Marion F. Mecklenburg and Julio del Hoyo

Interpreting Delta E*

In conducting tests for a single material at a fixed level of light intensity, it appears at first glance that there is a considerable amount of scatter in the data as shown in figure 1 below. This figure shows the light fading results for 15 light fading tests of new Blue Wool Standard 1. [1] All of the tests were conducted at the same light intensity of 7 Mega Lux (MLux). This material is a fabric and there can be no doubt that there is a texture to the surface perhaps leading to differences in light reflectance. On the other hand it seems difficult to understand how a single material that is fairly carefully controlled in its manufacture can have such variability. One might think that the fading rate for such a material should be fairly consistent.
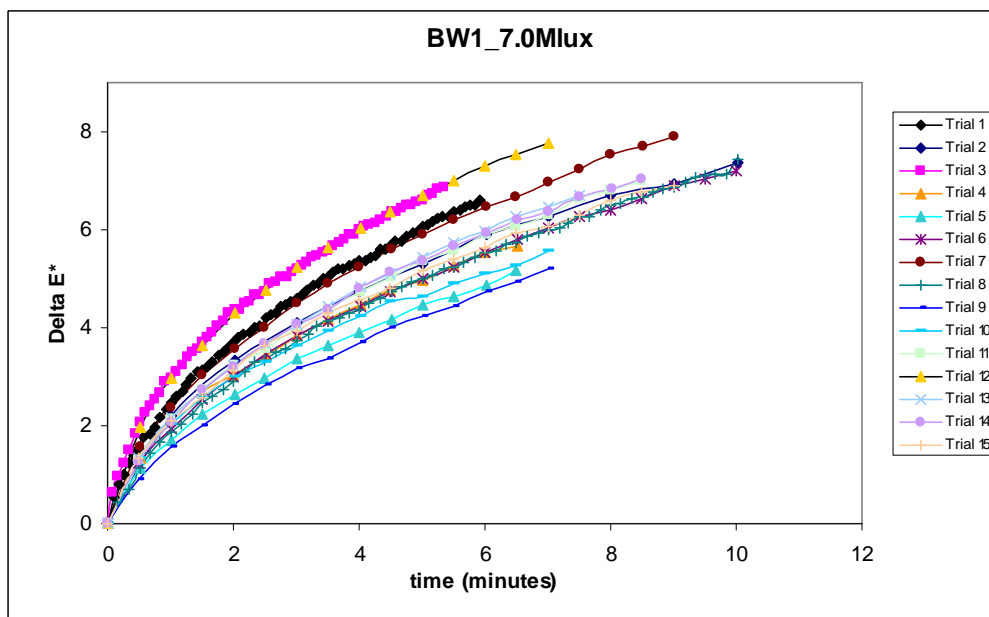

Figure 1, The original fading data (Delta E* versus time) for Blue Wool Standard 1, at a light intensity of 7.0 M-Lux.

For discussions sake let's assume that the fading rate of the Blue Wool Standard 1 is constant and the problem with the apparent scatter is a result of the initial starting

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measurements of the tests. That is to say there is some variability in the initial reference L*, a*, and b* values. This can be a result of calibration of the equipment, the actual variability of the color coating and other factors. In the case of the variability of the coating it will in all probability not be visible to the human eye but the micro fading tester will certainly detect it. But the end result is that the calculation of the Delta E* (our measure of fading) throughout the fading tests heavily depends on the initial reference L*, a*, and b* values. This is because Delta E* is calculated as:

$$\text{Delta E*} = ((L^*\text{-Ref }L^*)^2 + (a^*\text{-Ref }a^*)^2 + (b^*\text{-Ref }b^*)^2)^{0.5}$$

Where Ref L*, Ref a*, and Ref b* are the initial reference readings and L*, a*, and b* are the subsequent readings.

The other factor under consideration is the initial time at the start of the test. The equipment initializes the time to zero every time we start the test. If the micro-fading equipment measures the changing Delta E* from different starting values of Ref. L*, Ref. a*, and Ref. b* then there will be apparent differences in the rate of each fading record. The real question is whether or not all of the tests results can be normalized to a common curve.

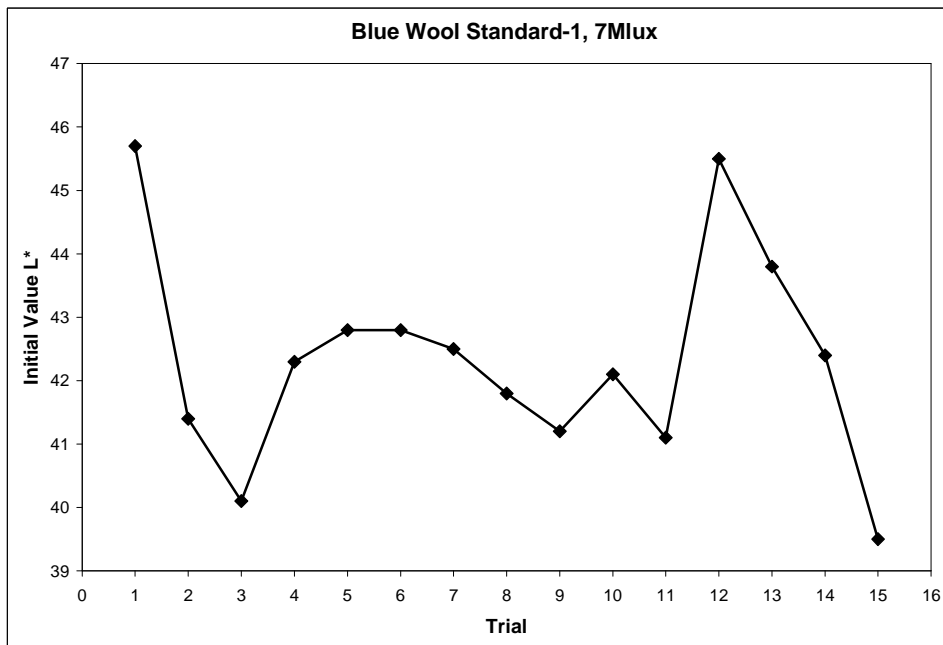Figures 2-4 show the variability of the Ref. L*, Ref. a*, Ref b* values for each of the 15 trials.

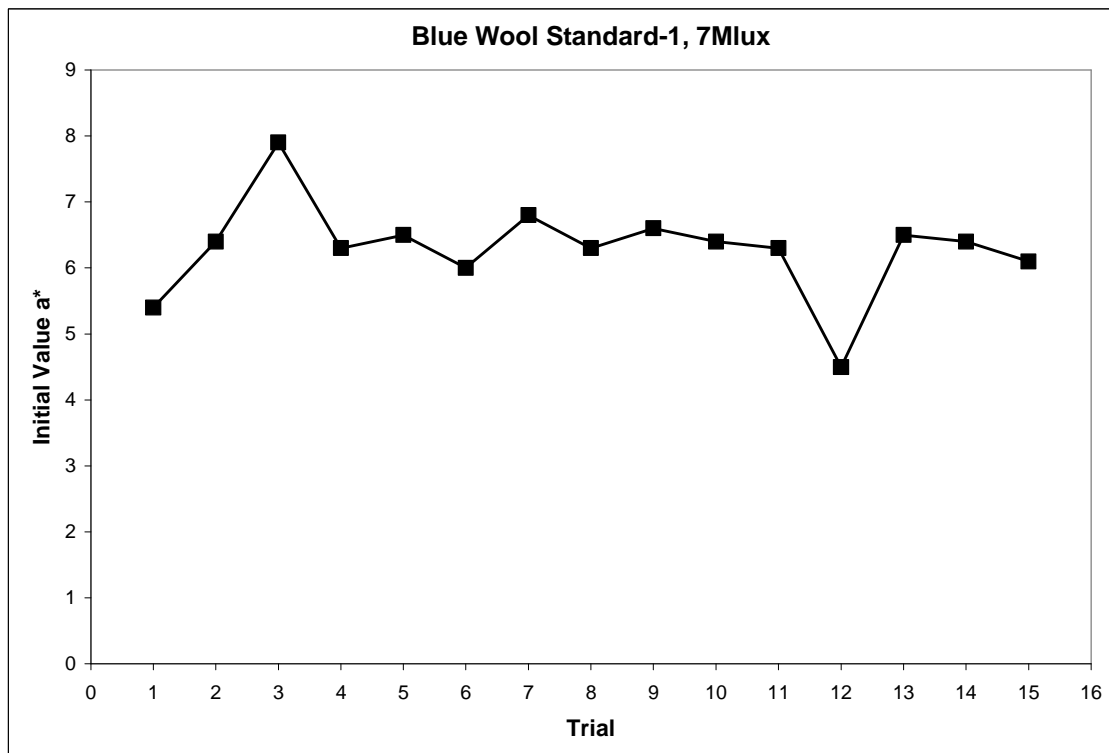Figure 2, The Ref. L* for 15 trials of Blue Wool Standard 1, at a light intensity of 7.0 M-Lux.

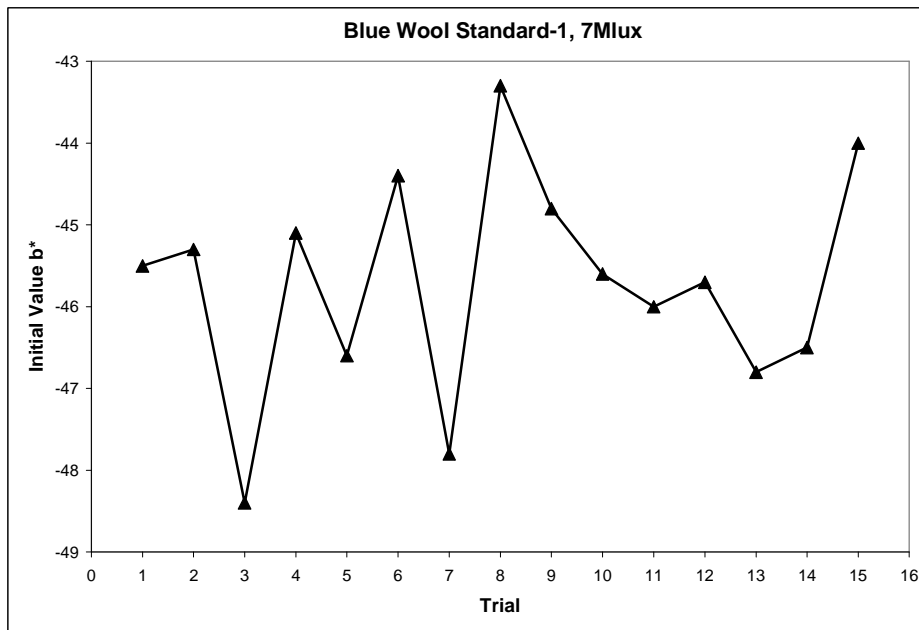Figure 3, The Ref. a* for 15 trials of Blue Wool Standard 1, at a light intensity of 7.0 M-Lux.

Figure 4, The Ref. b* for 15 trials of Blue Wool Standard 1, at a light intensity of 7.0 M-Lux.

The basic assumption we are making is that the Blue Wool Standard 1 actually fades at a consistent rate and that all of the fading plots are actually segments of the same curve. It remains to be shown if it is possible to find where the segments fit on a common fading curve.

Theoretical Considerations

Let's suppose that there is a fading curve that takes the mathematical form of the equation 1 below.

$$\text{Delta } E^* = A \cdot (T+B)^{0.5} + C \qquad \text{(Eq. 1)}$$

Where A, B, and C are constants and T is time in minutes.

Now let's suppose that there are two plots where the constants for Plot 1 are:

$$A=10, B=0, \text{ and } C=0$$

And the constants for plot 2 are:

$$A=10, B=1, \text{ and } C= -10$$

The equation for plot 1 is:

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$$\text{Delta E*} = 10 \cdot (T)^{0.5} \qquad \text{(Plot 1)}$$

And the equation for plot 2 is:

$$\text{Delta E*} = 10 \cdot (T+1)^{0.5} - 10 \qquad \text{(Plot 2)}$$

On looking at the two equations, the constant B represents an adjustment to time and constant C represents an adjustment to Delta E*. Another way of looking at Plot 2 is:

$$\text{Delta E*} + 10 = 10 \cdot (T+1)^{0.5}$$

Where Delta E* and the constant C are on the same side of the equation. They can be plotted as shown in figure 6 below.
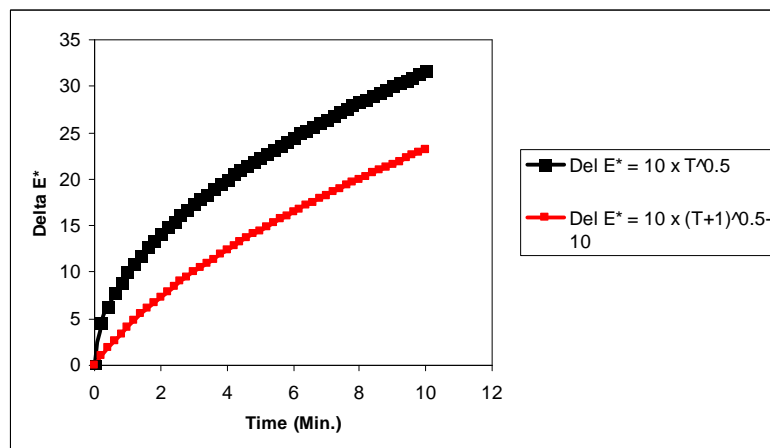

Figure 6 shows the plots of the two functions, Delta E* = $10 \cdot (T)^{0.5}$ and Delta E* = $10 \cdot (T+1)^{0.5} - 10$. They appear to be entirely two different functions but they are different only by constants B and C.

If one takes the derivatives of equations of plots 1 and 2, one eliminates one of the constants, in this case constant C, leaving only the Constant B as the difference between the two equations. The derivatives of both equations look like this:

$$d(\text{delta E*})/dT = 10 \cdot (T^{(-0.5)})/2 = 5 \cdot (T^{(-0.5)})$$

$$d(\text{delta E*})/dT = 10 \cdot (T+1)^{(-0.5)}/2 = 5 \cdot (T+1)^{(-0.5)}$$

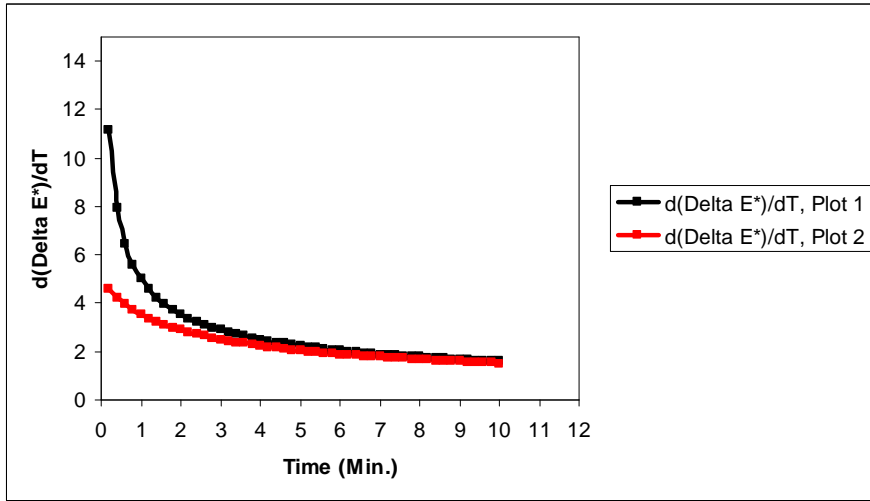The plots of the derivatives look like those shown in figure 7 below.

Figure 7, shows the derivatives of plots 1, and 2. Again while they look different they differ only by the time constant B=1.

Now the derivative of Plot 2 can be adjusted by the time constant B=1. This is done by shifting (adding one minute to all points) the derivative of Plot 2, to the right as shown in figure 8. Now the derivative of Plot 2 and the time adjusted derivative coincide for a segment of the Plot 1.
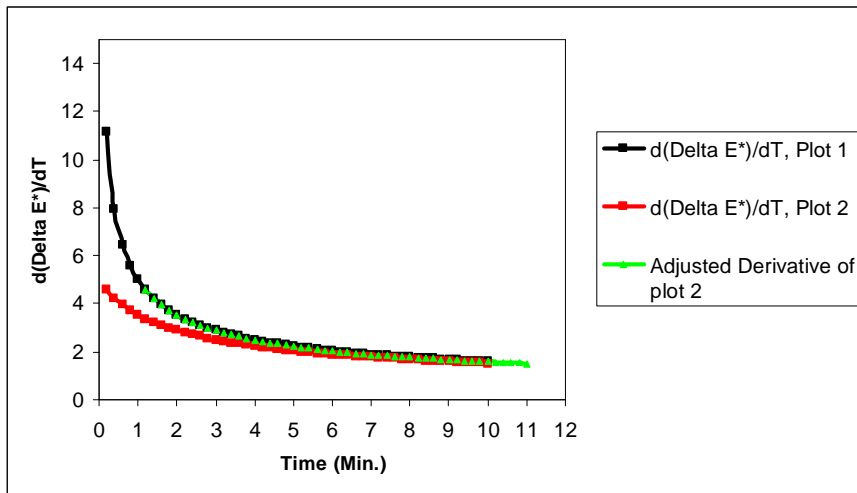

Figure 8, the derivatives of plots 1, and 2 and showing the time constant B (recall B = 1) adjustment to the derivative of Plot 2.

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Once it is shown that the derivatives are differing by only the time constant B=1, it is now necessary to show that the Delta E* constant C is the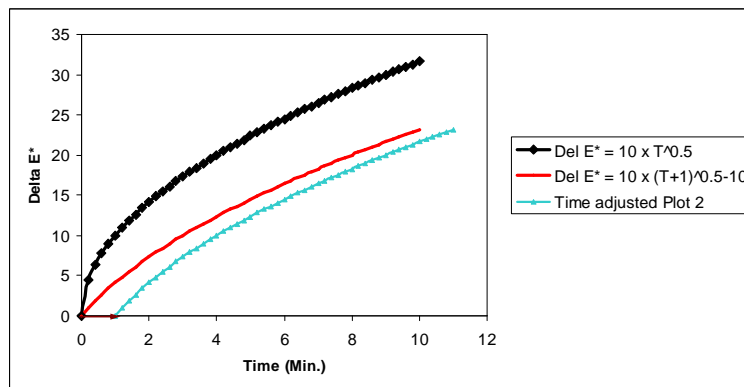 only further adjustment needed to align the original two plots. Figure 9, shows plots 1, and 2 and showing the time constant B (recall B = 1) adjustment to Plot 2. In this case the plot is shifted to the right by 1 minute. This leaves the final adjustment to the Plot 2 so that it coincides with Plot 1. This is accomplished by a vertical shift of the time adjusted Plot 2 to the Plot 1 and this is by adding 10 to all points. (Figure 10) It has now been shown that Plot 2 is actually a segment of Plot 1. The difference between the two equations can be expressed as the difference in the constants B and C.

Figure 9, shows plots 1, and 2 and showing the time constant B (recall B = 1) adjustment to Plot 2. In this case the plot is shifted to the right by 1 minute.
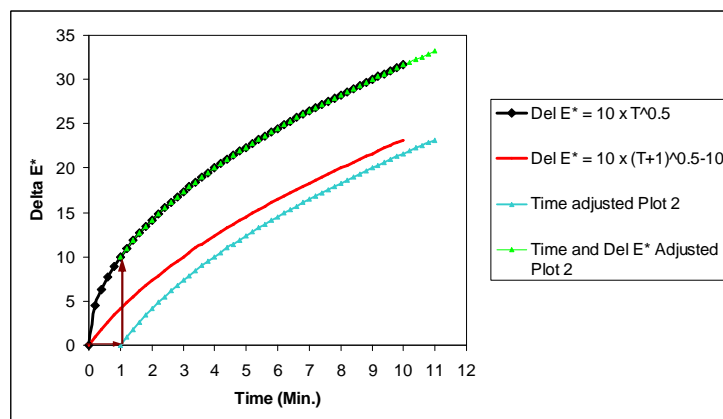

Figure 10, shows plots 1, and 2 and the full adjustments required to align plot 2 with plot 1. The horizontal shift was 1 minute and the vertical shift was 10. These are in fact the values of constants B and C respectively.

Normalizing Actual Light Fading Data, Case 1

It is not always possible to know the exact mathematical function that governs the fading of a material due to light. However it is still possible to estimate the adjustment necessary to "normalize" acquired fading data.

Figure 11 shows the values of Delta E* at the one minute point for each of the Blue Wool Standards 1 (15 trials). If the difference in these initial values of Delta E* are the sources of the scatter of the fading data then it might be possible to normalize these initial values. Let any one of the trials become the "reference trial" or "master curve". In the case of the Blue Wool Standards 1 trials, trial 12 was selected for no other reason than it demonstrated the fastest rate of fading and therefore conservative if one is trying to use the information do determine light fading in the future.
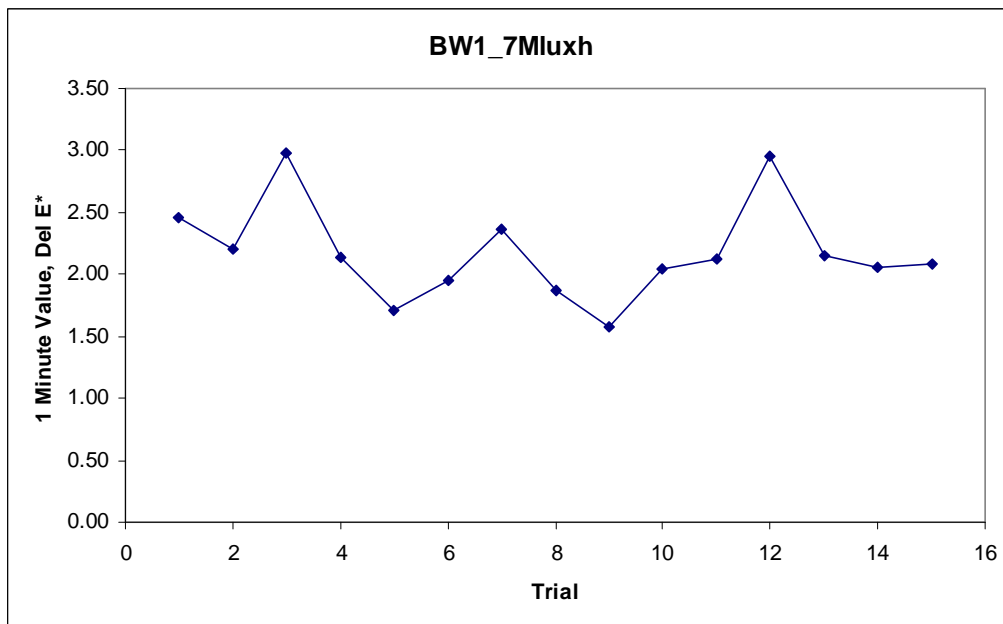

Figure 11, The Delta E* values at the 1 minute point for 15 trials of Blue Wool Standard 1, at a light intensity of 7.0 M-Lux.

Since we are looking for the fit both in a Delta E* correction and a time correction it is useful to look at the adjustments made in detail. Figure 12 below shows the Delta E*

versus time plots for trails 12 and 8. It can be see that the plots for trial 12 and trial 8 appear quite different indicating that the fading rate for trial 8 is slower that that of trial 12. It is possible to take the derivatives of the plots from trial 12 and trial 8 and compare them as shown in figure 13. If the earlier discussion has meaning then these plots will only differ by a time constant. In this case the time constant distance appears to be about 0.69 minutes.
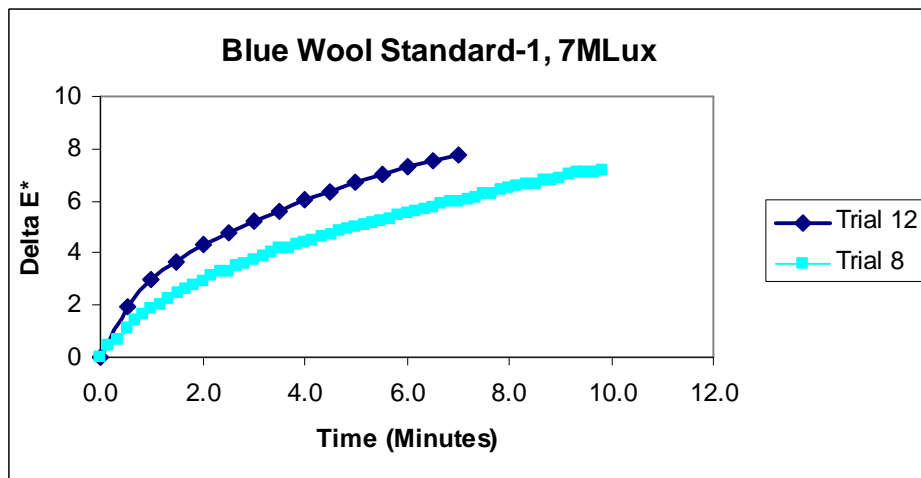

Figure 12 shows trial 12 and trial 8. These plots suggest that the fading rates for the same sample of the blue wool standard 1 are different from spot to spot.
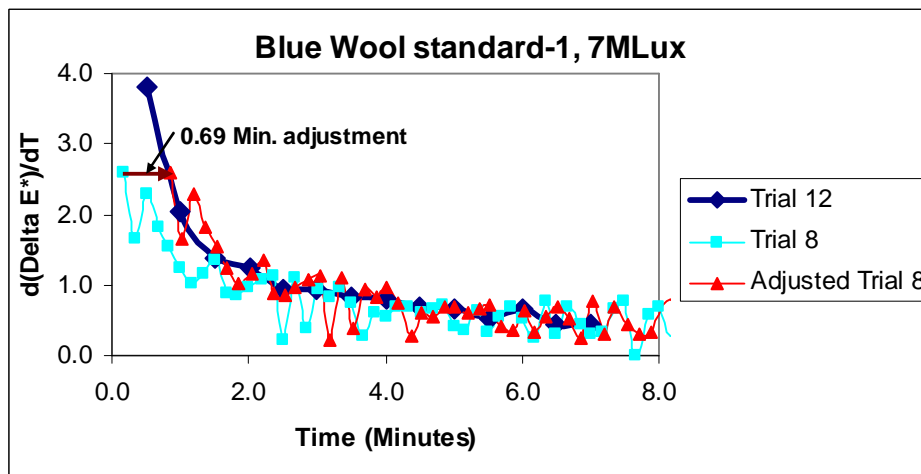
Figure 13 shows the derivatives of the Delta E* versus time plots for trial 12 and trial 8. Also in this plot is the adjusted derivative of trial 8 to coincide with the derivative of trial 12. The shift required to do this was 0.69 minutes.

Using the time shift of 0.69 minutes it is possible to go back to the original plots of Delta E* versus time for trials 12 and 8 and shift trial 8 to the right. Now it is only a matter of a vertical shift of trial 8 to coincide with trial 12. The Delta E* adjustment to complete this shift is 2.18. As can be seen in Figure 14, Plots for trial 12 and trial 8 coincide with the exception of the starting points. It now appears that the fading rates for the two different locations on the same Blue Wool Standard sample are the same.
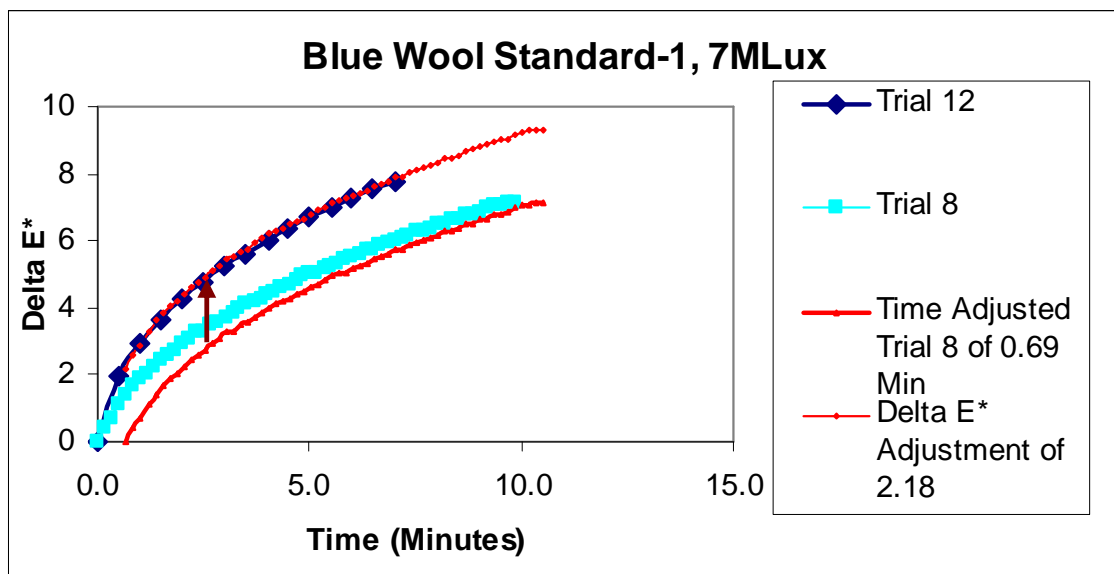

Figure 14 shows the time and Delta E* shifts required to have trial 8 coincide with trial 12.

It is now necessary to apply adjustments to all of the other trials using trial 12 as the "Master Curve." If one determines the difference in Delta E* between trial 8 and trial 12 at the one minute mark of the record it comes out to be -1.09. The Delta E* correction used in adjusting the two plots was 2.18 or the difference in the two Delta E values times -2. If all 15 of the trials can be "normalized" to trial 12 then there must be a common adjustment. One of the ways is to assume that the Delta E* and time adjustments are

proportional for all of the trials. That is to say that the (time adjustment)/(Delta E* adjustment) is constant. For trial 12 and 8 then:

(time adjustment)/(Delta E* adjustment) = 0.69/2.18 = 0.3165

So for every trial that is to be normalized to trial 12, the Delta E* adjustment will be:

-2 times the difference in Delta E* at the one minute mark = Delta E* Adj.

And the time adjustment will be:

Delta E*Adj. times 0.3165 = Time Adj.

Table 15 below shows the results of the above calculations when normalizing all of the trials to trial 12. The Delta E* and time adjustments were applied to the Blue Wool Standard 1 fading test data and this suggests that the starting or initial values of Ref. L*, Ref. a*, and Ref. b* are largely responsible for the apparent differences in the original fading plots shown in Figure 15. With few exceptions the plots for all of the light fading data are fairly coincident.

Table 1, shows the corrections made to each of the Blue Wool Standard 1 trials.

| A	B	C	D	E	F
Trial	Delta E* after 1 min,	Diff. from Trial 12 (Col. B- 2.96)	Delta E* corrections –(Cx2)	Time corrections (Min.)	Slope (Col. E/Col. D)
1	2.46	-0.5	1	0.3165	0.3165
2	2.21	-0.75	1.5	0.47475	0.3165
3	2.98	0.02	-0.04	-0.01266	0.3165
4	2.13	-0.83	1.66	0.52539	0.3165
5	1.71	-1.25	2.5	0.79125	0.3165
6	1.95	-1.01	2.02	0.63933	0.3165
7	2.36	-0.6	1.2	0.3798	0.3165
8	1.87	-1.09	2.18	0.68997	0.3165
9	1.58	-1.38	2.76	0.87354	0.3165
10	2.04	-0.92	1.84	0.58236	0.3165
11	2.12	-0.84	1.68	0.53172	0.3165
12	2.96	0	0	0	0.3165
13	2.15	-0.81	1.62	0.51273	0.3165
14	2.06	-0.9	1.8	0.5697	0.3165
15	2.09	-0.87	1.74	0.55071	0.3165

Blue Wool Standard-1, 7Mlux
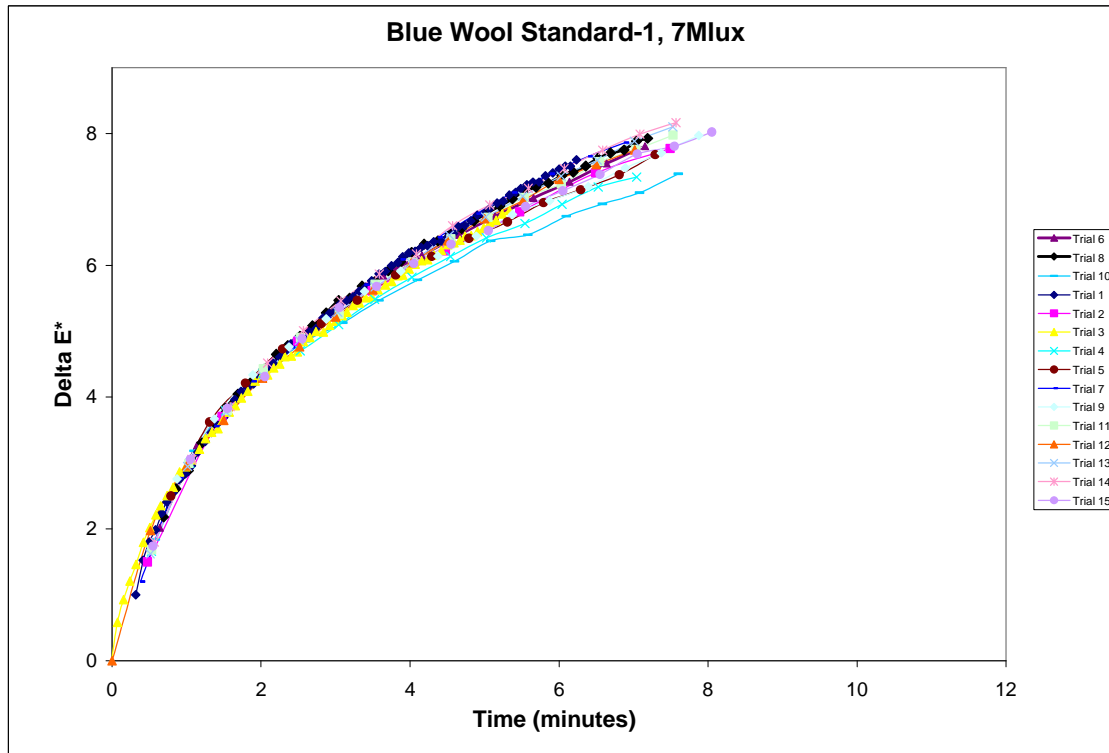
Figure 15 shows all of the 15 trials for the Blue Wool Standard 1 fading tests when normalized to trial 12. With the exceptions of trial 4 and 13, the plots are fairly coincident. This suggests that the variability of the starting or initial values of Ref. L*, Ref. a*, and Ref. b* are largely responsible for the apparent differences in the original fading plots shown in Figure 1.

Normalizing Actual Light Fading Data, Case 2

If the concept of normalizing the Delta E* versus time data holds meaning then it should be possible to look at other fading test results and adjust them in a similar manned. In his paper [2] Paul Whitmore examines the fading rates of Winsor & Newton Bengal Rose Gouache. The author was generous enough to supply some of the original fading data from figure 6 in that paper for this study. All of the Winsor & Newton Bengal Rose

Gouache data shown below was conducted at a light intensity of 6.4 M-Lux. Figure 16 shows the original light fading data reproduced but for the full time duration of the tests.
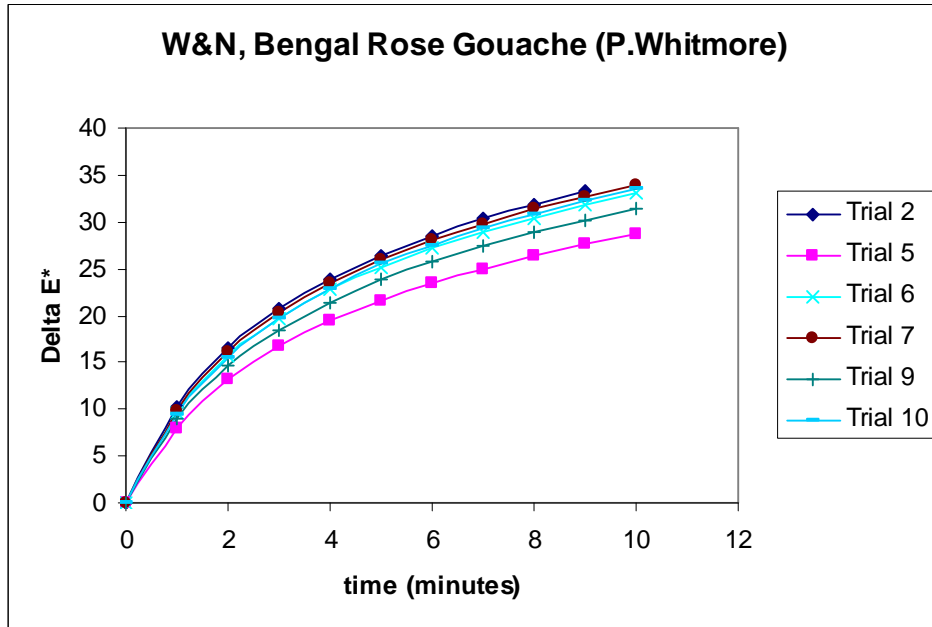

Figure 16, Show the original Delta E* versus time for the full time duration of the Bengal Rose Gouache fading tests.

Figure 17 shows the variability of the initial Ref. L*, Ref. a*, and Ref. b* values for the Bengal Rose Gouache light fading tests. Figure 18 shows the variation in the Delta E* values after one minute of testing for the Bengal Rose Gouache light fading tests
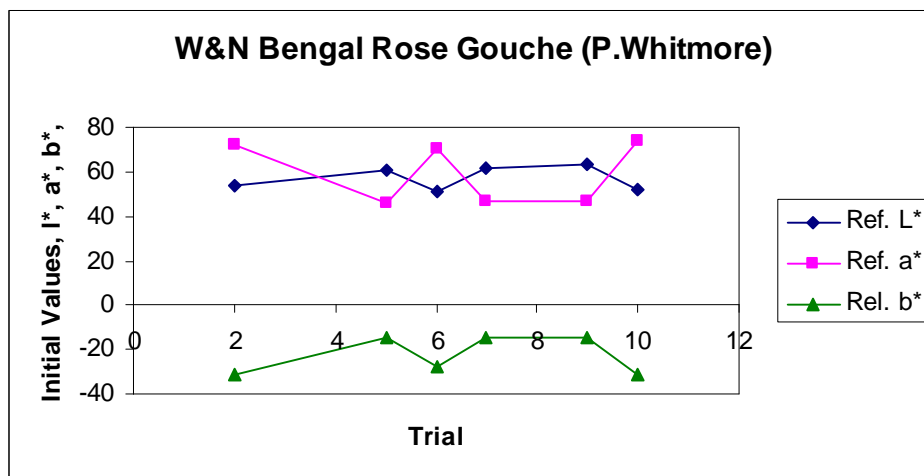
Figure 17, shows the initial Ref. L*, Ref. a*, and Ref. b* information for the Bengal Rose gouache light fading tests.

Figure 18, shows the Delta E* values after one minute of testing for the Bengal Rose gouache light fading tests.

As with the Blue wool standards discussed in the Case 1 study, the Bengal Rose Gouache data was normalized using the same approach. In this case the Delta E* adjustment was determined as -2 times the difference of the Delta E* values at the 1 minute mark of any two tests. In this case trial 2 was used as the "Master Curve" and trial 9 was normalized. Once the Delta E* adjustment was determined the time correction could be found. In this case the Delta E* correction was 2.553 and time correction was 0.1455 Min. The correction slope was calculated as:

(time adjustment)/(Delta E* adjustment) = 0.1455/2.553 =0.057

So for every trial that is to be normalized to trial 2, the Delta E* adjustment will be:

-2 times the difference in Delta E* at the one minute mark = Delta E* Adj.

And the time adjustment will be:

Delta E*Adj. times 0.057 = Time Adj.

Table 2 below shows the results of the above calculations when normalizing all of the trials to trial 2. The Delta E* and time adjustments were applied to the Bengal Rose Gouache fading test data. As before this suggests that the starting or initial values of Ref. L*, Ref. a*, and Ref. b* are largely responsible for the apparent differences in the original fading plots shown in Figure 16. This data adjustment show the fading rates as remarkably consistent.

Table 2, shows the corrections made to each of the Bengal Rose Gouache 1 trials.

A	B	C	D	E	F
Trial No.	1 Minute Delta E*	Difference from Trial 2 (Col. B-10.2231)	Delta E* Correction (-2 x Column C)	Time Correction (Min.)	Slope (Col. E/Col. D)
2	10.2231	0	0	0	0.057
5	8.06106	-2.16204	4.32408	0.2464	0.057
6	9.61878	-0.60432	1.20864	0.0689	0.057

7	9.85281	-0.37029	0.74058	0.0422	0.057
9	8.94642	-1.27668	2.55336	0.1455	0.057
10	9.42216	-0.80094	1.60188	0.0913	0.057

W&N, Bengal Rose Gouache (P.Whitmore)
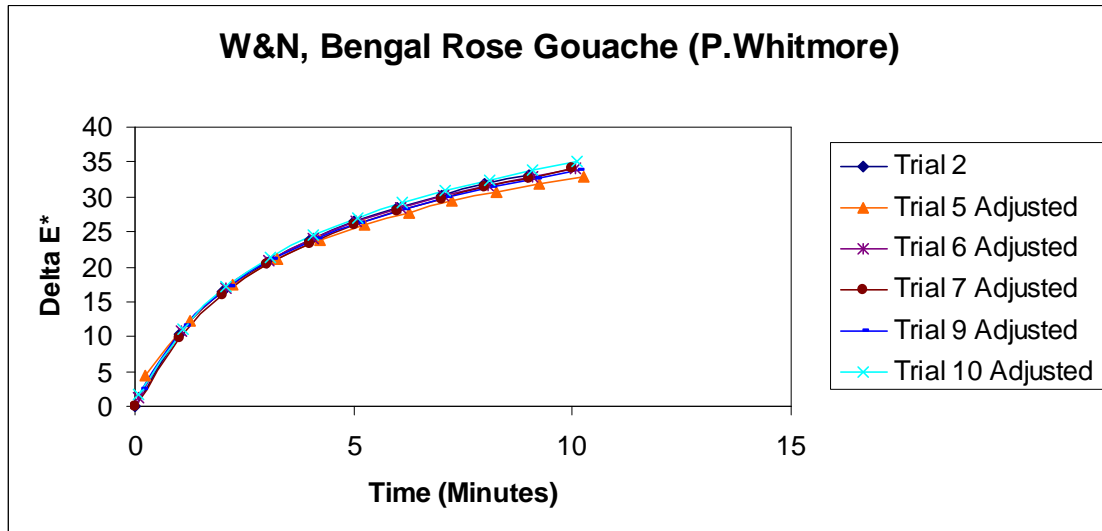
Figure 19 shows all of the 6 trials for the Bengal Rose Gouache fading tests when normalized to trial 2. These plots are remarkably coincident.

Looking at the Past as Well as the Future

One of the more challenging objectives of this program is assessing the stability of existing, and antique, cultural materials that have suffered unspecified light fading. How much light damage have they suffered in the past? How much more can they suffer before they are totally faded? Figure 20 below shows Delta E* plotted with respect to Time in minutes. In this example, a new blue wool standard-1 (BWS-1) is exposed to 3.84 M Lux for a total of 52.4 minutes. To reach an initial ΔE^* of 5 it takes about 9.89 minutes

Blue Wool Standard-1, 3.84 M Lux
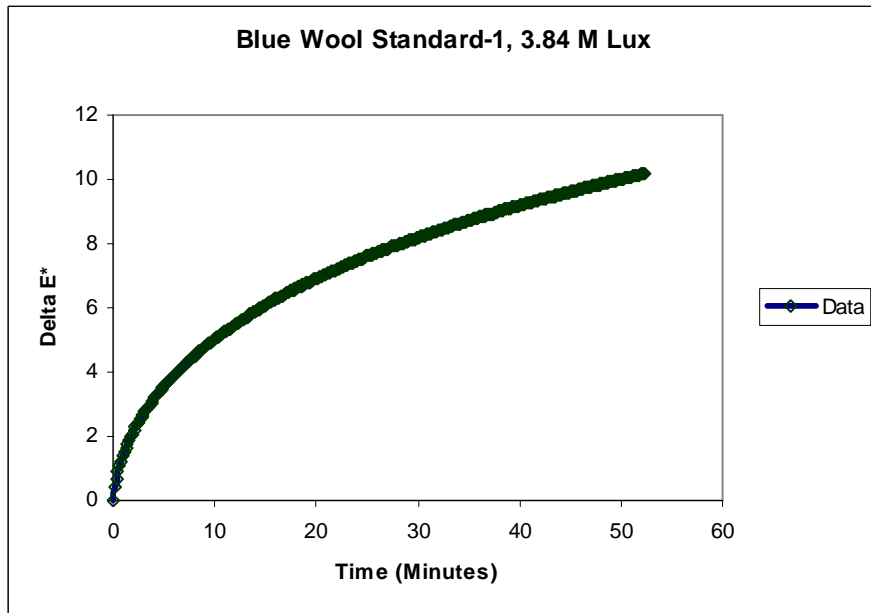
Figure 20 shows Delta E* versus time for a Blue Wool Standard-1 at 3.84 M Lux.

To simulate prior light fading of a museum object, let us suppose that a fading test of a new material such as the BWS-1 was run until its Delta E* reached 5 and then stopped. This was at 9.89 minutes. Without moving the test equipment or object being tested, the test is resumed with the clock restarted. This second test or "restarted test," is of interest as it is analogous to the lighted exhibition of an artwork, its storage in the dark, and its subsequent lighted exhibition for a second (third, or fourth) time.

Figure 21 shows the full cumulative Delta E* versus Time for the Blue wool Standard-1 at 3.84 M Lux. Included in Figure 21 is the curve of the "restart" BWS-1 test. The plots for the original "data" and the "restart run" do not look at all similar and it might be said that this is not the same material or there are other influences such as temperature or relative humidity influencing the tests.
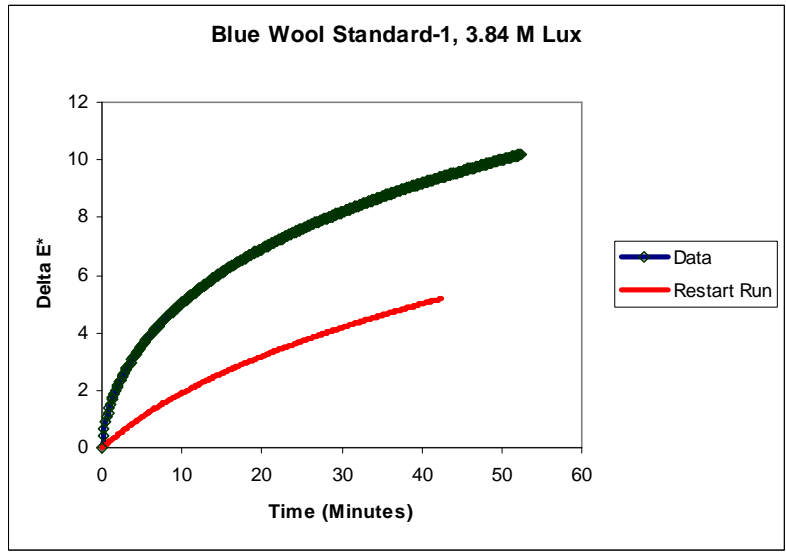
Blue Wool Standard-1, 3.84 M Lux

Figure 21 shows the full plot of Delta E* versus time for a Blue wool Standard-1 at 3.84 M Lux. Also shown in this figure is the plot of the hypothetical "restarted" BWS-1 test.

Blue Wool Standard-1, 3.84 M Lux
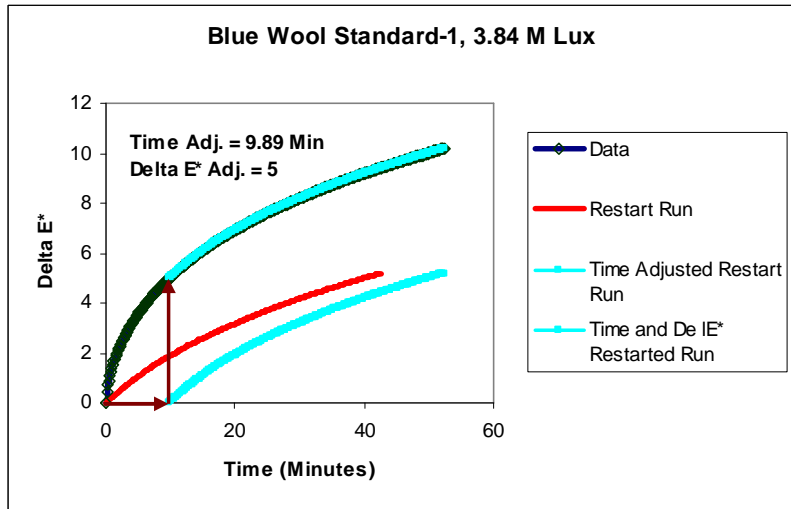
Figure 22 shows the full plot of Delta E* versus time for a Blue wool Standard-1 at 3.84 M Lux. Also shown in this figure are the plot of the hypothetical "restarted" BWS-1 test and the adjusted "restarted" plots.

It only remains to find where the two data sets coincide. Since the hypothetical test was stopped at 9.98 Minutes when Delta E* was 5 we actually know the time and Delta E*

adjustment values. Figure 22 shows the fully adjusted plots and as can be see they coincide very well.

If these were actual materials found in a museum object or artifact, then the comparison of the rates of change between a material in the older object and a new sample of the same material provides a possible method for determining the prior light history of the object. For this hypothetical case, and if reciprocity holds, the implication is that the object was previously exposed to 0.65 M Lux-Hours, without regard to the intensity of the light levels. If a reliable materials data base is established, then it might even be possible to say what level of Delta E* had been reached for the material. Furthermore, since the fading rates of materials seem to slow as time of exposure increases, objects with prior exposure, evidenced by their barely perceptible changes in a fading test, may remain at least visually fairly stable for many Lux-Hours in the future. With a standard for maximum allowable change, a model could predict a maximum allowable cumulative exposure. What makes this approach promising is that so much of the data found in the literature demonstrates similar behavior.

Actual Restart Fading Test Results

To check whether full light fading test data and restarted light fading tests data fit in the same curves, a common yellow manila envelope was used as a test material. There were initially three light fading tests conducted at 4.76 M-Lux. The first test took about 50 minutes and reached a Delta E* of about 9. The second or partial test of the same material and same light intensity level was conducted for 25.5 minutes and reached a Delta E* of 5.59 at which time the test was stopped. Without moving either the equipment or the sample the test was restarted after a period of time where the equipment was allowed to cool down. This test was continued for about 25.5 minutes and reached a Delta E* of 3.48. The results of these three tests are plotted in figure 23.
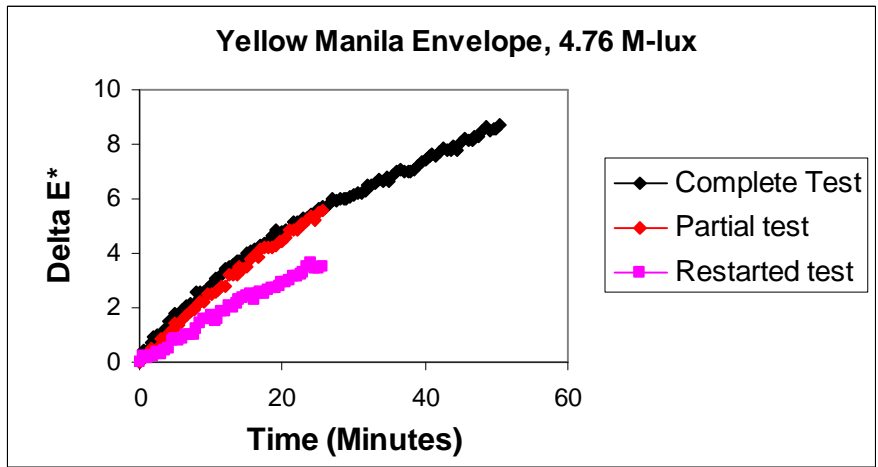
Yellow Manila Envelope, 4.76 M-lux

Figure 23 shows the light fading results of three separate tests on a yellow manila envelope. The first was a complete test that was conducted for about 50 minutes and reached a Delta E* of about 9. A second test that of the same material that went for 25.5 minutes and reached a Delta E* of 5.59 at which time the test was stopped. And a restarted third test of the same spot as the second test.

Since we know the stop-restart time (25.5 minutes) of the tests, this represents the time adjustment and as we know the value of Delta E* (5.59) when the partial test was stopped, this value represents the Delta E* adjustment. Using those adjustment values it is possible to relocate the restarted data to coincide with the full test data and this is shown in Figure 24.
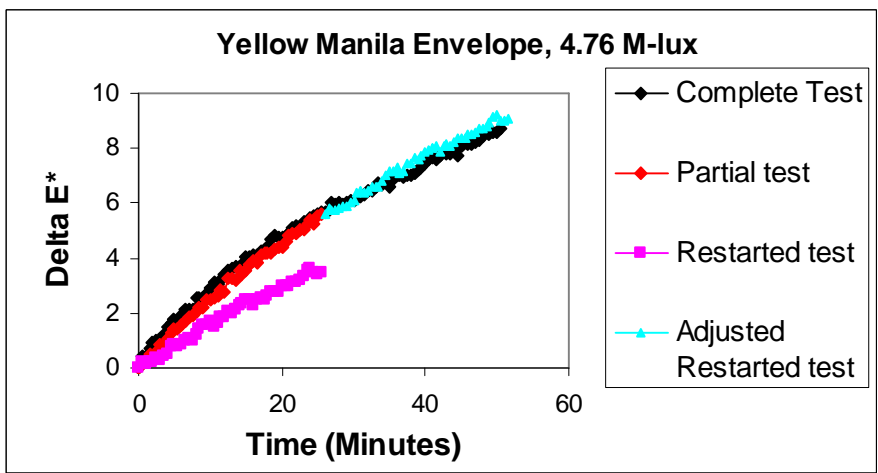

Yellow Manila Envelope, 4.76 M-lux

Figure 24 shows the light fading results of three separate tests on a yellow manila envelope. The first was a complete test that was conducted for about 50 minutes and reached a Delta E* of about 9. A second test that of the same material that went for 25.5 minutes and reached a Delta E* of 5.59 at which time the test was stopped. And a restarted third test of the same spot as the second test. Also shown is the adjusted restarted test to coincide with the full test.

A second start, stop and restart test was conducted at a higher light intensity and these test results are shown in figure 25.
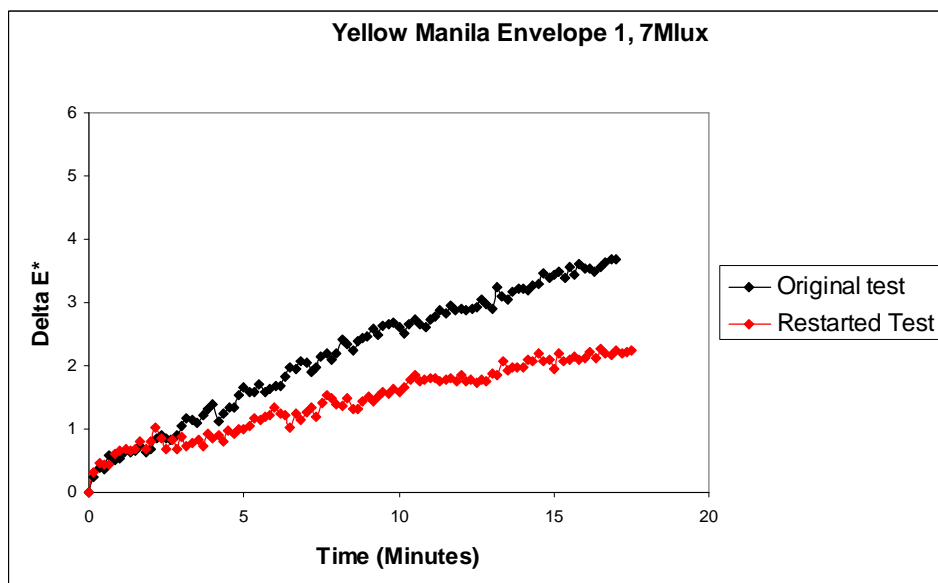

Figure 25 shows a second set of light fading results for the yellow manila envelope conducted at a higher light intensity. As before the results shown were the result of stopping the fading an initial fading test and then restarting it at a later time but using the same spot.
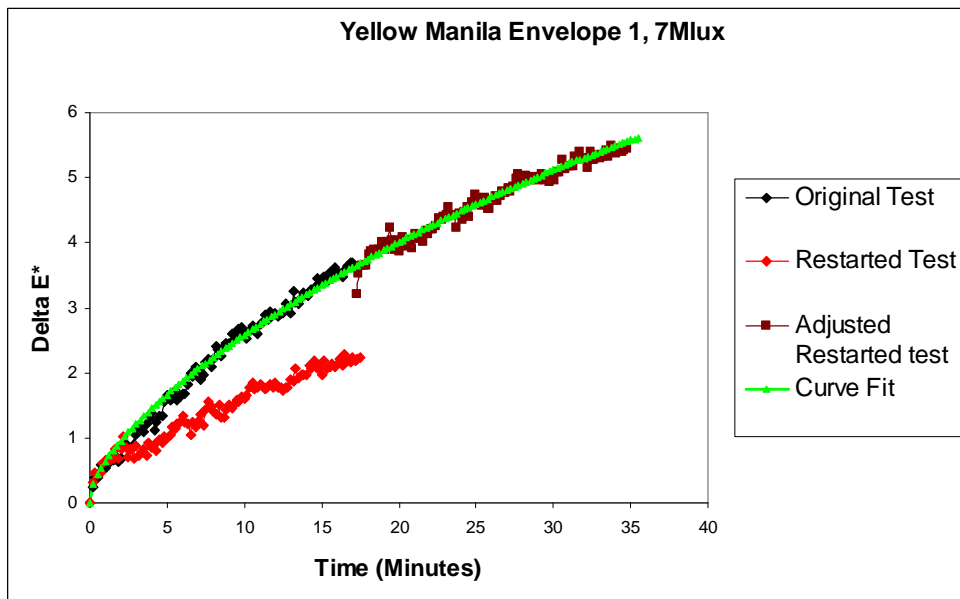
Yellow Manila Envelope 1, 7Mlux

Figure 26 shows a second set of light fading results for the yellow manila envelope conducted at a higher light intensity. In this figure the adjusted restart curve is show along with a "fit" to the curves.

Looking at Previously Faded Material

If a material has been faded over a long period of time, is it possible to determine the exposure dosage that the material has experienced? Figure 27 shows a detail of a yellow manila envelope that had been partially covered by a stack of other envelopes. As a consequence the edge of the envelope was exposed to the light from over head fluorescent lighting in the mechanics laboratory at the Smithsonian's Museum Conservation Institute. This exposure caused the edge of the envelope to fade while the center of the envelope was protected from the light.

Using the Micro Fading tester, fading tests were conducted at both faded edges (exposed) and the center area (protected) of the envelope. The light fading tests were conducted in May 2008.
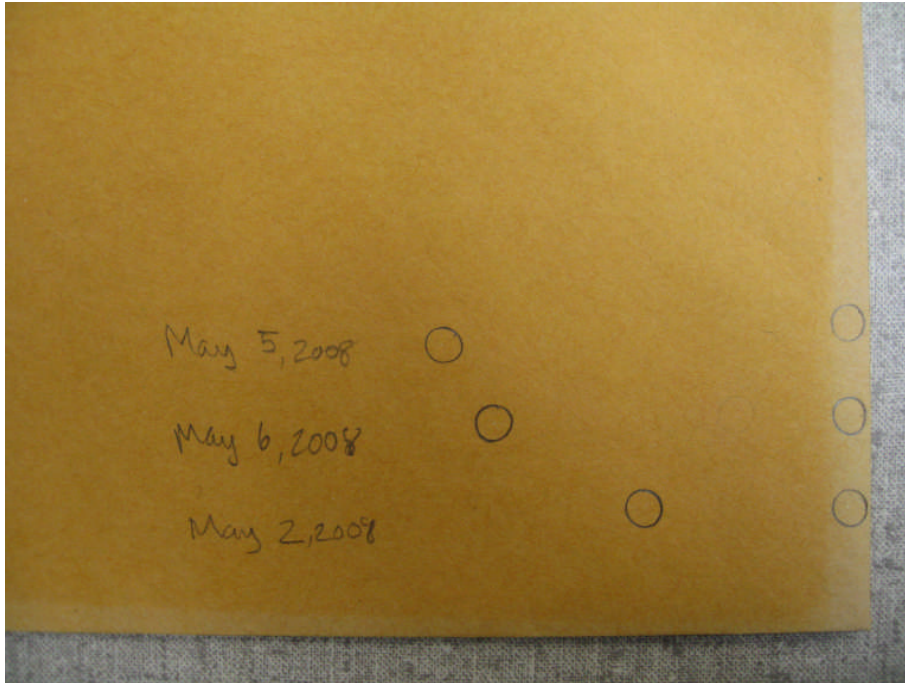
Figure 27 shows the faded edges of a yellow manila envelope that had been exposed to overhead fluorescent lighting in a laboratory at the Smithsonian's Museum Conservation Institute.

In theory it should be possible to show that the fading test results for the exposed area of the envelope is actually a continuation of the prior fading from the overhead lighting. It should also be possible to establish a light fading base line by testing the protected area of the envelope. Figure 28 shows the results of the fading tests of the envelope for both the protected and exposed areas. As can be seen the fading curves look entirely different. However it is possible to shift the plot for the exposed area onto the plot of the protected area and this is shown in figure 29. The time adjustment needed was 18 minutes and the Delta E* adjustment was 3.5. This shift represents a light dosage of 18 minutes times a light intensity or 18 x 7.2 M-Lux = 129.6 M-Lux-minutes or 2.16 M-Lux-hours. It is now possible to attempt to calculate the time of exposure for the envelopes while they were under the overhead lights. This is possible since the light level of the room is measurable and at the location of the envelopes it was 1,180 Lux. So the number of hours that the envelopes were exposed to the overhead light was; 2.16×10^6 Lux-hours / 1180 Lux = 1830 hours. And the number of days calculated becomes; 1830 hours (10 hours/day) =

183 days since the lights are on only 10 hours a day for five days a week. The number of weeks of overhead light exposure is; 183 days / (5 days/week) = 36.6 weeks. The number of months then becomes ; 36.6 weeks / (4 weeks/month) = 9.15 months. As the tests were conducted in May 2008, 9 months before that was August 2007. The envelopes were actually placed in the lab in July 2007, about 10 months before the May 2008 tests.
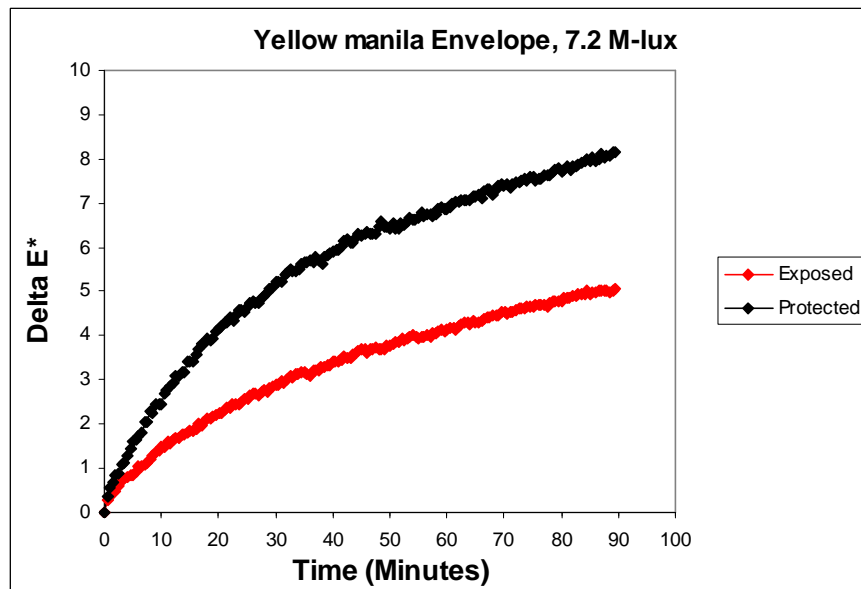

Figure 28 shows the results of the fading tests of the envelope for both the protected and exposed areas.

Yellow Manila Envelope, 7.2 M-lux

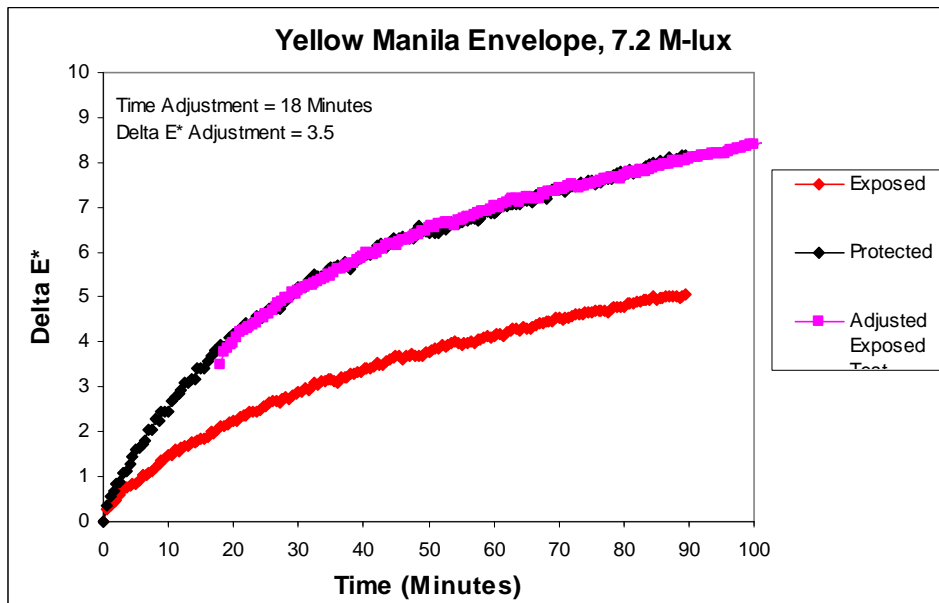Time Adjustment = 18 Minutes
Delta E* Adjustment = 3.5

Figure 29 shows the light fading results for the exposed area of the envelope, the protected area of the envelope, and the adjusted plot of the exposed area onto the protected plot.

References

1. Week of June 2- 6, 2008
Blue wool 1 standard tests (fresh card from Talas)
Intensity at illuminated spot: 7 Mlux
Illuminant/observer: D65/2deg
Integration time/spectra averaged: 6ms/10

2. 1999, Whitmore, P. M., Pan X. and C. Bailie, "Predicting the fading of objects: identification of fugitive colorants through direct nondestructive lightfastness measurements", Journal of the American Institute for Conservation 38: 395-409.