Effect of Dry Time on Rate of Image Change in Xenon, Ozone, and Humidity Tests

Matthew Comstock, Ann McCarthy; Lexmark International, Inc.; Lexington, Kentucky, USA

Abstract

The digital print industry is working toward the goal of adopting improved test methods for image permanence. As part of this effort, new test methods are being designed to enhance test repeatability and reproducibility between laboratories. This study focused on the impact of dry time on the performance of inkjet print samples in Xenon, ozone, and humidity fastness experiments. The data collected in this study is useful for determining appropriate dry times for image permanence tests involving inkjet print samples. This research is part of ongoing work contributing to the development of standardized test methods for image permanence.

Introduction

Durability of printed images is assessed through a variety of image permanence tests. Particular digital printing technologies, such as inkjet, require a period of curing and image stabilization after printing, known as 'dry time'. The dry time must be factored into print quality and print image permanence tests because color measurements and physical properties of the colorant on the media are affected by dry time. This study examined the impact of dry time in three types of image permanence tests: humidity fastness, ozone stability, and Xenon light stability. The purpose of investigating these three tests was to understand the influence of dry time on the test results and balance requirements for predicting realistic long term customer performance along with being able to collect timely data during product development.

Experiment

The following equipment was used in testing:

- Teledyne 400E UV Absorption O3 Analyzer
- Kahn Optidew Bench chilled mirror hygrometer
- Ocean Optics HR4000CG-UV-NIR Spectrometer
- Minolta T-10M Illuminance Meter
- ESPEC ESL-4CW environmental chamber
- Atlas Ci4000 Xenon Weather-Ometer
- SATRA/Hampden Model 903 ozone chamber
- Gretag Spectrolino/Spectroscan

Because not all print systems are affected by dry time, the scope of this study was limited to consumer inkjet printers. A total of 14 unique printer media systems were tested. To minimize variability in the test results, all samples from a given ink media system were tested simultaneously. This was accomplished by staggering the print times of the samples so that all samples were ready to begin testing together. To further ensure consistency in the test data, the same ink cartridges were used to generate all test samples on a given printer. Samples were dried in an ozone free environment at 23C/50% relative humidity.

Due to limited chamber space, the test was divided into two groups. The first group used the following dry times for the humidity test: 1 day, 3 days, 1 week, 2 weeks, and 6 weeks. And for the Xenon and ozone tests: 3 days, 1 week, 2 weeks, and 6 weeks. After examining the results from the first group it was decided to eliminate the 1 week dry time samples from the second test group.

Earlier work has been done with respect to dry time and humidity fastness testing [1]. Following the recommendations of that work, the humidity test was run at 30C/85% relative humidity and an average delta E was calculated. The test target used was based on the modified humidity fastness target with checkerboard patterns as shown on the left side of Figure 1.

The ozone test was run at a concentration of 5 ppm ozone and 23C/50% relative humidity. The Xenon test was configured with a borosilicate inner filter and soda lime outer filter to simulate sunlight through window glass. Sample illumination was maintained at 80 klux as determined from measurements at the sample. The chamber environment was kept at 23C/50% relative humidity and the sample temperature was approximately 28C.

Figure 1. Humidity Fastness Test Target (left, 84 patches)). Ozone and Xenon Light Stability Test Target (right, 40 patches).

The ozone and Xenon light stability tests used a simple KCMY test target as shown on the right side of Figure 1.

Although the intent of the image file was to isolate pure ink colorants, some printer drivers may have mixed ink colorants to produce the cyan, magenta, and yellow patches.

All test samples had a replicate, but the replicate could not be tested under identical conditions for all the tests. The humidity chamber was capable of testing all samples and their replicates together at the same conditions. The ozone chamber had samples mounted on a rotating carousel, but half the samples were mounted facing outward on the carousel while the other half (the replicates) were mounted facing inward. Both sets of samples saw the same environmental conditions and ozone concentration, but the inward facing samples had a lower average airflow. This provided an opportunity to study the effect of airflow by comparing the two sets of samples; however, when studying dry time it was necessary to check trends for each mounting position separately. A similar problem existed with testing in the Xenon chamber. The Ci4000 has three racks for mounting samples which then rotate around the lamp. Previous measurements had shown some variation between these three positions. A full set of samples was mounted in the middle rack, and the replicates were distributed on the top and bottom racks—each is smaller than the middle rack and could not accommodate all the replicates, but all dry times for a given system were tested on the same rack and could likewise be compared as a group.

Results and Discussion

All three image permanence tests used samples prepared from the same set of printers and media. Eleven commercially available consumer printers (designated by a number) were tested in combination with eight commercially available photo media (designated by a letter). Media G and H were swellable, while the rest were porous. Although a subset of the first group of test samples had dried for 1 week—that data has been omitted for conciseness. Printers 1 through 7 used dye based ink while printers 8 through 11 used pigment ink. All tabular data is organized by dry time, not test time.

Humidity

Table 1 shows the average delta E calculated from the data measurement after 2 weeks of testing. The data is an average of two sample replicates; however, differences up to 0.5 delta E may be within the noise of this test. An example of a noisy data set was from System 2B which varied from 13.1 to 14 delta E with no trend.

During testing it was observed that the 6 week dry time samples of system 1G were close to the return air vent in the chamber during the first test cycle. The positioning of the samples was adjusted to prevent this in further test cycles. By the fourth week of testing the delta E between the 2 week and 6 week dry time samples was equal, although the 6 week dry time samples had changed more at the beginning of the test. Based on observation, it was concluded that the higher airflow at the return vent could have contributed to the increased delta E. If this is the case, then System 1G would have been affected by dry time, but only slightly.

Printer 2 was another printer that had not shown an effect from dry time on a porous media, but did on a swellable media. This trend was also slight, with only a 1 delta E difference.

Printer 3 was affected by dry time on both a porous media and a swellable media, although to a greater extent on the swellable media with nearly a 3 delta E difference between the 1 day and 6 week dry times.

Printers 4 through 7 were also affected by dry time, but to a lesser extent. The data point from printer System 5C with the 2 week dry time stands out; particularly because this data point was consistent between replicates. For an unknown reason, the printer printed differently that day with no detectable difference in visual appearance or initial measurements compared to the other samples printed on different days. This is a concern because this subset of samples also behaved differently in the Xenon and ozone testing.

The printers with pigment ink showed no impact due to dry time in the humidity testing and all had excellent humidity fastness. Problems with the sample size of System 10E prevented accurate measurements of the 2 week and 6 week dry time samples.

Although only the average delta E calculation was shown at a single test time in Table 1, similar trends were observed with the maximum delta E and also with measurements at other test times.

Table 1. Humidity Test Data After 2 Weeks at 30C/85%.

	Dry Time Impact on Average Delta E			
System	**1 Day**	**3 Days**	**2 Weeks**	**6 Weeks**
1A	12.0	12.3	12.0	12.4
1G	10.2	10.3	9.2	9.8
2B	13.1	14.0	13.7	13.6
2H	12.9	12.7	12.7	11.7
3B	9.3	9.7	8.9	8.3
3H	9.6	8.6	7.7	6.8
4H	9.6	9.3	8.7	7.5
5C	3.5	3.4	7.3	2.9
6D	8.5	9.0	8.3	7.6
7E	3.6	3.2	2.6	2.3
8A	0.7	0.6	0.7	0.5
9B	0.6	0.4	0.4	0.5
10E	1.4	1.3		
11F	0.7	0.7	0.6	0.7

Xenon

The Xenon test was run in 70 hour test cycles with measurements at each stop point. The first group of samples was tested for 7 cycles to a cumulative 560 hours; the second group of samples was tested for 9 cycles to a cumulative 840 hours (two 140 hour cycles at the end). Data will be shown with the actual % optical density loss at a common time interval as well as at a converted failure time. The failure time was determined from a 40% loss in the red density for cyan, green density for magenta, and blue density for yellow. The cumulative test light exposure at failure was calculated and converted in terms of an equivalent ambient exposure of 250 lux for 12 hours a day. As a rough approximation, each 70 hour test cycle has about the same cumulative illumination as would be experienced at 250 lux for 12 hours a day over a period of 5 years.

Table 2. Xenon Test Data. % OD Loss at Measurement Closest to Failure Criteria.

	Cyan (% OD Loss)			Magenta (% OD Loss)			Yellow (% OD Loss)		
System	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks
1A	39.7%	38.4%	38.9%	51.8%	49.7%	49.4%	42.9%	41.8%	41.2%
1G	39.5%	41.2%	41.1%	42.1%	42.4%	40.0%	28.6%	31.3%	28.0%
2B	42.0%	42.5%	41.6%	41.2%	41.8%	41.8%	37.2%	36.3%	37.9%
2H	34.3%	35.1%	35.0%	51.4%	52.1%	53.6%	42.7%	43.7%	44.4%
3B	45.4%	43.8%	43.4%	43.4%	42.9%	41.5%	35.6%	34.6%	34.5%
3H	29.6%	28.8%	28.5%	47.4%	47.1%	46.8%	46.4%	47.5%	47.9%
4H	42.0%	40.6%	40.8%	42.7%	42.5%	42.6%	45.2%	47.9%	48.9%
5C	39.6%	20.3%	40.5%	44.7%	63.7%	44.5%	32.7%	58.1%	32.2%
6D	34.9%	36.6%	38.2%	35.3%	36.1%	38.3%	39.1%	39.4%	37.9%
7E	32.4%	29.1%	29.2%	40.6%	41.0%	41.5%	35.1%	34.3%	34.2%
8A	6.4%	5.6%	5.3%	6.8%	7.1%	6.2%	44.1%	32.6%	35.9%
9B	9.7%	10.4%	9.8%	11.9%	12.0%	11.5%	42.4%	42.2%	39.9%
10E	6.1%	5.8%	5.0%	7.9%	7.9%	7.1%	44.4%	44.1%	35.1%
11F	11.3%	12.1%	11.8%	17.9%	18.5%	18.5%	40.6%	45.5%	48.4%

Table 3. Xenon Test Data. Typical Life Conversion Method Assuming 250 Lux for 12 Hours a Day (1095 klux-Hours per Year).

	Cyan (Years)			Magenta (Years)			Yellow (Years)		
System	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks
1A	25.2	26.2	25.8	6.6	7.0	7.0	32.0	33.3	33.9
1G	21.1	19.5	19.6	23.7	23.3	25.6	80.9	76.7	83.9
2B	28.6	28.2	28.8	34.2	33.9	33.9	43.2	43.8	42.0
2H	71.8	69.8	69.5	48.7	48.3	47.1	49.0	48.3	47.6
3B	25.9	27.0	29.0	22.8	23.0	23.9	44.5	45.5	45.9
3H	98.2	100.9	102.5	47.9	48.3	48.4	46.2	45.4	45.1
4H	47.7	50.1	49.7	33.3	33.5	33.2	47.2	44.8	44.0
5C	25.1	48.1	24.7	22.2	14.4	22.5	50.1	27.1	49.9
6D	17.7	16.8	15.8	16.8	16.4	15.6	30.6	30.6	31.3
7E	46.1	51.5	50.9	34.1	33.3	32.7	48.4	53.5	52.1
8A	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100	28.9	34.2	32.5
9B	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100	39.2	39.4	41.0
10E	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100	14.2	14.3	16.6
11F	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100	40.5	37.7	36.2

Table 4. Xenon Test Data. Comparing Middle Rack (M) with Top Rack (T) in Chamber.

	Cyan (Years)			Magenta (Years)			Yellow (Years)		
System	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks
3B (M)	25.9	27.0	29.0	22.8	23.0	23.9	44.5	45.5	45.9
3B (T)	27.9	28.1	29.0	25.1	25.3	25.6	46.0	45.9	44.3
7E (M)	46.1	51.5	50.9	34.1	33.3	32.7	48.4	53.5	52.1
7E (T)	58.3	61.5	65.9	39.0	40.0	39.3	46.8	53.0	50.2
6D (M)	17.7	16.8	15.8	16.8	16.4	15.6	30.6	30.6	31.3
6D (T)	19.3	19.2	20.2	17.3	16.3	17.7	24.5	27.2	28.4
1G (M)	21.1	19.5	19.6	23.7	23.3	25.6	80.9	76.7	83.9
1G (T)	28.1	26.2	25.6	30.2	28.2	28.9	86.8	85.5	83.8

Tables 2 through 4 contain data from the Xenon testing. Table 2 presents the percent loss of optical density for each color for a 0.5 initial optical density patch. This density was chosen because it faded faster than the darker patches, and its fade response to dry time was consistent with the darker patches. The measurement displayed in the table was the closest to the failure criteria of 40% density loss, chosen independently for each color but a constant value across dry times. For example, the cyan data displayed for all dry times for system 1A was taken at 350 hours into test, all of the magenta data was taken at 140 hours into test, and all of the yellow data was taken at 490 hours into test.

Table 3 presents the data using an alternative approach of converting to an equivalent ambient life exposure. This approach requires two assumptions: setting a failure criteria and an ambient exposure level. Adjusting the values for different ambient exposure levels is a simple scaling calculation (e.g. just double the life estimate if assuming 125 lux instead of 250 lux); however, adjusting the failure criteria may not be as simple because fading is often nonlinear. Table 3 contains some life estimates that are extrapolations; any large extrapolations are indicated as lasting greater than 100 years.

Based on data in Table 2, lengthening the dry time reduced the fade rate of some systems while increasing it for others and it wasn't consistent for a given media type or colorant. Differences of 1% are within the noise of the measurement. A few systems had a stronger response to dry time, such as System 6D, which faded faster with longer dry time for cyan and magenta, and slower for yellow. Therefore, systems with balanced fading across colorants could see different colors reach the failure criteria first based on changes to the dry time and changes in dry time may also strongly affect color imbalances.

It is not possible to make a generalized statement about the effect of dry time on the Xenon test results. For a majority of systems it was weak relationship within the range of dry times investigated. The pigment yellow inks as a group displayed the strongest sensitivity to dry time, although there was no consistent trend: System 8A faded less with a 2 week dry time, System 11F faded less at a 3 day dry time, and System 10E faded less at a 6 week dry time.

System 5C continued to show dramatically different image permanence test results at the 2 week dry time compared to the other print dates. This was not due to dry time, but some other unknown factor that occurred while printing from that one printer on that particular day.

Table 4 shows data comparing sample replicates for select systems. For each of these systems, one sample was tested in the middle rack of the chamber while its replicate was tested in the top rack. In many cases the difference in predicted life was greater due to test location within the chamber than due to dry time.

Ozone

The ozone test was run at progressively longer cycle times due to the nonlinear fading behavior of many colorants in ozone. The first test group was measured at 2, 5, 10, 25, 50, 120, 200, and 300 hours; the second test group contained more durable samples and was measured at 20, 100, 200, 400, 600, and 1000 hours.

Tables 5 through 7 contain data from the ozone testing. Table 5 presents the percent loss of optical density for each color for a 0.5, 1.0, or 1.5 initial optical density patch. The actual density chosen was dependent on which faded faster, but was kept constant across dry times. The measurement displayed in the table was the closest to the failure criteria of 40% density loss, chosen independently for each color but a constant value across dry times.

Table 6 presents the data using an alternative approach of converting to an equivalent ambient life exposure assuming 5.7 ppb ozone (50 ppm-hours per year). Table 6 contains some life estimates that are extrapolations; most large extrapolations are indicated as lasting greater than 100 years.

The ozone fastness test showed a strong relationship between dry time and sample fade rate for many systems. Pigment inks were generally less sensitive to dry time than dye inks. Surprisingly, dye inks on porous media were more sensitive to dry time than dye inks on swellable media, although this could be due to the much longer test times required for dye inks on swellable media.

In general, longer dry times resulted in slower fade rates with the only exceptions occurring with some yellow colorants (e.g. System 11F) and possibly the cyan of System 7E and magenta of System 11F. The nonlinear fade rates typical in ozone testing resulted in a large disparity between the variations in optical density loss compared to the life prediction. This is because the slope of the optical density loss with respect to time becomes small, and a slight difference in density loss can cause a large variation in the failure time as shown in Figure 2. In that situation the 3 day dry time cyan patches of System 1A had faded about 34% more than those with the 6 week dry time, but the failure time was nearly 300% faster. This disparity is more pronounced with color imbalances.

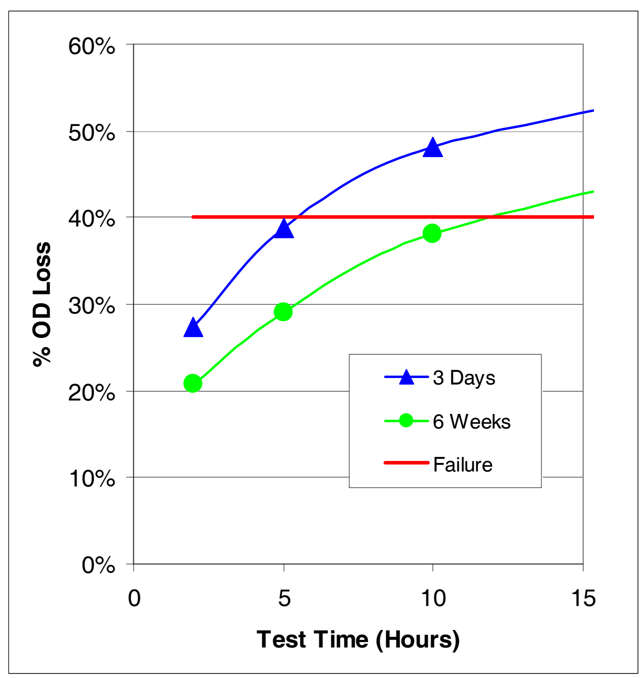

Figure 2. Comparing Ozone Fade Rates of Cyan Patches of System 1A with 3 Day and 6 Week Dry Times.

Table 5. Ozone Test Data. % OD Loss at Most Relevant Measurement.

	Cyan (% OD Loss)			Magenta (% OD Loss)			Yellow (% OD Loss)		
System	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks
1A	50.6%	41.8%	37.7%	52.6%	48.7%	45.0%	44.9%	44.4%	42.1%
1G	10.7%	11.8%	10.2%	15.3%	15.5%	14.3%	17.1%	18.4%	19.5%
2B	50.6%	45.6%	43.5%	43.4%	36.7%	32.3%	39.1%	38.4%	37.5%
2H	13.3%	13.4%	13.4%	6.7%	6.6%	6.5%	8.2%	8.2%	8.0%
3B	47.9%	42.2%	32.3%	37.9%	33.9%	31.1%	53.9%	53.0%	52.1%
3H	26.9%	24.8%	23.1%	12.5%	11.5%	10.3%	6.1%	7.0%	6.8%
4H	21.3%	20.5%	20.3%	13.4%	12.4%	12.5%	7.8%	8.3%	8.4%
5C	44.0%	41.0%	41.5%	38.5%	35.9%	36.3%	49.8%	38.1%	45.4%
6D	42.8%	39.9%	37.6%	42.5%	40.1%	35.3%	51.7%	51.5%	51.1%
7E	40.7%	40.7%	42.0%	40.7%	40.1%	38.7%	13.4%	12.8%	13.2%
8A	26.2%	23.6%	20.7%	8.9%	9.2%	8.4%	22.1%	17.5%	17.2%
9B	30.0%	29.6%	30.3%	19.0%	17.8%	17.4%	12.9%	12.0%	12.2%
10E	35.8%	36.1%	36.0%	33.6%	34.5%	29.1%	16.5%	17.3%	14.6%
11F	30.8%	33.1%	29.9%	25.4%	26.7%	26.6%	31.9%	35.9%	36.6%

Table 6. Ozone Test Data. Typical Life Conversion Method Assuming 50 ppm-Hours per Year.

	Cyan (Years)			Magenta (Years)			Yellow (Years)		
System	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks
1A	0.45	0.91	1.27	0.50	0.66	0.80	4.3	4.3	4.7
1G	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100	244	238	309
2B	2.6	3.8	4.3	0.85	1.27	1.57	12.4	12.7	13.1
2H	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100
3B	0.62	0.91	1.75	0.23	0.29	0.33	8.4	8.7	8.9
3H	292	311	332	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100
4H	361	366	363	>> 100	>> 100	>> 100	>> 100	>> 100	>> 100
5C	9.7	11.5	11.2	13.1	14.6	14.7	3.1	5.7	4.0
6D	10.6	12.1	13.9	10.9	12.0	14.9	1.8	1.7	1.8
7E	29.3	29.3	28.0	19.6	19.8	21.3	>> 100	>> 100	>> 100
8A	194	216	265	>> 100	>> 100	>> 100	209	267	254
9B	172	173	172	393	401	400	389	432	414
10E	126	121	124	155	142	193	209	206	226
11F	160	143	169	223	210	208	128	113	111

The sample replicates for the ozone test were mounted facing inward on a moving carousel, such that the average airflow on the replicates was less than on the primary test samples. Table 7 shows the deviation in optical density loss of the lower airflow (inward facing) compared to the higher airflow (outward facing) based on the same time measurement as selected for Table 5.

The cyan and magenta pigment inks showed little sensitivity to airflow while the pigment yellow inks generally faded less at lower airflow.

The same effect was seen with dye based inks on porous media, where the yellow dyes were fading less at lower airflow. While many dye based inks on porous media were insensitive to airflow, the swellable media were showing a complex response. For example, System 3H cyan actually faded faster at lower airflow even as the yellow faded less. And all the System 1G colorants faded faster with less airflow at the 3 day dry time but slower at the 6 week dry time.

Table 7. Ozone Test Data. Comparing Lower Airflow with Higher Airflow (Inward vs. Outward Facing Samples).

	Cyan (% Deviation)			Magenta (% Deviation)			Yellow (% Deviation)		
System	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks	3 Days	2 Weeks	6 Weeks
1A	-2%	0%	-2%	-3%	-3%	-1%	-11%	-12%	-12%
1G	17%	11%	-3%	10%	6%	-19%	29%	19%	-18%
2B	2%	0%	-3%	0%	-1%	-1%	-2%	-3%	-5%
2H	9%	10%	7%	0%	8%	2%	-12%	-2%	-8%
3B	0%	-1%	3%	-4%	-2%	-1%	-2%	-3%	-2%
3H	14%	10%	13%	7%	2%	4%	-11%	-11%	-16%
4H	9%	4%	4%	1%	2%	0%	-10%	-12%	-12%
5C	-6%	-2%	-2%	-3%	-3%	-5%	-12%	-13%	-9%
6D	-2%	6%	3%	-5%	1%	10%	-9%	-5%	-7%
7E	-3%	-2%	-1%	-4%	-2%	-1%	-7%	1%	0%
8A	-1%	-2%	2%	4%	-2%	-2%	-9%	-9%	-2%
9B	2%	1%	1%	-2%	1%	1%	-8%	-8%	-4%
10E	3%	-2%	-1%	2%	-1%	-1%	-7%	-6%	-4%
11F	0%	0%	2%	2%	-1%	0%	2%	-5%	-7%

Conclusion

Based on the collected data, dry time does affect the results of image permanence testing, but to varying degrees depending on the type of test and technology used.

For humidity fastness, dye based inks benefited more from longer dry times on swellable media than on porous media—pigment inks were not affected by dry time.

For Xenon light stability, the effect of dry time was mixed. Pigment yellow inks showed the strongest response to dry time, but as with many other systems, some benefited from longer dry times while others benefited from shorter dry times. As a group, they showed a weak relationship between fade rate and dry time.

For ozone stability there was once again a mixed response, but a majority of systems benefited from longer dry times. Dye based inks on porous media showed a strong relationship between fade rate and dry time. Dye based inks on swellable media and pigment inks had a weaker response to dry time.

In addition to investigating dry time, test replicates in Xenon and ozone testing showed the impact of sample position on fade rate within a single test. In the case of Xenon, sample position had a larger effect on sample fade than the dry time. For ozone testing, lower airflow resulted in slightly lower fade rates for many systems, although dye based inks on swellable media had a complex response.

It was also observed that the 2 week dry time samples from System 5C showed unusual behavior compared to samples printed at other times. The variation in image permanence of these samples dwarfed the response to the controlled test variables. The reason for this variation is unknown and of great concern for the purpose of developing a test method with consistent results.

For humidity fastness the length of the dry time does not appear to be significant to achieve consistent test results. Since humidity can affect print samples immediately after printing, a short dry time such as one day is reasonable.

For Xenon light stability, the length of the dry time within the range investigated was not significant except for pigment inks. The dry time should be no less than 3 days to stay within the scope of this study. And to achieve agreement between test laboratories the deviation from any selected standard dry time should not be more than several days.

For ozone stability, the length of the dry time had a strong effect on the test results. Better simulating real world conditions requires a long dry time, but it is also not feasible for development work. Therefore, the recommended dry time should not be less than 2 weeks, and unless a dry time of many weeks is selected, the allowable deviation from any selected dry time should be kept to within a couple days.

References

[1] H. Kaimoto et al., "Test Methods of Humidity Fastness of Inkjet Printing Materials," Final Program and Proceedings of IS&T's NIP23: International Conference on Digital Printing Technologies, Anchorage, Alaska, pp. 728-731 (2007).

Author Biography

Matthew Comstock received his B.S and M.S. degrees from Purdue University in Mechanical Engineering specializing in heat transfer and thermodynamics. He joined Lexmark International, Inc. in 1999 as a development engineer for color laser products. Since 2005 he has been responsible for the Lexmark Image Permanence Lab in Lexington, KY. His work is primarily focused on image permanence test method development and image permanence testing.