fiber* 12(2): 121(1980).
5. Andrady, A. L. and Jahan, S., personal communication.
6. Gellerstedt, G. and Patterson, E., *Svensk Papperstidn.* 80(1):15(1976).
7. Lin, S. Y. and Kringstad, K. P., *Norsk Skogindustri* 25(9): 252(1971).
8. Brunow, G. and Eriksson, B., *Acta. Chem. Scand.* 25(7): 2779(1979).
9. Gierer, J. and Lin, S. Y., *Svensk. Papperstidn.* 75(7): 233(1972).
10. Kringstad, K. P. and Lin, S. Y., *Tappi* 53(12): 2296(1970).
11. Leary, G. J., *Tappi* 51(6): 257(1968).
12. Lin, S. Y. and Kringstad, K. P., *Tappi* 53(9): 1675(1970).
13. Heitner, C., in *Photochemistry of Lignocellulosic Materials* (C. Heitner and J. C. Sciano, Eds.), American Chemical Society, Washington, 1993, p. 2.
14. Andrady, A. L., in *UV-B Radiation and Ozone Depletion: Effects on Humans, Animals, Plants, Microorganisms and Materials* (M. Tevini, Ed.), Lewis, London, 1993, pp. 193–240.
15. Norlan, P. A., Van den Akker, J. A., and Wink, W. A., *Paper J.* 121(11): 33(1945).
16. Andrady, A. L., Song, Y., Parathasarathy, V., et al., *Tappi J.* 74(7): 185(1991).
17. Andrady, A. L., Searle, N. D., Crewdson, L. F. E., et al., *Polymer Degrad. and Stab.* 35: 235(1992).
18. Bag, S. C., *Cellul. Chem. Tech.* 18(2): 149(1984).
19. Forsskahl, I. and Tylli, H., in *Photochemistry of Lignocellulosic Materials* (C. Heitner and J. C. Sciano, Eds.), American Chemical Society, Washington, 1993, p. 45.
20. Holmbom, B. and Gratzl, J., *Factors Influencing Light-Induced Yellowing and Bleaching of Spruce Groundwood*, North Carolina State University, Raleigh, 1986, pp. 347–351.
21. Forsskahl, I. and Janson, J., *Nordic Pulp Paper Res. J.* 6(3): 118(1991).
22. Feist, W. C. and Hon, D. N.-S., *Adv. Chem. Ser.* 207: 401(1984).
23. Yoshimoto, T., *Mokuzai Gakkaishi* 18(2): 49(1972).
24. Hon, D. N.-S., in *Wood and Cellulosic Chemistry* (D. N.-S. Hon and N. Shiraishi, Eds.), Marcel Dekker, New York, 1990, p. 525.

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