Development of a Micro-fading Tester with near-UV Capability

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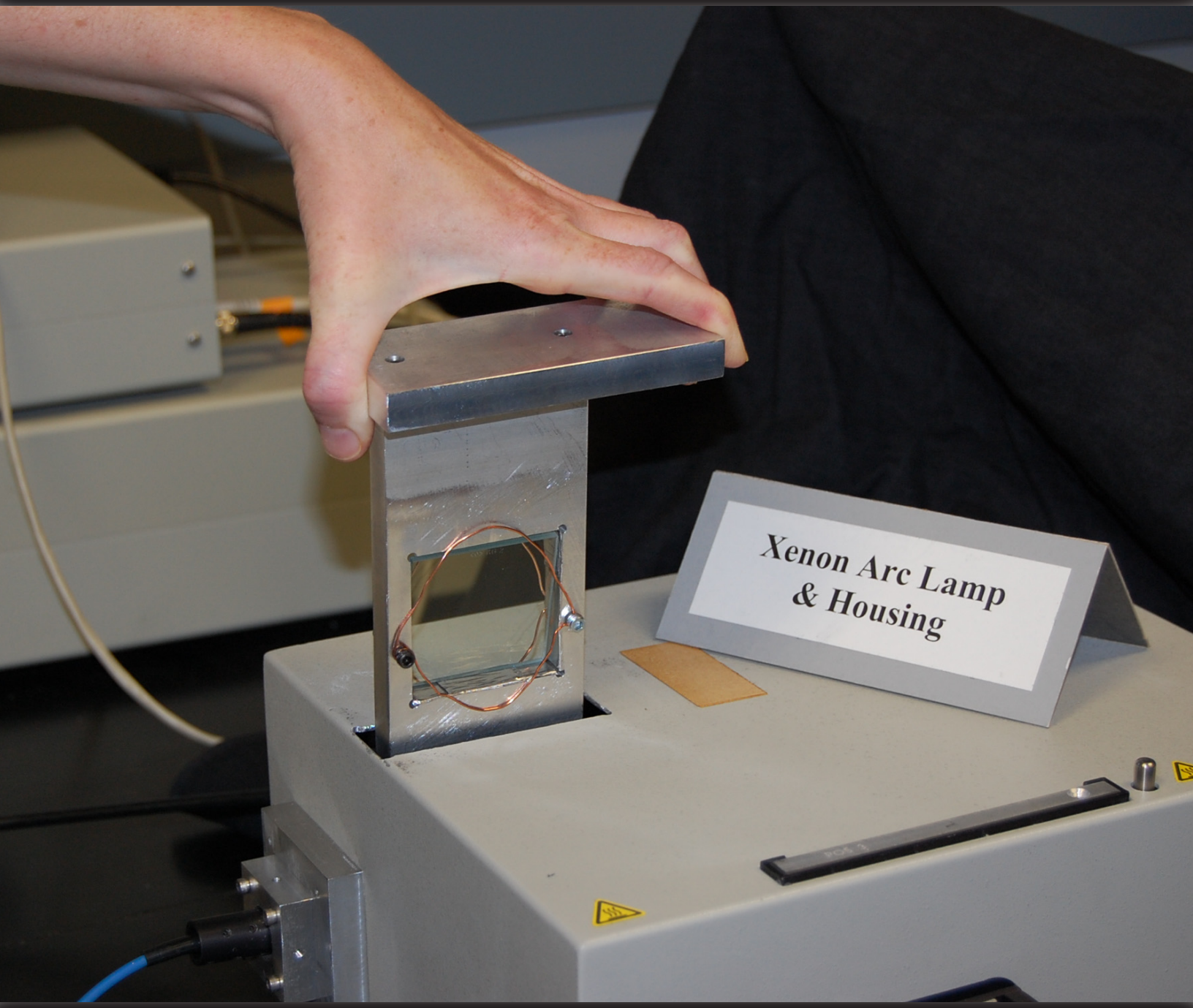

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Final Report

to

THE NATIONAL CENTER FOR PRESERVATION TECHNOLOGY AND TRAINING

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Executive Summary

This project was part of a continuing effort to further develop the micro-fading tester (MFT), a device that permits assessment of the light sensitivity of a colored artifact. The modified device allows for reproducible testing using light exposures that include the ultraviolet portion of the spectrum. The central limitation in using the standard configuration of the MFT in this way is posed by the chromatic aberrations of the simple lenses used in delivering the light from the xenon lamp to the sample. Those aberrations cause the light to be focused slightly differently for different wavelengths, so the position of the fiberoptic tip alters the spectrum of light delivered to the sample. Delivering a light spectrum that includes the visible wavelengths as well as near-ultraviolet radiation requires determining the optimum position of the fiberoptic connector, and in identifying the spectrum of visible light (which is the range that can be detected with the typical spectrometer supplied with the system) that indicates this optimum position. In this project, a protocol was developed to describe how that adjustment can be done. In a second phase of the work, a new lamp system was designed and built using mirrors, which are free of chromatic aberrations, rather than the lenses in the standard system. This new source delivers light having a very reproducible spectrum that includes UV wavelengths, with no need for adjustments to tailor the spectrum. Consequently, the fading test results with this new MFT source, especially those performed with light spectra including the visible and UV, are much more reproducible and compare well with xenon fading tests performed in conventional exposure cabinets.

Introduction

The micro-fading tester (MFT) was first introduced to the field of conservation in 1999 (Whitmore et al. 1999). This device was built to detect colored materials that will change (usually fade) relatively rapidly (within months or a few years) upon exposure to ambient light in indoor UV-free environments. In order to make such a prediction, the MFT exposes very tiny regions of a material to very intense light (about 50 times the intensity of visible sunlight outdoors), so that in a few minutes the sample receives a light dose that is equivalent to a few years in a gallery setting. By making rapid, repetitive, and very sensitive color measurements of the sample while it is exposed to this intense light, the tendency of a color to change from that light dose can be assessed nondestructively and compared to ISO Blue Wool lightfastness standards, measured under the same test conditions. This ability to identify vulnerable colors on cultural property has provided some crucial information in the development of exhibition policies for specific objects. Addressing such a centrally important preservation need has made the MFT an increasingly valuable tool for conservators. That value, and the offering of a convenient packaged MFT kit by a vendor, has made it possible for many institutions to obtain and use this device. To date the MFT is in use in about 17 institutions worldwide.

As the MFT has gained an increased number of operators, the nature of the questions about the impact of light exposures to cultural property have naturally expanded beyond the original one, of identifying extremely fugitive colors. A particularly important issue is the light stability of colored materials that are not exhibited in controlled UV-free lighting environments. Many collections, particularly those in smaller museums, historic houses, or protected outdoor settings, are displayed in natural sunlight, often without filtration to exclude ultraviolet wavelengths. The stability of colors in those settings cannot be tested with the MFT in its usual configuration, which delivers only visible wavelengths of light. Consequently, users have become interested in adjusting the MFT so that it can deliver a wider spectrum of light to samples, which will include the UV portion as well as the visible. Such an adjustment of the MFT seems straightforward, for the xenon source emits light down into the mid-ultraviolet range that simulates well the spectrum of natural sunlight. An UV-blocking filter is normally used to prevent that portion of the spectrum from reaching the sample, and it is sensible to expect that simply removing this filter would provide the broader light spectrum needed to perform the tests including UV.

One soon discovers, however, that simply removing the UV-blocking filter is not sufficient to adapt the MFT to allow reproducible testing with light including UV and visible wavelengths. The reason for this is that the simple lenses used to focus the xenon light output into the fiberoptic and from the fiberoptic onto the sample suffer from chromatic aberrations: the lenses do not focus all the wavelengths to the same point. So at any given focusing position, some portion of the light spectrum will be focused well, while the rest of the xenon output will not be. The result will be the capture (from the lamp) and delivery (to the test sample) of a spectrum of light that is variable and rather narrow in wavelength range. In particular, the position of the lens that focuses the light from the lamp into the fiberoptic can alter the spectrum of light that is delivered to the sample.

The first phase of this project was aimed at developing the protocol by which the conventional MFT system can be used to perform such UV+visible tests in a reasonably reproducible way. There were two objectives in establishing the procedure. First, the positioning of the fiberoptic tip that delivered the most reasonable spectrum of UV-visible light was determined, and the validity of the MFT results in that condition was verified by testing ISO Blue Wool cloths. Secondly, since most MFT systems were built using a spectrometer that does not measure intensities in the UV region, the shape of the visible spectrum when the optimum UV-visible spectrum has been achieved was established. By recovering that shape of the visible spectrum, a user would be creating a spectrum that also has the appropriate UV output for reasonable UV+visible tests.

In the second phase of the project, a completely new light source was designed, based on a new compact xenon lamp and using focusing mirrors rather than lenses to introduce light into the fiberoptic. Since reflective optics (i.e., mirrors) are free of chromatic aberrations, all wavelengths focus at a single point and the spectrum of light does not change with position near that focus. Consequently the spectrum of light delivered to the sample is insensitive to the position of the fiberoptic tip, and no adjustment is needed in order to deliver the appropriate UV+visible spectrum to the sample. The focusing of light from the lamp to the fiberoptic was also designed to allow the necessary filtration of the infrared (to minimize sample heating) as well as occasional intensity reduction (for focusing and alignment). The spectrum of light produced by this new device thus provides very reproducible UV+visible intensities that exactly match the broadband xenon lamp output. The performance of the new compact UV-capable MFT was demonstrated with tests of ISO Blue Wool fading standards.

Methods and Materials

Modification of standard MFT

The MFT utilized in Phase One of the project was a slightly modified version of the conventional MFT system described in Whitmore et al. (1999) and also available as the Oriel Fading Test System sold by Newport Corp. This design utilizes simple quartz lenses to focus light from the xenon lamp into the fiberoptic, lenses which have the chromatic aberrations described above. In order to adapt this MFT for testing including UV wavelengths, two modifications were necessary. First, the glass interference filter (also called a hot mirror) typically used to block infrared wavelengths down to 700 nm (and thus minimize sample heating during testing) had to be replaced, since that element also absorbs light in the near-UV region. Different filters were tested to deliver the spectral range desired while blocking as much infrared light as possible. A borosilicate glass filter combined with a 2" water filter gave a spectral range of 300~1000 nm. The heating at the test area was found to be below 38°C under ambient conditions, which should not pose a significant risk for most applications. A Schott KG-2 glass filter (Newport cat. No. FSQ-KG2) was also tested, which produced a spectral window between 300 nm and 800 nm, and according to the specifications it also transmits less than 20% of the lamp output in the infrared region between 1 μm and 2.5 μm. Using this filter alone would generate the desired spectral window and cause only a slight temperature increase in the test area, up to 36°C under ambient conditions. The only drawback of the KG-2 glass filter is that it cannot withstand illumination intensities greater than 30W/cm^2 without damage. While that did not seem to be a problem for its use in the MFT, for all the experiments described in this report using the conventional MFT system, the combined water and borosilicate glass filters were used to generate the spectral power distributions delivered to the samples.

The second modification of the standard MFT configuration was the substitution of a different spectrometer for measuring the spectrum of light reflected from the sample surface. The photodiode array spectrometer used in the original MFT design covers only the visible and near-infrared wavelength region (usually 380-900 nm or so). In order to measure light intensities at near-UV wavelengths, that spectrometer was replaced with another that covers a wavelength range from 250-780 nm, thus allowing measurements in the visible range as well as the critical 300-400 nm portion of near-UV.

In the conventional MFT design, light from the Xe lamp is collimated with a condenser lens in the lamp housing, then focused by a lens in the optical fiber coupler onto the fiber tip, before being delivered to the illumination lens assembly in the test head. Because of the chromatic aberration in the lens in the optical fiber coupler, the spectral power distribution delivered into the fiber is slightly altered depending on the position of the fiber tip in the region near the focal point of the lens. At any given position of the fiber tip, some wavelengths will be more tightly focused and thus more efficiently injected into the fiber. So adjusting the optical fiber position slightly near that focal point enables the sampling of different portions of the light spectrum. The fiber tip can be positioned at slightly different distances from the focusing lens by simply changing the position of the SMA connector (onto which the fiber is screwed) within the

barrel of the mount. Different spectral power distributions were thus obtained, and the spectral power distribution was adjusted to achieve the best match with indoor natural sunlight, or with another commercial xenon exposure cabinet, the Atlas SunTest CPS, that was designed to utilize a glass filter to simulate sunlight exposures indoors.

In order to evaluate the fidelity of the fading tests produced with this adjustment of the MFT spectral output, fading tests were performed on ISO Blue Wool standards. Including the UV content of the illumination should bring the fading of those standards closer to the nominal factor of two rate differences between the Blue Wool scale steps. The standards were faded according to typical test conditions: 600 millilumens irradiance, 100 millisecond spectrometer sampling rate, averaging of 10 spectra, and one minute intervals between saved data points.

New compact MFT design utilizing Apex source and focusing mirrors

In order to avoid using lenses having chromatic aberrations, a new optical design was developed using mirrors to direct and focus the light from the lamp into the fiberoptic. Such an optical system could not be retrofitted inside the lamp housing used in the conventional MFT system for lack of space. Instead, another lamp from the same vendor, an Apex 75W xenon arc fiber illuminator (Newport Corp. cat. no. 71206), was selected. Not only does this lamp housing have sufficient interior space to build the mirror system, but the housing also contains the power supply for the lamp. The convenience of the all-in-one lamp and supply will probably make this Apex device a superior choice for future MFT systems.

The Apex system as provided by the vendor uses a lens and a spherical back reflector to direct and focus light into the fiberoptic tip mounted on the front of the housing. For the UV-included application, a mirror system was installed so it would not compromise the original lens and reflector optical path. Thus the Apex can still be used in its original configuration. In order to direct the lamp output using mirrors, two 90° off-axis parabolic mirrors were employed. The 2”-high aluminum mirror facing the lamp had an effective focal length of 3” (Edmund Optics cat. no. NT47-105), and the output mirror an effective focal length of 2” (Edmund Optics cat. no. NT47-103). These mirrors were mounted on a platform next to the lamp, whose height was designed to center the mirrors at the level of the arc in the xenon lamp. The first mirror collects the lamp output and collimates a beam that is directed toward the rear of the housing (in the opposite direction from the lens output). That collimated beam is then collected and focused by the second off-axis parabolic mirror, where it is focused onto the fiberoptic tip attached on the side of the housing. Once aligned approximately, the final position of the mirror assembly was achieved by sending a bright light through the fiberoptic into the housing and tracing its path back to the arc position in the xenon lamp (which remains turned off during this alignment). The schematic of the optical system is shown in Figure 1, and a photo of the interior of the modified Apex source is shown in Figure 2. The exterior of the modified Apex source is shown in Figure 3. Finally, a filter holder was fabricated and installed to be inserted through the top of the housing cover into the path of the light beam between the two mirrors, where the beam is collimated. Inserting filters into this collimated portion of the beam will not affect the direction or focus of the beam at the output. Figures 4 and 5 show the filter holder and its insertion into postion through a slot cut into the lid of the Apex source. Figure 6 shows a close up view of the

lens holder at the test head (which includes a pen cam for viewing the test spot). The overall view of the portable UV+visible MFT is shown in Figure 7.

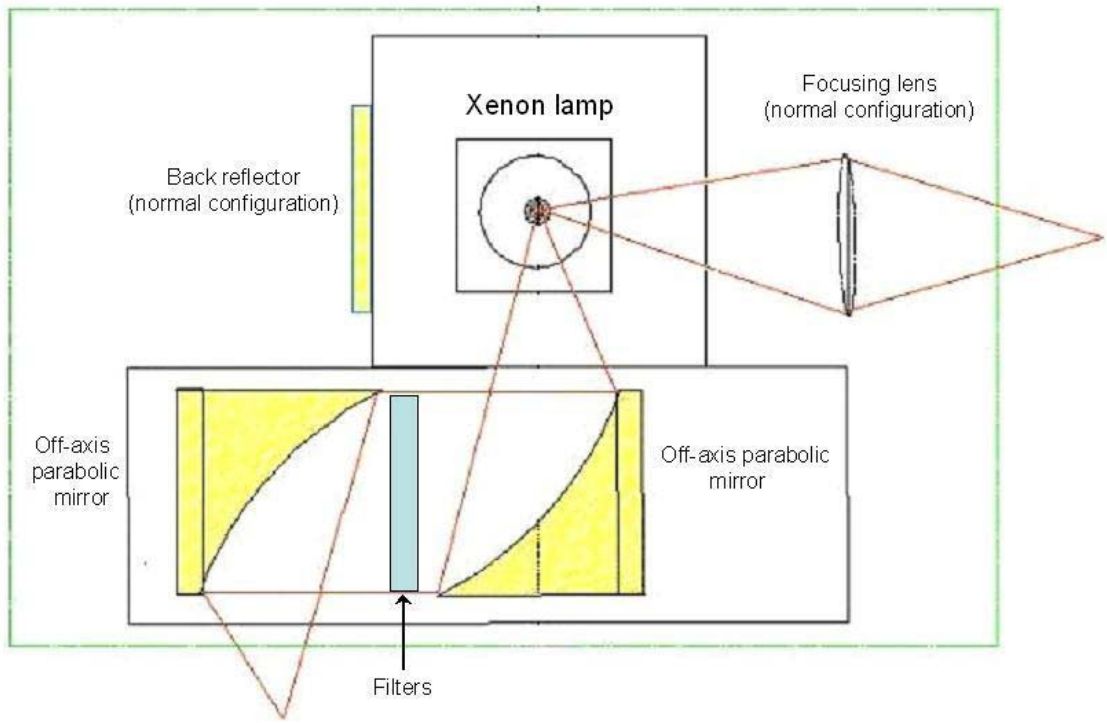

Figure 1. Schematic of optical path in modified Apex source

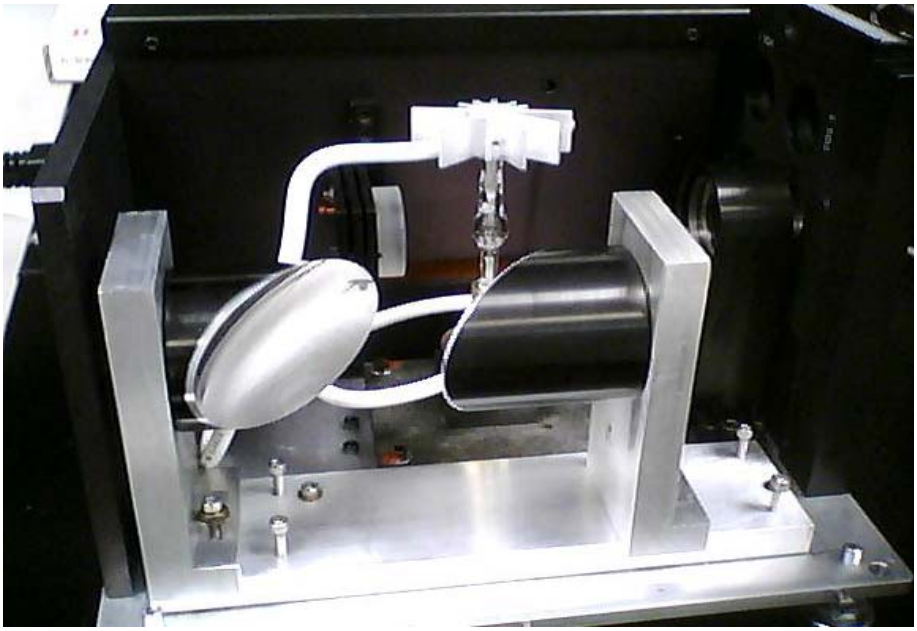

Figure 2. Photograph of interior of modified Apex source, showing the pair of off-axis parabolic mirrors mounted inside the housing

Figure 3. Photograph of exterior of modified Apex source. Fiberoptic connection for normal configuration is on right side of photo, fiberoptic connection for modified UV+visible output is on left.

Figure 4. Close-up of filter holder, which positions IR filters and neutral density filters between the two off-axis parabolic mirrors.

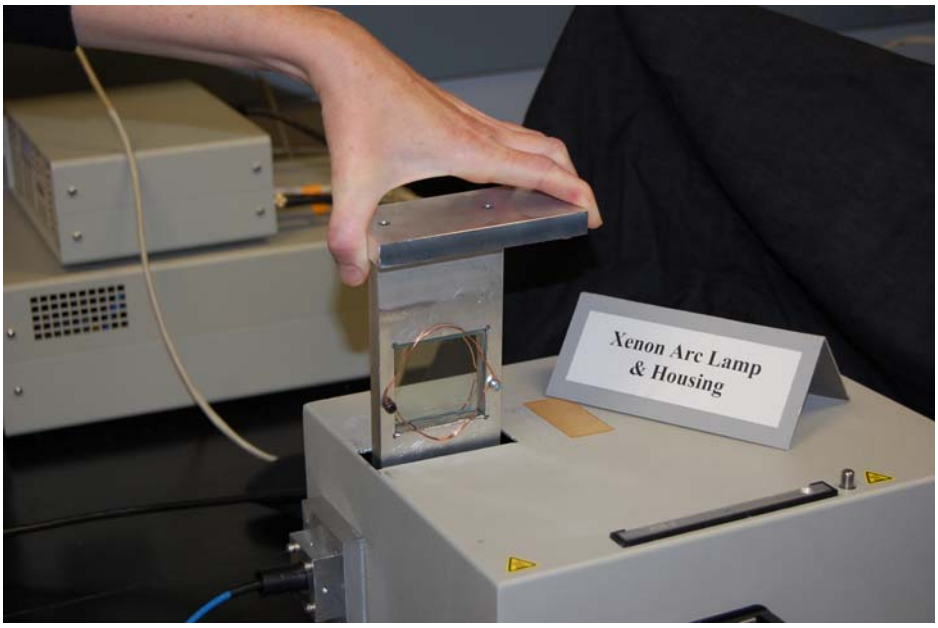

Figure 5. Photograph of filter holder being inserted into position through slot in top of modified Apex source.

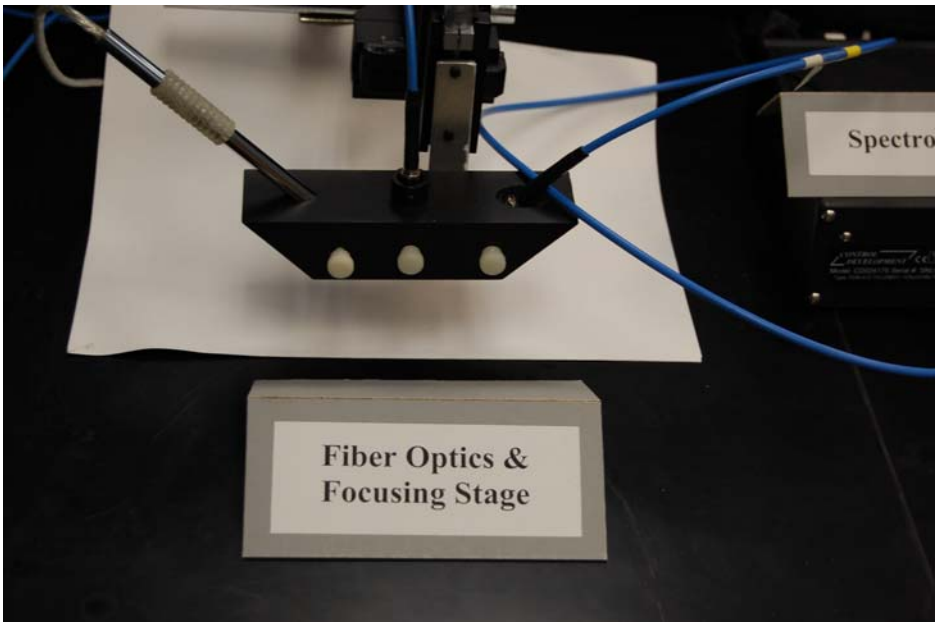

Figure 6. Photograph of test head of the MFT. Illumination fiber is attached to the central lens, the collection lens and fiber are on the right side. On the left side of the assembly is a pen cam, for viewing of the illuminated test spot.

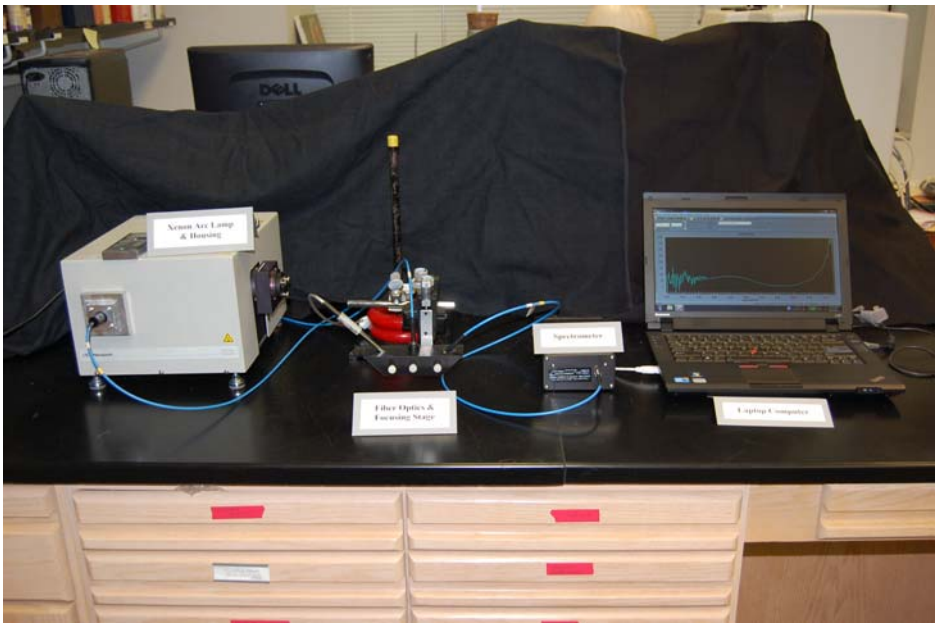

Figure 7. Photograph of the portable UV+visible MFT. The modified Apex source is at the left, the test head in the center, and the diode array spectrometer and laptop at the right.

As with the conventional MFT system, the spectral output of the Apex system was examined and tested by fading of the ISO Blue Wool standards. The same conditions of the fading tests were used for the compact Apex MFT, with the exception that 1000 mlm irradiance levels were used rather than the 600 mlm typically used in the conventional MFT. This higher irradiance represents the level that was obtained with the xenon lamp running at its normal operating condition, which, unlike the conventional system, cannot be adjusted on the Apex source.

Results and Discussion

Phase One: Characterization of UV-enabled conventional MFT system

As mentioned in the previous section, all the lenses in our MFT system are simple quartz lenses, which have slight chromatic aberrations. The effect of those aberrations on the spectral power distribution of the fiberoptic output is shown in Figure 8. In that figure, four different spectra are produced simply by positioning the fiberoptic tip at slightly different points near the focal distance from the fiberoptic coupler lens. At any given position of the fiber tip, some wavelengths will be more tightly focused than others and thus more efficiently injected into the fiber. So adjusting the optical fiber position slightly enables the sampling of different portions of the focused light, and the resultant variations in the output spectrum are the central challenge to conducting consistent UV+visible fading tests.

Knowing that the chromatic aberrations of the coupling lens effectively "sculpt" the resultant spectrum of the output light, however, one can utilize this effect to create a spectrum (shown in Figure 9a that is a reasonably good match to the desired solar spectrum containing near-UV and visible light (Figure 9b), or in this case, with the spectral power distribution in a commercial xenon exposure cabinet, the Atlas SunTest CPS, that was designed to simulate the solar spectrum (also shown in Figure 9a). The near-UV light below 400 nm accounts for about 16% of the total energy in the solar spectrum, so the fiberoptic position has been selected to produce about this same proportion. Also shown in Fig. 9a is the spectral power distribution of the MFT when it is aligned for its typical use in visible-only tests. The usual optimization to maximize lumen output (i.e., maximize output at around 550nm) causes reduced intensities to be delivered at the UV wavelengths.

The adjustment of the spectral power distribution to provide the appropriate near-UV intensities to simulate the solar spectrum produces a more familiar result for micro-fading tests of ISO Blue Wool standards. Figure 10a shows the fading test results for ISO Blue Wools 1-4 in the conventional MFT configuration, in which the near-UV intensity has been blocked, simulating a UV-filtered gallery environment. The Blue Wool 1 and 2 standards fade rapidly from exposure to the visible spectrum. The fading of Blue Wool 3 is very slow, much slower than the expected rate, which would be about half as fast as Blue Wool 2. The reason for this is the absence of near-UV intensity, which is required for the fading of Blue Wool 3 at its designed rate. Figure 10b shows the fading of these same Blue Wool standards using the configuration that delivers a spectrum that includes the appropriate intensities of near-UV wavelengths. The fading of Blue Wools 3 and 4 is easily measured with these exposures that include near-UV intensity, and the relationship of Blue Wools 2-4 is approximately what one would expect. Blue Wool 1 seems to fade slower than one would anticipate, as it does not seem to fade twice as fast as Blue Wool 2. The reason for this discrepancy is still unknown.

One final challenge remains in the modification of the conventional MFT to perform reliable UV+visible fading tests: nearly all current users of the MFT have systems whose spectrometers do not measure in the near-UV range. To address this difficulty, the shape of the

visible spectrum was examined after adjustment to deliver the appropriate near-UV intensities. After that optimization of the UV+visible output, it can be seen that the measured intensity at 400 nm is about 65% that measured at 500 nm. That proportion can be used to assess when the spectrum has been adjusted appropriately, without having to make the measurement of intensities in the near-UV range. This result allows the proposal of a protocol for using the conventional MFT system for use in fading tests including near-UV intensities:

PROPOSED PROTOCOL FOR MFT TESTING INCLUDING NEAR-UV WAVELENGTHS

1. Choose appropriate filters: KG-2 glass or Borosilicate glass with water filter.

2. Adjust the illumination fiber coupler end to sample different portions of the light. This adjustment can also be made by delicate movement of the lamp condenser lens. (Using the condenser lens for this spectral tuning will require re-optimizing the focus of the lenses at the test head.) The UV content in the beam should be similar to that of daylight indoors or the Suntest CPS. For systems with spectrometers sensitive only to the visible region, this UV spectral output can be roughly achieved by tuning the visible spectrum to have an intensity at 400 nm about 65% of the intensity at 500 nm.

3. Using a bandpass filter to allow only 450nm light into the fiber, adjust the test head lenses to optimize the focus at that wavelength. This condition should then produce reasonably good focus across the entire 300-700nm region.

4. Fade Blue Wools 1-4, and check their relative fading rates.

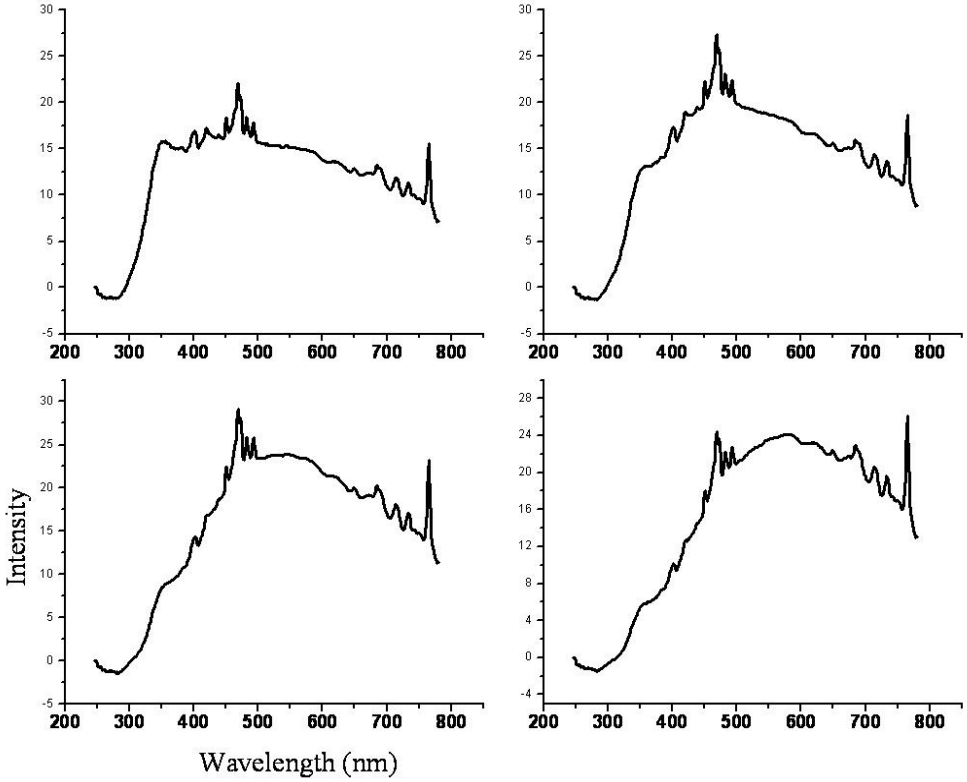

Figure 8. Spectral power distributions of the conventional MFT system without UV-absorbing filters, with the fiberoptic tip at four different positions near the focus of the fiber coupler lens.

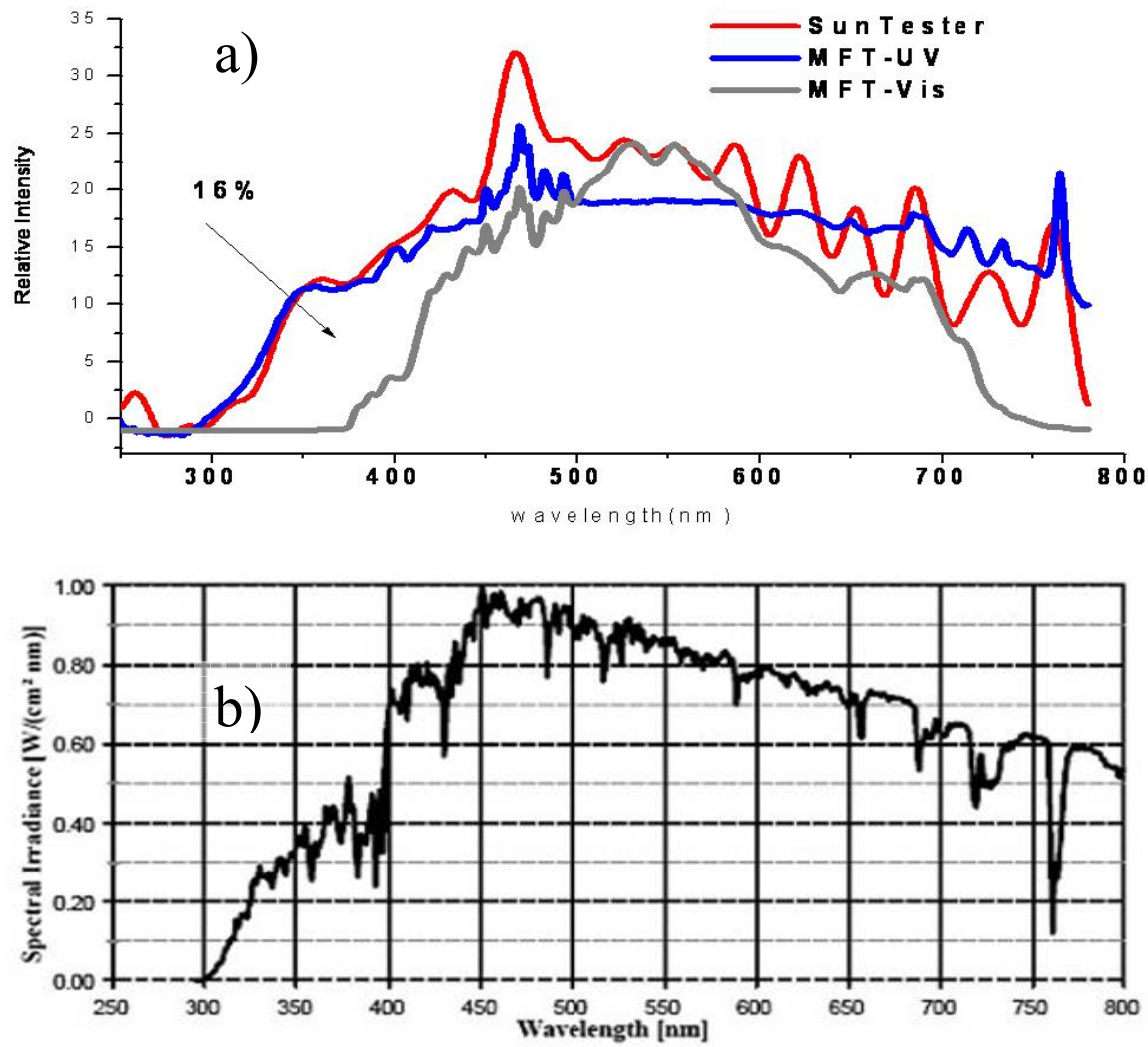

Figure 9. a) Spectral power distributions for MFT in normal visible and UV-adjusted configurations, along with output from commercial xenon exposure cabinet (Atlas SunTest CPS). b) Spectral power distribution of sunlight indoors, filtered through window glass.

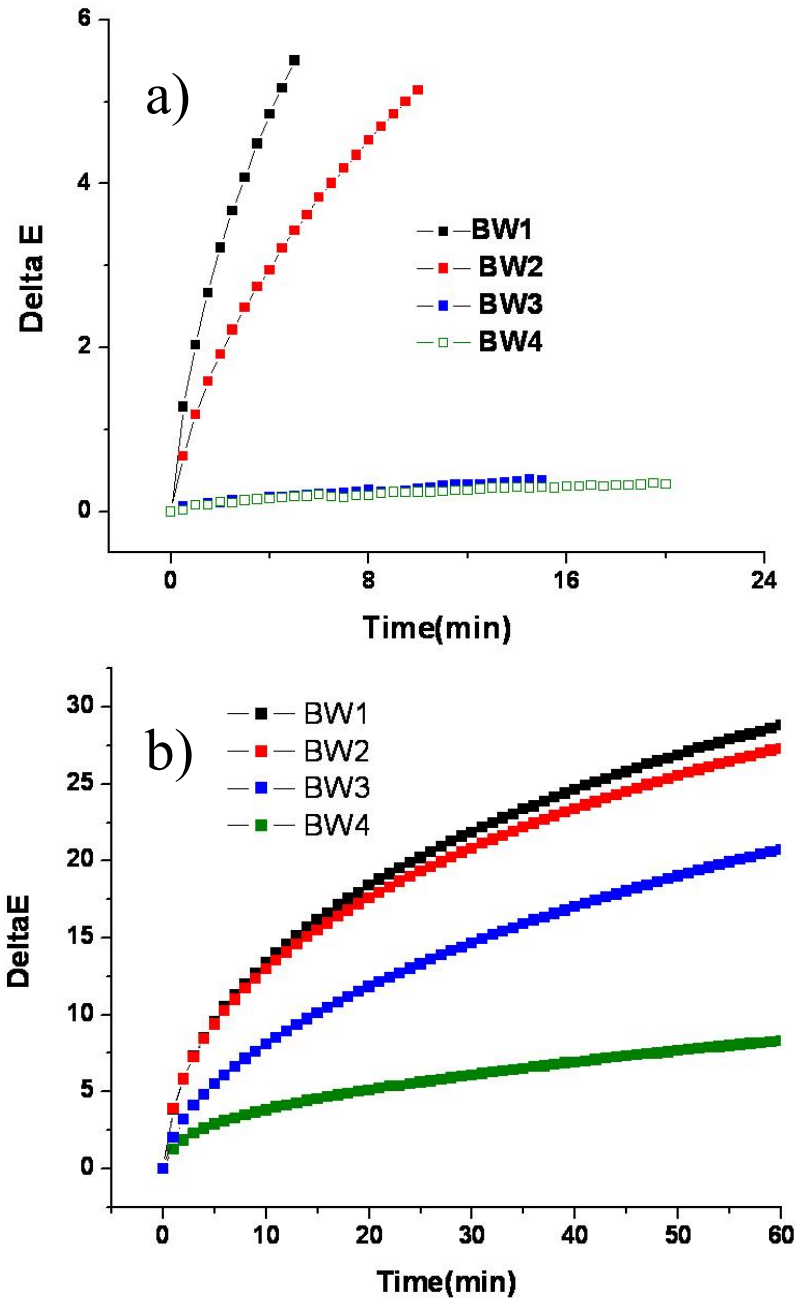

Figure 10. Fading test results for ISO Blue Wool standards 1-4 using a) normal visible-only MFT configuration, and b) UV+visible MFT configuration.

Phase 2: Characterization of compact Apex MFT system using reflective optics

Since the major obstacle to producing a consistent UV+visible spectral power distribution is the chromatic aberration of the simple lenses in the conventional MFT, the solution is to eliminate these optical elements from the design. The simplest way of avoiding such aberrations is to use mirrors rather than lenses. A compact version of the MFT has been fabricated, built around the Newport Apex xenon source, which includes the lamp power supply within the housing. That device has sufficient interior space to accommodate the simple mirror system, and the modifications were easily made. Using the pair of off-axis parabolic mirrors and a KG-2 glass filter between them to filter most of the IR from the beam, the beam is focused into the fiberoptic tip that is held in place by a connector mounted to the exterior of the housing. That focused spot is very small, and the fiberoptic must be located at that focus. The output of the fiberoptic is uniform and free of chromatic aberration, as evidenced by the purity of the white color of the beam and the lack of chromatic color at the edges of the spot (Figure 11). The spectral power distribution of the output is identical to the emission of the xenon lamp and contains the near-UV portion of the spectrum (Figure 12). Since there are no chromatic aberrations, the spectrum is constant and does not change with different positions of the fiberoptic tip.

Aside from the suitability of the spectral power distribution, this design does pose some other features that differ significantly from the conventional MFT system. Most importantly, there is no intensity control for the lamp, nor is any positioning adjustment possible to re-align the arc when it moves as the lamp ages. As a result, the long-term decrease in lamp output could limit the useful life of the lamp in the Apex system. Long-time users of that compact source report no problems with lamp life over many months, however. While the lamp has no easy adjustment, it may be possible to compensate with slight movement of the arc position by moving the position of the fiber tip to find the focused spot. That alignment of the fiberoptic to capture the focused spot is a very critical and difficult procedure, and that is the second area of concern for this particular design. It may be appropriate in the next version to mount the fiber attachment on a translation stage that would allow smooth and precise adjustments to be made. This matter is more likely to be important for initial set-up only. Once operational, the Apex source is essentially ready to use once the lamp is ignited and warmed up; no further lamp alignment is needed (or possible). Finally, mention should be made of the filter holder assembly (not shown in the illustrations), which lowers the 2” glass filters through the top of the cover into place between the mirrors. That particular position is close to the top electrode of the lamp itself (indicated by the vanes on the heat sink on the electrode connection shown in Fig. 2). There is an electrical hazard here that is easily avoided by adding an electrical insulator (a panel of non-conducting ceramic sheet, for example) to the side of the filter holder facing the lamp. This will eliminate any possible danger of contacting the lamp electrode with the filter holder assembly.

Figure 11. Image of the spot delivered from the fiberoptic in the compact Apex MFT system. Note the evenness of the white color and the lack of colored rings at the edges of the spot, indicating the absence of chromatic aberrations.

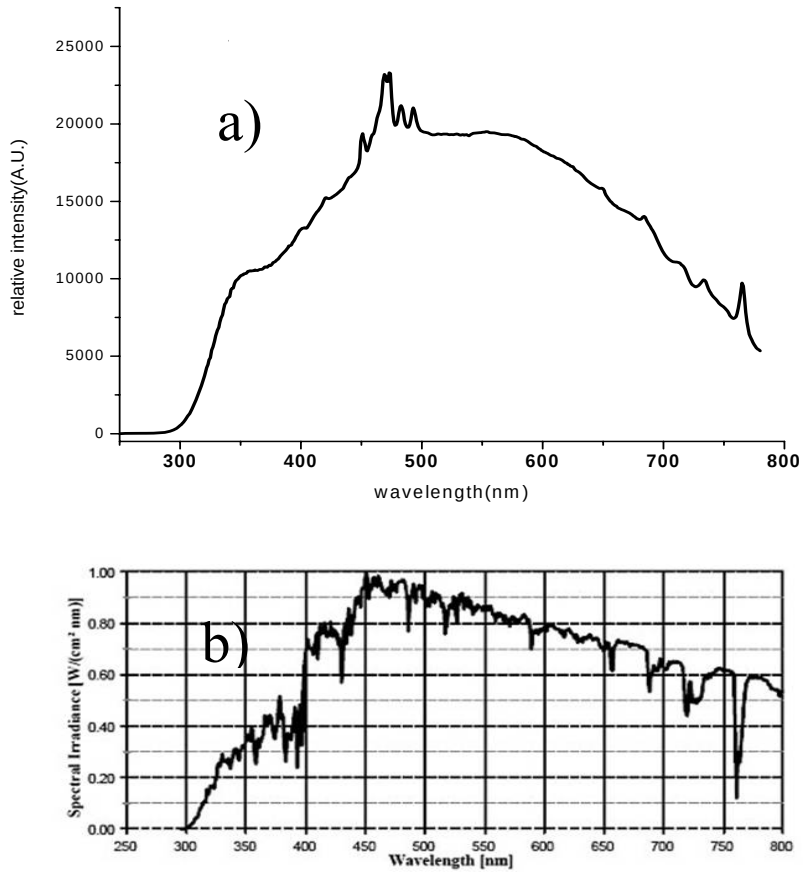

Figure 12. Spectral power distribution of a) output of compact Apex MFT, and b) natural sunlight indoors filtered through window glass.

The performance of the compact Apex MFT device is once again evaluated by the test results for the fading of the ISO Blue Wool standards. Figure 13 shows the results for those tests. Since the instrument delivers the appropriate intensities of the near-UV wavelengths, the fading of Blue Wools 3 and 4 is measurable and more in agreement with expected fading rates compared to Blue Wools 1 and 2. In this case, the fading rate of Blue Wool 1 and 2 is not quite the factor of 2 difference expected. Either Blue Wool 1 is fading slightly too slowly, or Blue Wool 2 slightly too rapidly, for reasons that are poorly understood. Still, the ladder of fading behavior is mapped out well by the Blue Wool test results, comparable to the UV-adapted conventional system (see results in Fig. 10). (Note that Fig. 13 presents data only for the first 5 minutes of the test, unlike the longer test times shown in Fig. 10.)

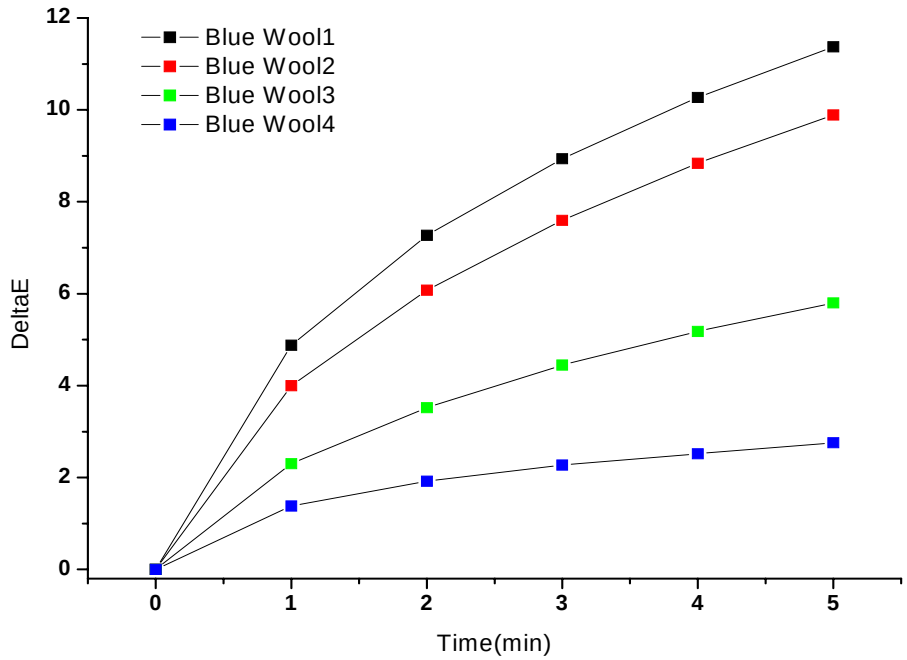

Figure 13. Fading test results of ISO Blue Wool standards 1-4 using the portable UV+visible MFT that incorporates the modified Apex source.

Dissemination

The findings in Phase One of the project have been presented at the annual Meeting of the American Institute for Conservation, in a session of the Research and Technical Studies specialty group devoted to micro-fading technology. In that presentation, the obstacles posed by the chromatic aberrations in the conventional MFT system were described, and the protocol for using the conventional MFT system to produce reliable tests including near-UV radiation was introduced. That presentation has been written as a postprint and will be published in the Postprints of the Textile Specialty Group of the AIC.

The results of Phase Two of the project, the fabrication and testing of the compact Apex MFT system, will be written and submitted for publication as a technical note to the *Journal of the American Institute for Conservation* later in 2011.

Conclusions

The objectives of this project were to provide guidance on the use of the conventional MFT system and to develop a next-generation MFT system that allows reliable micro-fading tests to be performed during exposure to near-UV and visible light. Those goals have been achieved. Even though most conventional MFT systems lack a spectrometer that can measure light intensities in the near-UV range, they can still be used for UV+visible testing by following the protocol described here. The new MFT design, using a compact light source and reflective optics, will provide a much more convenient and robust means to extend the utility of the MFT into performing these UV+visible tests. These UV-included tests are likely to be of limited value for predictions of fading from outdoor sunlight exposures—after all, even with the high light intensities used in the MFT, the tests only accelerate outdoor light exposures by a factor of about 50, so an hour-long micro-fading test only delivers an equivalent light dose as a few days of direct sunlight. But in more protected naturally lit environments where intensities are lower than direct sunlight, or in indoor environments that have natural daylight or lack UV-filtration, the results of micro-fading tests including near-UV radiation can be very useful predictors of damage from UV exposure. In addition to damage to colored artifact material from exposure during exhibition, UV-enabled MFT examinations can also be useful in predicting the outcome of conservation light bleaching procedures that may use light containing blue or near-UV wavelengths in order to bleach yellow discoloration. The progress resulting from this project should make reliable predictions of such conservation treatments feasible for the first time.

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