Ultra-Accelerated Weathering System I: Design and Functional Considerations

by **Henry K. Hardcastle**, Atlas Material Testing Technology LLC, and
Gary J. Jorgensen and **Carl E. Bingham**, National Renewable Energy Laboratory

This article describes the structure and initial results of a new Ultra-Accelerated Weathering System (UAWS). The system allows a 63-year (approximate) equivalent South Florida 45° UV-radiant exposure within a single year of ultra-accelerated exposure. The system provides high fidelity to natural solar UV spectral power distributions while attenuating visible and IR wavelengths to maintain acceptable specimen exposure temperatures. Data is included that shows correlation between ultra-accelerated exposure and real world exposure on a rapidly weathering standard reference material.

INTRODUCTION

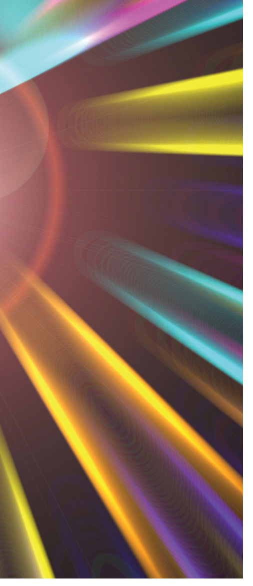
Ultra-accelerated approaches to weathering testing differ significantly from prior approaches of "real time" (not accelerated) and "moderately accelerated" weathering test methods. In real-time weathering, test specimens are directly exposed to weather in end use or worst-case end use environmental conditions. Test specimens mounted on racks that directly face the sun in South Florida or Arizona represent real-time, unaccelerated exposures. The ASTM G7[1] test method represents an example of a real-time exposure method. Moderately accelerated exposures can be categorized into natural and artificial classes.

Artificial accelerated methods utilize artificial light sources to simulate natural sunlight (typically filtered xenon arc or fluorescent light sources). Many of the developments in artificial weathering technologies have been focused on getting the light right—achieving good spectral match with natural sunlight in order to produce the same balance of photochemical degradation observed in real-time exposures.[2] ASTM G155[3] and SAE J2527[4] test methods represent examples of moderately accelerated artificial exposures.

Natural accelerated methods seek to intensify natural sunlight. The most popular method at present utilizes multiple mirrors to reflect multiple images of the sun onto a single exposure area where specimens are mounted. In this method (detailed in ASTM G90[5]) mirrors which reflect the entire solar spectrum with high reflectance from 295 to 2500 nm are used. Many recent developments in natural accelerated weathering technologies have been focused on achieving appropriate specimen exposure temperature since concentrated total solar light results in significant heating of many specimen types at moderate light concentrations.[6,7] Currently, specimen exposure temperature is managed by forced convective specimen cooling in these methods.

Moderately accelerated techniques typically accelerate UV-radiant exposures between two and 10 times over real-time South Florida exposures. A historical average for an outdoor South Florida 5° global southern exposure is approximately 300 MJ/m^2 UV (295–385 nm) per year. An average for moderately accelerated (~2X light intensity) artificial xenon exposure per SAE J2527 is approximately 1040 MJ/m^2 UV (295–385 nm) per year. A historical average for moderately accelerated natural exposure per ASTM G 90 is approximately 1500 MJ/m^2 UV per year.

Ultra-accelerated weathering techniques attempt to dramatically increase the UV-radiant exposure per unit time over that attainable with current moderately accelerated techniques. However, a critical constraint becomes apparent at these intensities—the material exposure temperature is a co-variable of the increased light intensity and moderately accelerated techniques have been limited by maximum allowable exposure temperatures for many materials. Therefore, ultra-accelerated methods must include alternative specimen temperature management not found in real time or moderately accelerated techniques.



The objectives of the UAWS project were not simply a matter of exposing materials to high irradiance. It is a fairly simple task to increase the exposure light intensity by moving specimens closer to artificial sources and using the inverse square law or exposing materials to multiple light sources or more reflected images of the sun. The real difficulty this project addressed was represented by a triple constraint: (1) expose test specimens to ultra-high irradiances with (2) high fidelity to natural solar spectra without (3) burning or melting the test materials or otherwise introducing unrealistic thermal damage.

The system developed is an outdoor accelerated weathering device. As such, it must be robust for use in the outdoor environment and able to withstand weathering elements with a high degree of reliability. It was desired that the intensity on specimens be approximately an order of magnitude greater than conventionally accelerated weathering devices in order to study highly accelerated radiant exposures and the effects of significantly greater intensities. To accomplish this, the design needed to achieve a direct normal optical concentration factor of approximately 100:1 (defined as the ratio of the area of the highly reflective facets to the target area). The reflecting facets needed to have high spectral reflectance in the solar UV spectra and not excessively distort the solar spectrum being reflected. Gerlock, Nichols, et al. at Ford Research, have shown the possible consequences of unnatural UV spectra on photochemistry of degrading automotive coatings.[2] Temperature is a critical constraint in high intensity weathering exposures. The system could not excessively heat the specimens. Heat distortion, exceeding onset of glass transition, melting, burning, and other heat- and temperature-related effects often present the most challenging difficulties for accelerated weathering test systems. The system developed and used for this article is shown in *Figure* 1.

Figure 1—Ultra-Accelerated Weathering System installation, Arizona.

STRUCTURE

Reflective Facets

By far, the most critical components of the system are the reflecting facets. Each reflecting facet of the system utilizes a 96-layer selective reflective coating. The coating technology used was based on conventional electron beam evaporation for deposition of interference coatings. The coating utilized a system of several quarter wave interference reflectance packages, each consisting of alternating layers of materials with high and low refractive indexes. A Blazers BAK-1400 evaporation unit was used for the coating deposition process. In general, this procedure included cleaning materials in the vacuum chamber and accessories, cleaning the crucibles and the electron beam evaporators, cleaning the glass substrates, and depositing the interference layers consisting of alternating layers of zirconium oxide with silicon oxide and hafnium oxide with silicon oxide. High uniformity of the deposited coating was achieved over the entire substrate surface using masks resulting in an estimated non-uniformity in attained film thickness less than ± 1.5%. The absolute reflectance spectra obtained from this process is shown in *Figure* 2.

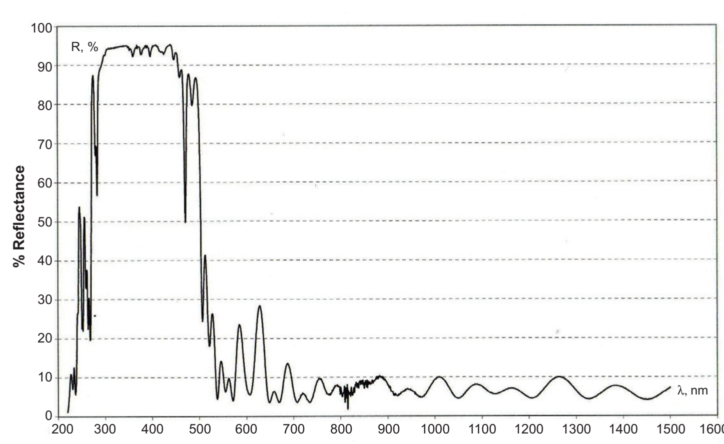


Figure 2—Reflectance spectrum of mirror facet.

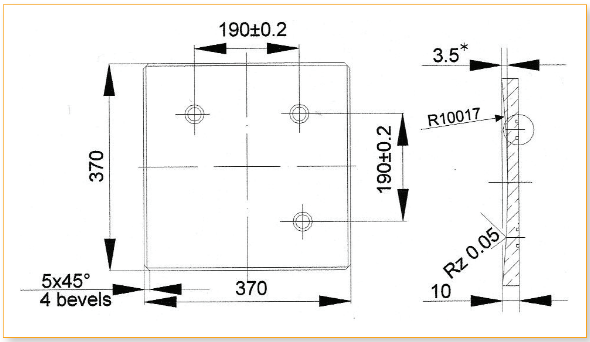


Figure 3—Reflective element construction (units in mm).

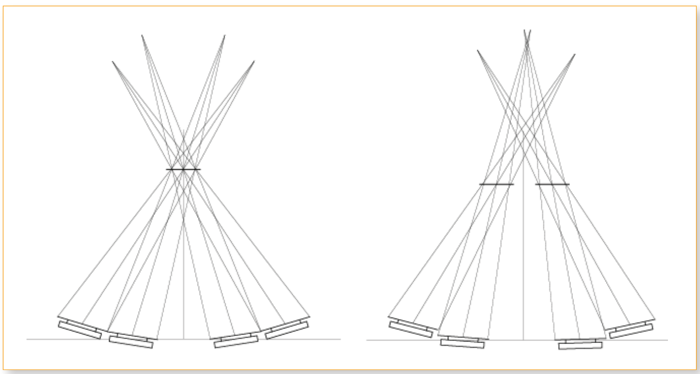


Figure 4—Single and multiple targets with independent facet alignment.

The key operating characteristics of the reflective interference coating obtained included (1) providing extremely high reflectance in the UV portion of the solar spectrum responsible for photodegradation of test materials, (2) attenuating near infrared (and long wave visible) portions of the solar spectrum that contributes to thermal loading but not photodegradation of test materials, and (3) providing a robust reflective surface for use outdoors.

The 96-layer reflective coating was applied to 29 glass focusing elements formed from K-8 borosilicate crown glass. Each facet was ground (prior to coating deposition) and polished to a 10-meter radius and bevelled along the edges. Three attachment points for mounting and alignment were ground into the back of each facet. *Figure* 3 shows the construction for the reflective facets. Attachment/alignment hardware was attached to the back of each reflecting facet which allowed both stable attachment to the concentrator structure as well as independent adjustable alignment of each facet. The adjustable alignment hardware provided a noteworthy capability of the system by allowing the concentrated sunlight to be split into up to four independent beams irradiating up to four different target areas. In this way, the single concentrator can have a single target area under 100% concentration or several target areas simultaneously with some fraction of the entire concentration as shown in *Figure* 4.

Concentrator Structure

The ILOT designed and constructed concentrator is the assembled collection of facets that collects sunlight and reflects and concentrates the light onto the target area. The concentrator was designed to hold the facets in a position approximating the concave surface of a 10-meter sphere. The supporting frame for the mirror facets included design elements which resulted in a radius in both horizontal and vertical axes. The 29 reflecting facets were then attached to the support structure using the three-point attachment/alignment hardware. To accommodate the curvature of the support structure and facet interference, four of the facets were slightly trimmed. The resulting collector structure is shown in *Figure* 5. The focused beam in the target plane is shown in *Figure* 6.

It is important that the concentrator design allows proper protection of the reflecting facets when the device is not in use. A pivot was designed which allowed the concave surfaces to be oriented facing the ground when not in use. In this way, the back side of the facet would be exposed to the elements and the front side reflecting surfaces would be protected from falling dust, rain, and other environmental variables by orienting the reflective surfaces in a protected environment facing the ground.

Target Area

The 10-meter radius of each reflective facet and the 10-meter radius concave shape of the facet support structure results in a focusing optical system with a focal length of approximately 5 meters. To achieve the 100:1 direct normal concentration factor, specimens were mounted approximately 2.5 meters toward the focal point from the collector. To accommodate this position, a target area support arm was constructed and attached to the concentrator structure so the entire system could be aligned with and track the sun. In the present configuration, this results in a 150 x 150 mm square target area with approximately 100:1 direct normal optical concentration.

One important flexible feature resulting from this design is the adjustability of the target area's distance closer to or farther from the focal point. The facets can be independently aligned to accommodate this positioning of the target as shown in *Figure* 4. In this way, even higher optical concentrations can be achieved with a corresponding tradeoff with target area size.

At 2.5 meters from the reflector toward the focal point, the target area support arm has hard point attachments to accommodate a variety of specimen mounting devices. This flexible attachment platform can accommodate a variety of specimen target fixtures and thus provide a cus-

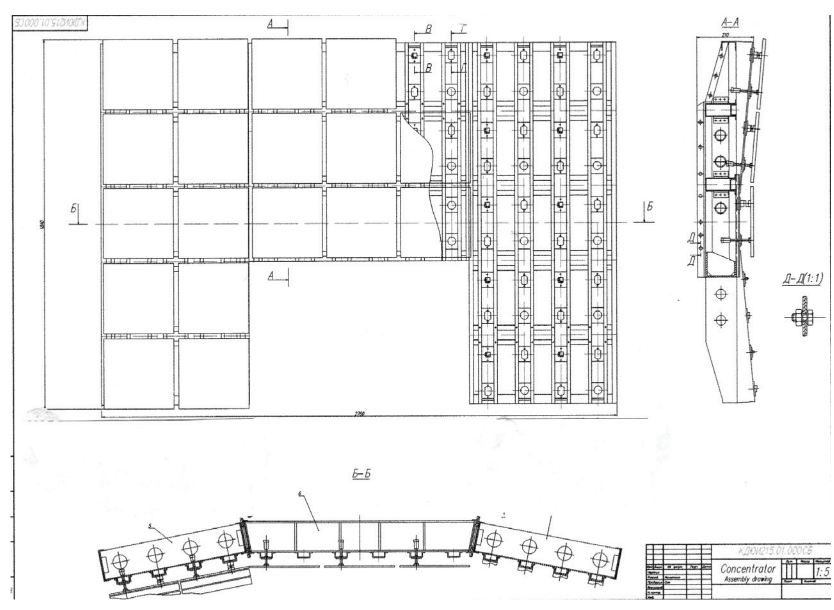


Figure 5—Collector support structure construction.

Figure 6—Reflective facets, collector structure, and focused beam in target area.

tomizable testing platform for a variety of materials, mounting configurations, and research program requirements. Some of these configurations so far have included: mounting specific for radiometric instruments, backed and unbacked specimen mounting, front clamping specimen fixtures, air cooled targets, back side water cooled mounting surfaces, multiple target area fixtures, and specially constructed environmental chambers. Electrical power, temperature measurement thermocouple wires, chilled water, and vacuum have been successfully delivered to the target area via service feed lines along the target area support arm. Axial blowers and beam attenuators have also been successfully mounted to the target area support arm. This flexibility is an important aspect for accommodating the large number of material types submitted for a variety of accelerated testing programs.

The concentrator and target area support arm are mounted on a high accuracy, commercially available solar tracking system which orients the tangent of the concentrator normal to the solar disc throughout the day (the system is not operated under cloudy conditions). The first device as installed and currently operating at Atlas' DSET laboratories (34°N, 112°W) is shown in *Figure* 1.

Uniformity in Target Area

A series of flux maps were taken at the DSET site to characterize the aiming and flux distribution of the UAWS. A target consisting of a 355 x 460 mm flame-sprayed alumina plate was utilized. The flux mapping system consisted of camera, lens, and frame grabber board, along with Beamview software from Coherent. The flux mapping system provides estimates of target uniformity, shown in *Figure* 7.The first image is a contour plot of the

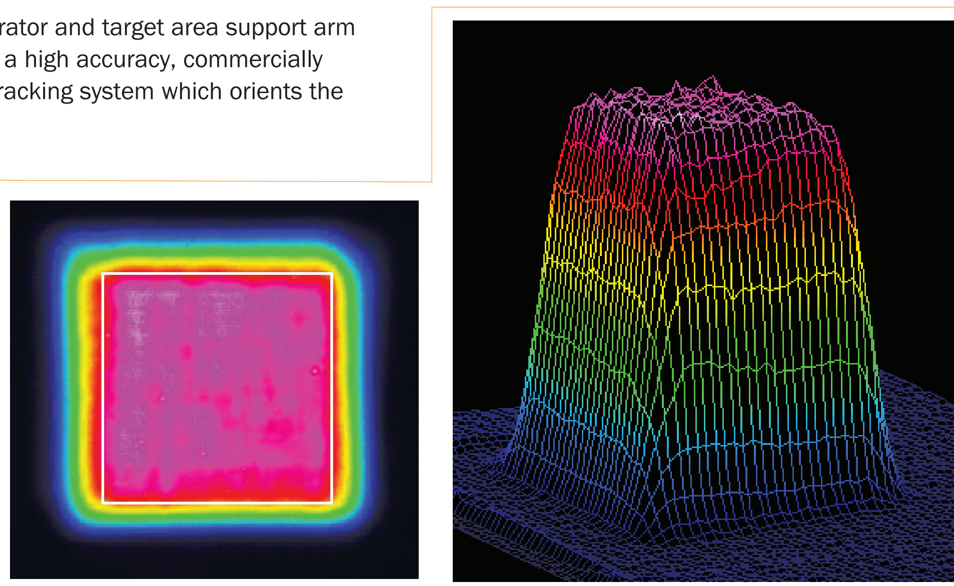


Figure 7—Images from flux uniformity measurements.

Figure 8—UV radiometers in unshaded and shaded configuration.

target, showing the brightness of the image, which is related to the flux intensity. The white square inscribed in the image is the nominal 150 x 150 mm target area for samples. The 3-D image is portrayed on the right-hand side. With all facets uncovered, this represents the full 100X of the UV spectrum. Using the Beamview software, the standard deviation of the uniformity of the intensity inside this box is +/–4.6% of the mean.

FUNCTION

Radiometry

Material changes are typically measured as a function of light exposure. Material degradation behavior is usually characterized as a degradation curve with change in property on the y-axis and UV-radiant exposure on the x-axis. Therefore, radiometry is typically a key part of weathering studies and must be carefully and correctly considered.

The first consideration for calculating radiant exposure of the device is the difference between global and direct normal irradiance. The ultra-accelerated device only concentrates direct normal solar irradiance—light from the circumsolar disk. Specimens on natural real-time exposure, on the other hand, see light from the solar disk plus light scattered throughout the entire sky dome, the direct plus diffuse component. The exact ratio of the UV from the entire sky dome vs. UV from only the circumsolar disk is always changing with the changing conditions of the sky, but it is on the order of approximately 2X.

For the installation in Arizona, the ASTM G90 standard was used as a guideline with an important modification to calculate radiant exposure at the UAWS target plane. The method within the G90 standard involves the use of two UV radiometers with response in the 295 to 385 nm spectral region. Both radiometers are pointed directly at the solar disc and track the sun as it moves across the sky dome during the day. One of these UV radiometers measures the light direct from the entire sky dome, both the light direct from the circum solar disk and the light reflected from the blue part of the sky—the diffuse component. The other radiometer measures only the diffuse component. It has a shading disk which excludes the direct normal component. It excludes the 6° circumsolar part of the sky so only diffuse irradiance is measured. These two radiometers installed at Atlas' DSET exposure laboratory are shown in *Figure* 8.

The direct normal component is simply obtained by subtracting the diffuse only UV component from the total global UV. Total, minus diffuse, equals direct. In this way, the direct normal UV (the only light the collector reflects on to the specimens being exposed) is measured throughout the exposure period. ASTM G90 clearly describes this instrumentation.

The next step in the G90 procedure is to multiply the direct normal irradiance by the optical performance parameters of the concentrating device. The incoming direct normal UV is multiplied by the integrated reflectance of the mirror facets. The reflectance graph presented in *Figure* 2 shows the results of this measurement. The current device mirror facets have a reflectance of approximately 0.95 in the UV region. Subsequently, the value is then multiplied by the number of facets reflecting light coincident on to the target area. In current use at 100% name plate capability, the Arizona UAWS utilizes 28 facets. (Although there are 29 facets in the design, one facet remains unused as an unexposed reference in order to monitor facet performance and optical alignment.)

A final step is added to the method which is not included in the G90 standard. A concentration factor must also be applied since the reflective facets have a radius (focusing optics). For this factor, the geometric ratio of the collector facet size to the target size is used. For the current geometry, a factor of four is used as the multiplier.

In summary, the direct normal UV irradiance, multiplied by the UV reflectance of the facets, multiplied by the number of facets, multiplied by the concentration factor of each facet, is used to calculate the irradiance in the target area. The instantaneous irradiance multiplied by time duration of exposure results in the radiant exposure of the exposed specimens in the 295 to 385 nm spectral region expressed in MJ/m^2.

It is noted, however, that an instrumental measurement providing confirmation of the calculated radiometry method is desired by the weathering community for the UAWS as well as the G90 and other outdoor accelerated exposures. The best approach may be to perform spectral radiometric measurements in the target areas of these devices. Unfortunately, non-trivial technical obstacles make such measurements difficult. High irradiances quickly saturate spectral detectors and can damage delicate instruments. Integrating spheres and other front-end optical components are also easily damaged during high irradiance measurements and require special cooling considerations. Use of neutral density filters and grid screens also require special optical, cooling, and mounting considerations as well as techniques extrapolating low irradiance target measurements (i.e., measuring a single facet's reflected solar spectral irradiance) to high irradiance levels. Given these considerations, it appears the calculated radiometric approach is the best currently available approach.

The general calculated approach to properly deal with accelerated levels of radiant exposures has been developed, prescribed, and well documented by the standards community. The only adaptation here is to account for the concentration due to focusing optics. The infrastructure at Atlas and NREL already exists to use this method. The method is theoretically sound and has been successfully confirmed with empirical measurements.

Using these concepts, it is possible to calculate expected radiant exposure using the UAWS as well as compare radiant exposure rate using the UAWS with unaccelerated and moderately accelerated exposure methods. For example, from historical observations, the Arizona laboratory averages approximately 162 MJ/m^2 UV direct normal radiant exposure per year. Based on the above calculation using 28 facets, 0.95 UV reflectance, an optical concentration of 4, the device may average approximately 17000 MJ/m^2 UV in the target area per year.

For comparison, real-time Florida historical observations indicate approximately 275 MJ/m^2 UV-radiant exposure on a 45° facing south facing surface in a single year (300 MJ/m^2 UV on a 5° South Florida exposure angle). Dividing the potential average yearly UV-radiant exposure using the ultra-accelerated device by the historical average yearly UV-radiant exposure on 45° south in southern Florida (17000/275), results in a radiant exposure acceleration factor of approximately 63 (approximately 56 for 5° South Florida). Under these assumptions, it appears possible to obtain 63 years' 45° South Florida equivalent UV-radiant exposure (56 years for 5° South Florida) in a single year exposure on the ultra-accelerated device. Similar comparisons indicate it would take approximately 13 to 17 years in a Xenon arc exposure using SAE J2527 (depending on settings and assumptions) to achieve the same radiant exposure as a single year on the ultra-accelerated device. Likewise, it would take approximately 13 to 14 years using current ASTM G90 exposures (depending on historical averages) to achieve the same radiant exposure as a single year on the ultra-accelerated device under these assumptions.

Exposure Temperature

Exposure temperatures experienced by specimens undergoing ultra-accelerated weathering are a complex function of material characteristics and exposure conditions. Material characteristics include UV spectral reflectance and transmittance (with resulting absorbance) as well as a material's thermal conductivity and dimensions (thickness). Exposure conditions include incident spectral intensity, ambient temperature, sky temperature, and specific parameters associated with different types of cooling used for the exposure (conductive and/or convective cooling). Therefore, the actual temperature a specific specimen will achieve during ultra-accelerated exposure will be partly material dependent and partly exposure dependent.

The UAWS exposure temperatures for black coatings were compared to direct normal (DiNor) natural exposure temperatures using "T" thermocouples welded to automotive grade steel paint panels measuring approximately 150 x 100 x 0.76 mm. The thermocouple was welded to the exposed surface of black panels. Panels were then sprayed with a primer and highly absorbing black paint. To qualify the reproducibility of readings between different black panels, the panels were then exposed side-by-side directly to the sun (unaccelerated) and

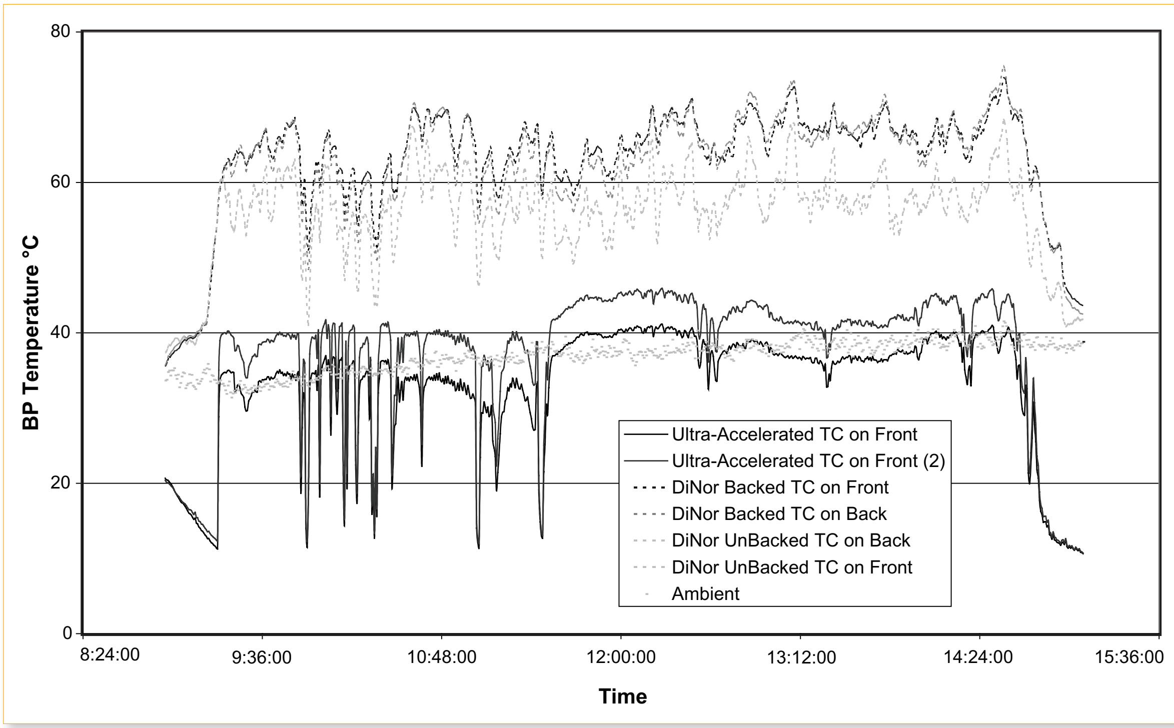


Figure 9—Ultra-accelerated and direct normal (DiNor) black panel temperatures.

none deviated more than 5°C in exposure temperature within the set.

Some of the panels were mounted direct normal to the sun in backed condition (mounted on plywood) while another was trimmed to approximately 75 x 55 mm and mounted in the target area of the UAWS backed by a water chilled cooling platen. Cooled water was circulated to the cooling platen to allow for backside conductive cooling of the black panel. The cooling water was set for the system's minimum temperature to provide data regarding minimum temperature capability of the system compared to natural exposure temperatures of the black panels. Panels were simultaneously exposed to the sun on May 18, 2009. Full ultra-accelerated capability (28 facets) was used to reflect the UV light on to the exposed black panel mounted on the water chilled cooling plate. The temperature observations are shown in *Figure* 9. The data indicate the black panels on ultra-accelerated exposure ran close to ambient air and well below the temperatures of black panels on direct normal backed exposure.

Correlation and Acceleration

Typically, whenever a new weathering technique is developed, a first step is to show correlation with outdoor real-time exposures as well as the acceleration capability. For this initial correlation and acceleration study, the European standard reference material "ORWET" produced by EMPA was used. ORWET is a pigmented thin film on aluminum substrate, a paint of melamine resin with a Ciba pigment. The ORWET standard reference material has been very highly characterized for color change as a function of UV-radiant exposure and is specifically designed to be used as a reference material for testing weathering methods.[8] The ORWET standard reference material exhibits rapid color change related to UV-radiant exposure. A simple comparison of different types of exposures with ORWET shows correlation as a function of radiant exposure and acceleration as a function of time of exposure (days). Correlation data indicates how well the new device simulates the natural degradation function. The acceleration data indicates how fast the device performs the simulation. It should be noted that a specific material's degradation function is highly dependent on the material's characteristics, thus degradation functions for a model standard reference material may not be indicative of other materials with different characteristics. References 9–15 show examples of other materials under ultra-accelerated exposure.

Specimens of ORWET were exposed unbacked, oriented 5° south to real-time exposure in South Florida and Arizona during the summer of 2008 at Atlas' EvTL (25° 52' North, 80° 52' West) and DSET (33° 29' North, 112° 8' West) exposure laboratories in accordance with ASTM G7-05. Additional specimens from the same lot were also exposed to natural moderately accelerated exposure at the DSET laboratory in accordance with ASTM G90-05 with approximately the same start time as the real-time exposures. UV-radiant exposure was measured in accordance with the G90 and G7 ASTM standards. Additional specimens from the same lot were also exposed during fall, 2008, using the UAWS device installed at the DSET laboratory. Ultra-accelerated exposure specimens were mounted backed with the same cooling block used to obtain the black panel temperatures shown previously. UV-radiant exposure was measured as previously described in this paper. Throughout the exposures, specimens were removed intermittently, measured for color change (Delta E) in reflectance, and replaced to continue exposure. The correlation graph showing color change as a function of UV-radiant exposure comparing the different exposure types is shown in *Figure* 10. The acceleration graph showing color change as a function of days of exposure comparing the different exposure types is shown in *Figure* 11. The data clearly show good approximation of the natural Arizona degradation by the ultra-accelerated exposure. Both the natural Arizona exposure and ultra-accelerated exposure were conducted in the Arizona desert environment. As with the natural Arizona degradation, the ultra-accelerated data lags the Florida exposure results. One hypothesis for this behavior may include the influence of moisture present in the Florida exposure but not in the natural Arizona or ultra-accelerated exposure as well as specific interactions between Florida's moisture variables and the ORWET material. Future efforts are planned to include the moisture variable in the UAWS. Another hypothesis for this behavior may include the temperature differences between the ultra-accelerated exposure and natural exposures. The ultra-accelerated exposure was conducted near the minimum system capability which may be a significantly lower temperature than the Florida exposure irradiation temperature and result in slower degradation rate per MJ/m^2 UV. Other hypothesis may also be considered.

The correlation demonstrated in *Figure* 10 has a number of significant implications. First, the color change of the standard reference material coating ORWET is approximately correct at ultra-accelerated rates compared with the Arizona natural exposure. This is an impressive result because the conventional wisdom has been that organic coatings could not be realistically and confidently tested at more than about 10 suns because of difficulties associated with adequately controlling sample temperature. Consequently, very abbreviated testing times can be substituted

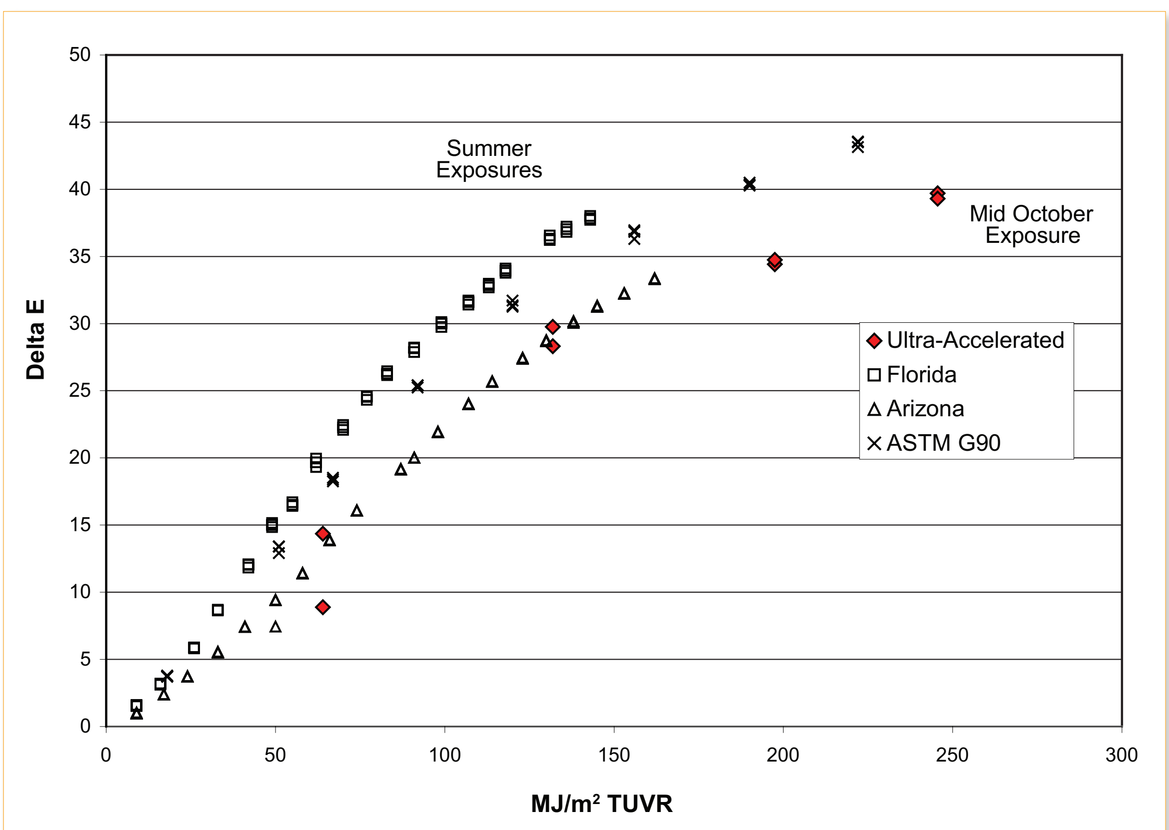


Figure 10—Correlation graph showing ultra-accelerated compared to real time and moderately accelerated exposures.

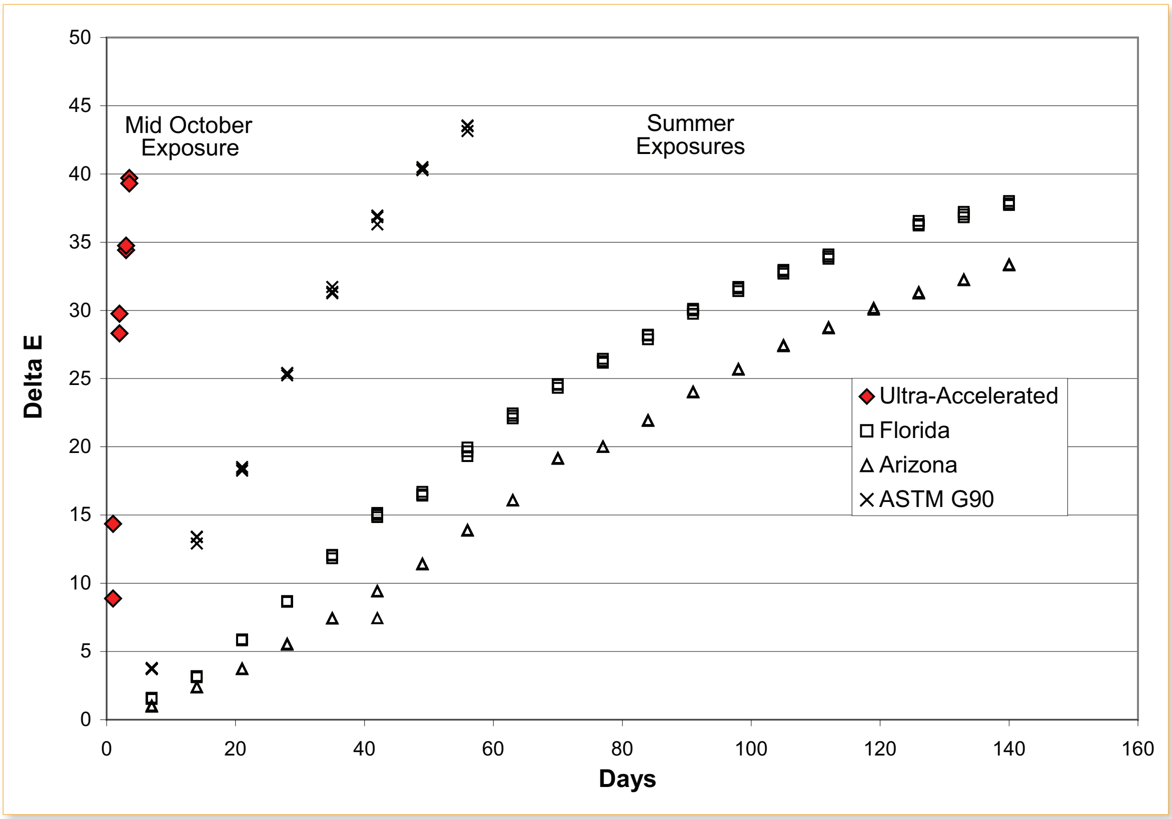


Figure 11—Acceleration graph showing ultra-accelerated compared to real time and moderately accelerated exposures.

for long-time exposures at low intensity levels, as shown in *Figure* 11 for this material. References 9–15 seem to indicate ultra-accelerated testing may be successfully used with other materials as well. If verified for specific material characteristics, ultra-accelerated weathering might allow much shorter development cycle times for new products; manufacturers will not be forced to wait months or years to ascertain if prospective coating systems will exhibit adequate UV-radiant exposure durability. This may provide a vital competitive advantage to such manufacturers and may result in greatly improved new products.

SUMMARY

Accelerated weathering exposures must be preceded with real-time, end use, or worst-case end use weathering exposures. Without such a base line for comparing with accelerated weathering results, highly questionable inferences and inappropriate extrapolations will result. Additionally, weathering data from a variety of sources should be used to make critical decisions about a material's weathering durability. These considerations are especially important to note as industries demand ever higher acceleration rates for material weathering testing.

Due to industry demand, a commercial scale ultra-accelerated weathering system has been developed allowing materials to be exposed to new levels of natural UV-radiant exposure. Using this system, it is now possible to expose specimens to approximately 63 years 45° South Florida UV-radiant exposure equivalent (56 years 5° South Florida UV-radiant exposure equivalent) within a single year. Additionally, ultra-accelerated exposures can be conducted using natural solar spectra while maintaining appropriate specimen exposure temperatures for many material types. The system has been installed and successfully used. Initial data indicates a potential for correlation with real-time exposure at ultra-accelerated degradation rates for some materials. Additional verification exposures using different materials as well as system modifications for introducing moisture and other weathering variables are warranted by the results and planned for the near future.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the memory, leadership, and technical vision of Dr. Alexey N. Alikhanov for preparing the foundation of this program for success—he is missed. The authors would also like to gratefully acknowledge the leadership and technical vision of Allan Lewandowski for providing the direction of this project. The authors would like to thank the DOE as well as organizers of the IPP program for support of this effort.

References

1. ASTM G7-05 "Practice for Atmospheric Environmental Exposure Testing of Nonmetallic Materials," *2005 Annual Book of ASTM Standards*, Vol. 14.02, American Society for Testing and Materials, West Conshohocken, PA, 2005.
2. Gerlock, J.L., Peters, C.A., Kucherov, A.V., Misovoski, T., Seubert, C.M., Carter, R.O. III, and Nichols, M.E., "Testing Accelerated Weathering Tests for Appropriate Weathering Chemistry: Ozone Filtered Xenon Arc." *J. Coat. Technol*., 75, No. 936, 35-45 (2003).
3. ASTM G155-05 "Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials," *2005 Annual Book of ASTM Standards,* Vol. 14.02, American Society for Testing and Materials, West Conshohocken, PA, 2005.
4. SAE J2527 "Accelerated Exposure of Automotive Exterior Materials Using a Controlled Irradiance Water Cooled Xenon-Arc Apparatus," *2003 SAE Handbook*, Vol. 1, Society of Automotive Engineers, Inc., Warrendale, PA, 2003.
5. ASTM G90-05 "Practice for Performing Accelerated Outdoor Weathering of Non-Metallic Materials Using Concentrated Natural Sunlight," *2005 Annual Book of ASTM Standards*, Vol. 14.02, American Society for Testing and Materials, West Conshohocken, PA, 2005.
6. United States Patent No.: US 6,659,638 B1, Dynamic Temperature Controlled Accelerated Weathering Test Apparatus, December 2003.
7. United States Patent No.: US 7,454,990 B2, Variably Controlled Accelerated Weathering Test Apparatus, November 2008.
8. Schultz, U., *Accelerated Testing: Nature and Artificial Weathering in the Coatings Industry,* Vincentz Network, Hanover Germany, 2009, p 138.
9. Jorgensen, G., Bingham, C., Netter, J., Goggin, R., Lewandowski, A., "Chapter 11: A Unique Facility for Ultra-Accelerated Natural Sunlight Exposure Testing of Materials." From *Service Life Prediction of Organic Coatings: A Systems Approach*, Bauer, D.R. and Martin, J.W. (Eds.), International Symposium on Service Life Prediction, 1997, Breckenridge, CO, ACS Symposium Series 722*,* American Chemical Society, Washington, DC, 1999, pp 170-185.
10. Jorgensen, G., Bingham, C., King, D., Lewandowski, A., Netter, J., Terwilliger, K., Adamsons, K., "Chapter 6: Use of Uniformly Distributed Concentrated Sunlight for Highly Accelerated Testing of Coatings." From *Service Life Prediction: Methodology and Metrologies*; Martin, J.W. and Bauer, D.R. (Eds.), International Symposium on Service Life Prediction in Organic Coatings, 1999, Monterey, CA. ACS Symposium Series 805, American Chemical Society, Washington, D.C., 2002, pp 100-118.
11. Jorgensen, G., Brunold, S., Carlsson, B., Heck, M., Köhl, M., Möller, K. "Durability of Polymeric Glazing Materials for Solar Applications." Reichert, T. (Ed.), 1st European Weathering Symposium on Natural and Artificial Ageing of Polymers, September 2003, Prague, Czech Republic. Karlsruhe, Germany. DWS Werbeagentur und Verlag GmbH, 2004, pp 201-215.
12. Jorgensen, G.J., "Phenomenological Approach to Obtaining Correlations Between Accelerated and Outdoor Exposure Test Results for Organic Materials," *J. Testing and Evaluation,* Vol. 32 (6), 494-499, November 2004.
13. Jorgensen, G., Terwilliger, K., Bingham, C., Milbourne, M., "Durability of Polymeric Glazing and Absorber Materials," NREL Report No. CP-520-37041, National Renewable Energy Laboratory, Golden, CO, 2005.
14. Jorgensen, G. J., Terwilliger, K. M., Bingham, C. E., Durability of Polymeric Glazing and Absorber Materials, NREL Report No. CP-520-39580, National Renewable Energy Laboratory, Golden, CO, 2006.
15. Jorgensen, G.J.*, Optical and Mechanical Durability of Polymeric Materials for Solar Collectors*, Society of Plastics Engineers, ANTEC 2007, pp 2283-2287.

AUTHORS

Henry K. Hardcastle, Atlas Material Testing Technology LLC, Chicago, IL. Email: KHardcastle@atlas-mts.com.

Gary J. Jorgensen and **Carl E. Bingham**, National Renewable Energy Laboratory Golden, CO.