Temperature control in accelerated weathering testing of polymers

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Abstract

Accelerated weathering testers are used widely to evaluate the performance of outdoor plastic materials. These instruments simulate outdoor environmental conditions, particularly UV light, high temperature, and water as either rain or condensation. Control of specimen temperature during accelerated weathering testing is critical for plastic materials for two reasons. For one, the rate of photochemical degradation experienced by polymeric materials is often strongly temperature-dependent. Additionally, if plastics are subject to excessive temperatures, they can soften or even melt, failure modes that will not actually occur in their service environments. For this reason it is important to understand and maintain proper specimen temperatures during accelerated weathering testing.

This paper will present and discuss temperature control for the two most common types of accelerated weathering instruments: xenon arc chambers and UV fluorescent testers. For both, temperature is most commonly controlled using a black surface thermometer, typically called a black panel. Two types of these control devices are available – insulated and uninsulated. The construction of these are such that insulated black panels are optimal for testing insulating materials like plastics, and uninsulated black panels are best for testing painted metals. However, international test standards often do not provide this guidance, and UV fluorescent devices in particular rarely if ever specify insulated black panels. This paper will discuss the construction and usage of insulated and uninsulated black panels, and provide data supporting the increased use of insulated black panel thermometers in UV fluorescent testers for insulating and three-dimensional specimens.

Background Information

Black Panel Temperature Control

Plastics are used extensively in a wide range of outdoor applications. Their use has been enabled by greatly improved understanding of- and protection against - polymer degradation resulting from the combination of ultraviolet (UV) light, heat, and water. Weathering testing, including both natural outdoor and laboratory accelerated testing, is an invaluable resource for developing polymer durability. In the laboratory, modern weathering testing is dominated by two technologies: xenon arc and fluorescent UV testers. The primary difference between the two light sources is that xenon arc lamps produce light in the UV, visible, and infrared (IR) regions in proportions similar to natural sunlight, while fluorescent UV lamps match well the sunlight spectrum in much of the UV region but produce nearly zero energy in the visible and IR regions. Although these spectral differences are very well-understood and are the focus of much discussion and study, the differences in specimen temperatures produced by the two architectures are discussed in detail less frequently.

Both UV fluorescent and xenon arc testers use black surface thermometers, commonly referred to as "black panels." Black panel temperature control standardizes the conditions delivered to specimens, independent of laboratory conditions or other test parameters. The black panel does not necessarily match any particular specimen temperature, because different materials have different thermal conductivities and absorb radiant light differently. The black panel temperature is often thought of as representative of the maximum test specimen surface temperature, but this may not be the case.

Although both tester architectures use black panel temperature control, the environmental conditions experienced by test specimens are fundamentally different in the two types of chambers.

Temperature Environment of a Fluorescent UV Weathering Chamber

Fluorescent UV weathering chambers position test specimens such that they form the walls of a trapezoidal structure over a heated water bath (Fig. 1). The specimens are exposed to light from UV fluorescent lamps. The water bath provides saturation humidity to the chamber interior. The specimens are cooled convectively by ambient air in the laboratory, which is by design allowed to circulate on the back side of the specimens. The specimen surface facing the chamber interior is thus cooled below the dew point of the interior, causing condensation to form.

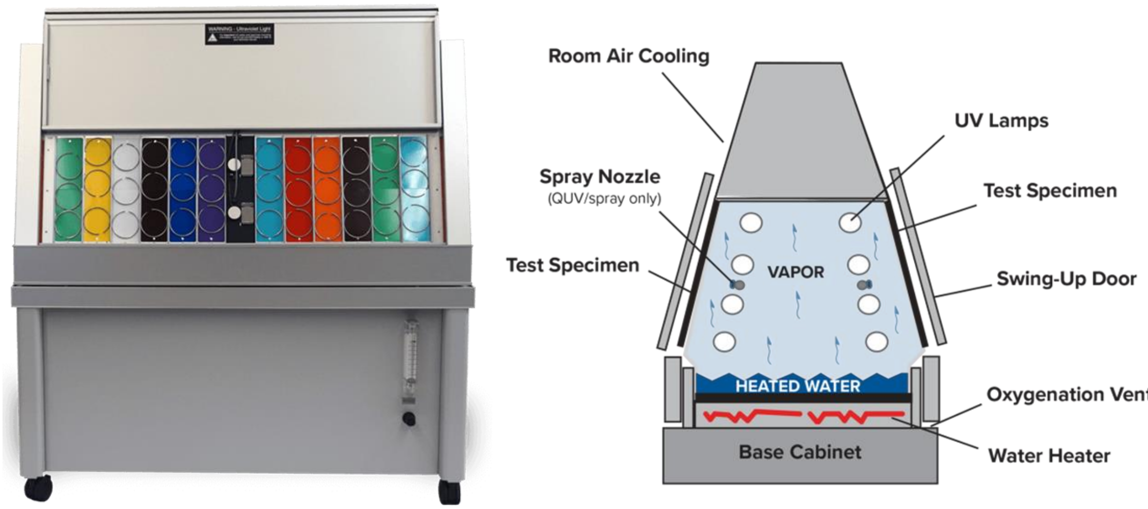

Figure 1. UV fluorescent tester with door open (left) and cross-sectional schematic (right).

Temperature is controlled in a UV fluorescent tester using a black panel temperature sensor (Fig. 2). This comprises a thermometer attached to a black anodized aluminum panel, allowing control of specimen temperature rather than chamber air or water bath temperature. Because of thermal transfer through specimens to the chamber exterior and the surrounding room, chamber air is always hotter than black panel temperature in fluorescent UV testing.

The thermal sensing element is located towards the inside of the tester (Fig. 2, left and center), within a housing (Fig. 2, right). The sensor faces the lamps, but does not directly receive radiation from them. The uninsulated black panel configuration (Fig. 2, center) is used in the vast majority of UV fluorescent testing. An alternate construction, referred to as an insulated black panel (Fig. 2, left), adds an insulating layer between the sensor and the black panel mount. This paper will provide results comparing plastic specimen temperatures using both configurations.

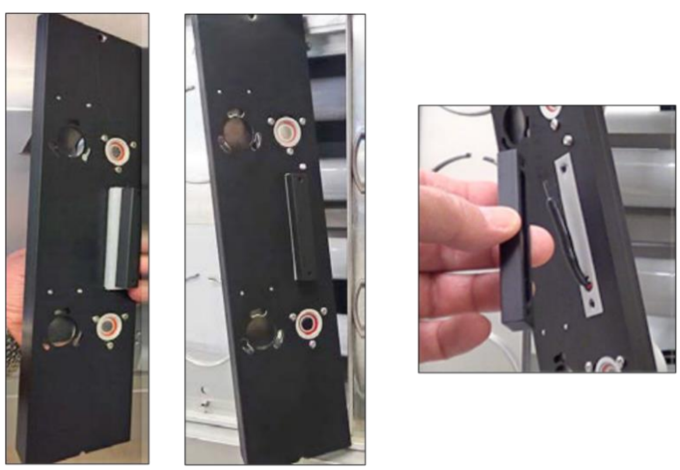

Figure 2. Black panel temperature sensor for UV fluorescent tester showing insulated (left) and uninsulated (center) configurations, as well as actual position of temperature sensor with housing removed (right).

Temperature Environment inside a Standard Xenon Arc Weathering Chamber

Xenon arc weathering test chambers (Fig. 3) expose specimens to full-spectrum sunlight, elevated temperatures, and water in the form of liquid spray and controlled relative humidity. The light spectrum produced by xenon lamps results in radiant heating of specimens, unlike in a UV fluorescent tester. In this environment, specimens are always hotter than the chamber air, opposite of fluorescent UV chambers.

Figure 3. Xenon arc weathering tester (left) and cross-sectional schematic (right). Flat array geometry shown here; rotating rack tester uses same operating principles.

Black panels are critical for standardized temperature control in xenon arc testers for the same basic reason as in UV fluorescent testers – to provide standardized test temperature control from test to test, laboratory to laboratory. Xenon arc testers also have two basic types of black panel (Fig. 4): an insulated black panel (referred to as a “black standard” in many international tests), and an uninsulated black panel (often called simply a “black panel”). The black panel is a painted aluminum panel that, for coated metals, approximates the highest temperature experienced by test specimens. The thermal sensing element in the uninsulated version is located in the housing on the irradiated side of the black panel (Fig. 4, right).

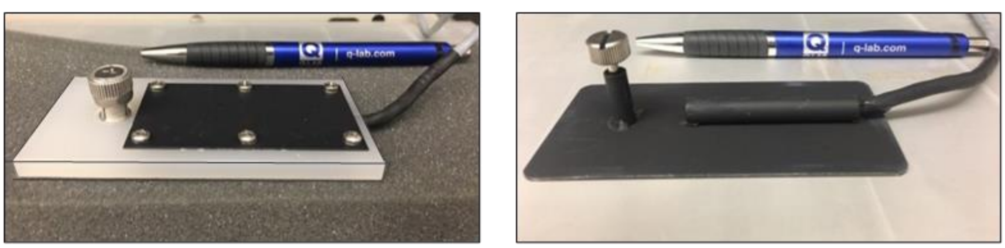

Figure 4. Black panel temperature sensor for xenon arc tester showing insulated (left) and uninsulated (right) configurations. Pen is included for scale.

The construction of a black standard is explained in detail in two major international standards for general laboratory weathering testing: ISO 4892-1 [1] and ASTM G151 [2]. This standard requires that the black-coated metal panel must be mounted on PVDF plastic, with the temperature sensing element residing on the non-irradiated side of the black panel Fig. 4, left). The element rests in the plastic base, in a cavity underneath the black panel and in good thermal contact with the metal plate.

Black Panel Usage in Test Standards

A very significant and common question in laboratory weathering testing is how test results correlate to natural weathering. Achieving the best possible correlation to natural weathering typically requires understanding the service temperature of the product or material and choosing an appropriate test temperature environment to simulate and accelerate that environment.

For xenon arc testing worldwide, both insulated and uninsulated black panels are in wide use. However, the divide tends to be according to test standard rather than material type, even though the uninsulated BP is clearly a better match for painted metals and insulated BP are best suited to polymeric materials. Consider ISO 4892-2 [3] and ISO 16474-2 [4], widely-used xenon arc test procedures for plastics and paints respectively. Both allow the use of either type of black panel, without expressing a preference. On the other hand, ASTM G155 [5] is the primary reference for general weathering testing within ASTM, and includes only uninsulated BP values, as does SAE J2527 [6]. Although both ISO and ASTM are international organizations, ISO standards are more prevalent in Europe and Asia whereas ASTM and SAE standards are popular in North America. Thus the BP / IBP selection often ends up being geography-based rather than application-based.

UV fluorescent exposures nearly always use uninsulated black panels, worldwide. The insulated black panel is rarely mentioned in major test standards. The work presented below demonstrates that this does the weathering testing community a disservice, as use of an insulated BP in a fluorescent UV tester is shown to provide a much better match to specimen temperatures for insulating and three-dimensional (3D) test materials than the typical uninsulated black panel.

Experimental Procedure

Experiments were conducted in a fluorescent UV accelerated weathering tester, shown previously in Fig. 1. This apparatus has 12 specimen holders on each side and can be divided into four "quadrants," left and right, front and back. The two front quadrants are shown in Fig. 2, outlined in green, with the black panel temperature sensor occupying the center spot. Note that the sensor itself faces the chamber interior. The rear of the tester is identical except without the temperature sensor.

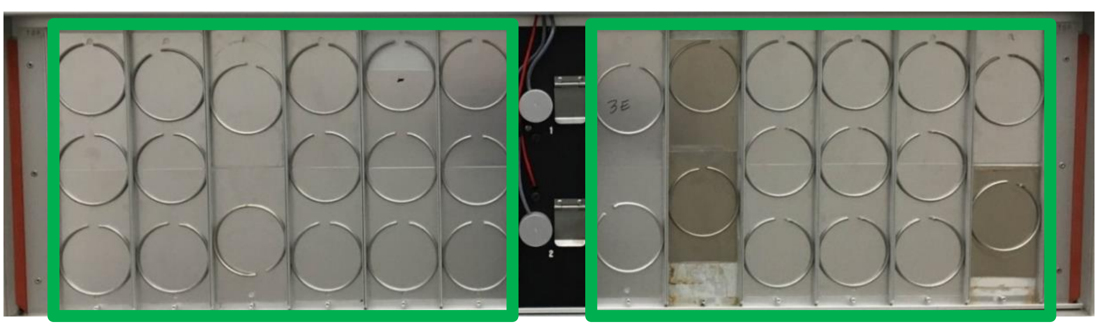

Figure 5. Front of a fluorescent UV weathering chamber with the door removed showing two quadrants (green outline).

Two sets of experiments were conducted. The first set used specimen holders mounted in a standard configuration with flat metal panels, as shown in Fig. 1 and Fig. 5. The surface under test of each panel in this configuration (inside the chamber, facing the fluorescent UV lamps) is at what is called the "specimen plane." The top and bottom panel of one specimen holder in each quadrant (3^{rd} from the end in each case) had thermocouples attached to their lamp-facing surfaces to monitor temperature during testing. Additionally, the blank metal panels were replaced with plastic panels in one specimen holder in the rear right quadrant (from the perspective of someone facing the tester from the front), 4^{th} from the end. This was done to evaluate the temperature differences between metal and plastic specimens. Thermocouples were attached to the top and bottom plastic panels in this specimen holder. Finally, a thermocouple was placed 1.3 cm (½ in) from the specimen plane to measure chamber air temperature.

A second experiment looked into the effects of three-dimensional specimens (Fig. 6, left image). For convenience, this experiment will be called the “3D test” and the previous group the “2D test.” Three-dimensional specimen boxes, both 5.1 cm (2 in) deep, replaced the specimen holders present in the standard configuration from the 2D tests. Note that the insulating door has been removed for this test. The front left quadrant had three thermocouples; one measuring chamber air temperature as in the 2D test, and two measuring temperature of an insulated black panel (IBP, or black standard) and an uninsulated black panel (BP, or black panel) on plastic standoffs (Fig. 6, right image). These black panels were both the same construction as those used in xenon arc testing (Fig 4). The right quadrant had three thermocouples affixed to two pieces of plastic lumber, a material with insulating properties. One piece was mounted to the back of the specimen box (thermocouple affixed to its front); the other set on insulating plastic standoffs to keep its face at the specimen plane (thermocouples affixed front and back).

Figure 6. Fluorescent UV weathering chamber with three-dimensional specimen boxes on the front quadrants (left image). Test configuration for the front left 3D specimen box quadrant, view perspective from inside test chamber (right image) shows, from left to right: insulated black panel mounted to specimen box, chamber air, IBP on standoffs, BP on standoffs.

All experiments used the same programmed test cycle of light, heat, and condensation. The test consists of alternating 4 hour cycles of UV light (controlled to 0.68 $W/m^2/nm$ @ 340 nm) and condensation. Three such cycles were conducted at each of three UV light temperature setpoints: 50 °C, 60 °C, and 70 °C. All condensation steps were conducted in a dark environment at 50 °C. A two-hour dark step was included between each segment to “reset” the chamber.

Results

Specimen Temperature in 2D Testing

The temperature data collected for the 2D test is shown below in Fig. 7. Each thermocouple’s output is represented by a single point for each of the 50 °C, 60 °C, and 70 °C UV light segments of the test cycle. Each point corresponds to an average temperature recorded during those four-hour segments. Temperature remains essentially constant once it stabilizes at the beginning of a UV light step, so information is not being lost from this representation. The y-axis temperature scale is adjusted to only show temperatures greater than 40 °C, such that the differentials between the various temperature measurements at each BP setpoint can be seen more clearly.

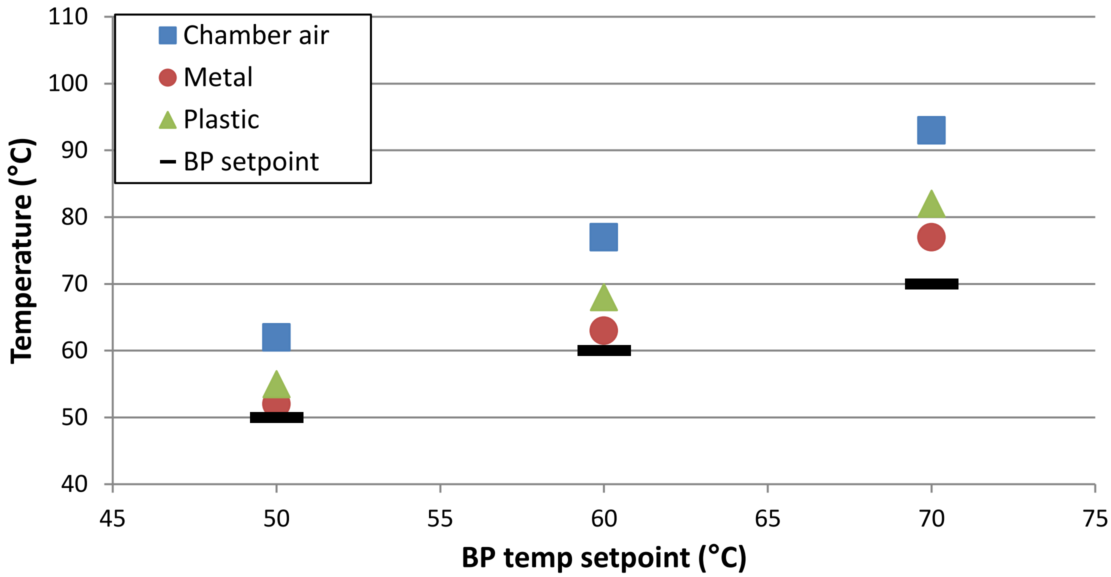

Figure 7. Average temperatures in 2D configuration recorded for chamber air (blue squares), a metal specimen (red circles), and a plastic specimen (green triangles) for black panel temperature setpoints of 50 °C, 60 °C, and 70 °C.

A critical observation from this data is the offset between the chamber air temperature and the black panel setpoint temperature. In all cases, the chamber air temperature (blue solid) exceeds the black panel temperature (black dashed) by a significant amount. As noted before, this is in contrast to the situation in a xenon arc weathering test apparatus. Furthermore, the magnitudes of the differences increase as the test setpoint increases. During the 70 °C UV light steps, the chamber air temperature is >20 °C higher than the black panel setpoint, a major difference that could impact test results significantly.

The temperatures measured at the metal (red) and plastic (green) specimen surfaces well exceed black panel temperature setpoints, with a greater differential observed at higher test temperatures. During the 70 °C UV light step, the plastic panel is 10 °C hotter than the black panel. For highly-temperature-sensitive plastic specimens, this difference between programmed setpoint and actual specimen surface temperature can have a major impact on test results. For materials with a low glass transition temperature, this can cause significant damage to specimens.

Specimen Temperature in 3D Testing

It is instructive to compare these temperature differentials from the 2D test to those observed during the 3D test (Fig. 8). Although the test temperature setpoints are the same as before, the measured temperatures have increased significantly. Chamber air temperatures are elevated by 6-13 °C relative to the previous test. Metal specimens are 3-4°C hotter; plastic specimens 5-7 °C hotter. As before, the differences are greater for higher-temperature setpoints.

These results may be counterintuitive, based on the experimental setup. Recall that in the standard “2D test” configuration, the specimens form the front and back walls of the chamber. A gap of about 2 cm is present between the back side of the specimen holders and the doors. This provides some limited insulation, but allows cool air to flow across the back of the specimen holders to promote condensation.

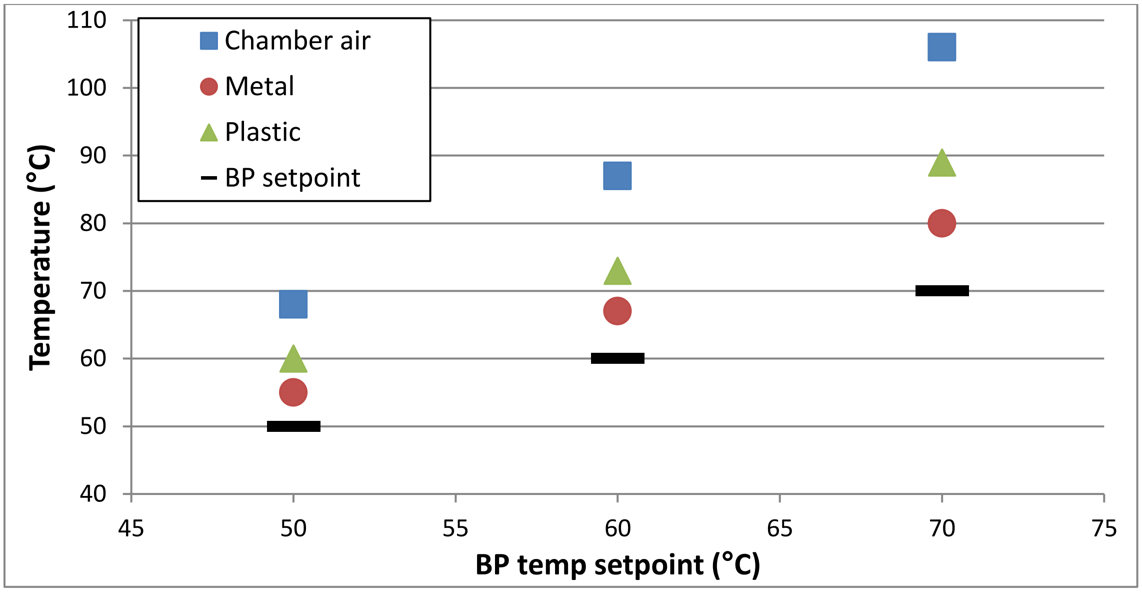

Figure 8. Average temperatures recorded in 3D configuration for chamber air (blue squares), metal specimen (red circles), and plastic specimen (green triangles) for black panel setpoints of 50 °C, 60 °C, and 70 °C.

In this 3D test configuration, however, the door must be removed. One might expect this to produce *lower* specimen temperatures because the chamber is less-well-insulated. However, the data indicates that the 3D setup produces *higher* specimen temperatures. The reason for this is the black panel temperature control. When the 3D specimen boxes are installed (Fig. 6), the BP temperature sensor is exposed to the laboratory environment, with no insulation provided by the door. The black metal panel thus more easily loses heat to the laboratory's ambient air. This in turn forces the tester to increase the heat delivered to the chamber in order to maintain the programmed BP setpoint. This effectively increases the temperature of the chamber air and the test specimens. This is a critical point to understand – removing the insulating door from a standard fluorescent UV weathering tester to perform testing of thick specimens will actually *increase* specimen temperature. The use of an insulated black panel counters this effect, as it retains heat better than an uninsulated black panel and therefore requires less heating to reach a setpoint value.

The ability of materials to lose heat by convection to the outside air and the metal specimen holders also explains some differences observed in measured temperatures between metal and plastic specimens. Consider the front left quadrant of the 3D test (Fig. 6, right image). The chamber air temperature thermocouple is affixed in the center of this specimen box, extending 1.3 cm (½") into the chamber, just like the 2D test. One IBP thermometer is in thermal contact with the back of the specimen box and thus is nearly 4 cm (1.5 in) farther from the lamps than the normal specimen plane. Additionally, an IBP and a BP sensor are mounted on plastic standoffs that align their faces with the specimen plane.

The temperatures recorded for this quadrant are shown in Fig. 10. The filled black circles and open circles represent the BP and IBP on standoffs, respectively. Both of them reached temperatures very close to the chamber air temperature, the hottest temperature recorded in this experiment. The insulated black panel mounted to the back of the specimen box (gray filled circle) was significantly cooler than the two mounted on standoffs – anywhere from 15-25 °C cooler. The key difference here is the specimens' ability to dissipate heat. The BP and IBP at the specimen plane have no thermal contact to the specimen box and are mounted on insulating plastic standoffs, and thus have no way to remove heat. As a result, they find themselves at temperatures very close to the chamber air and as much as 30 °C above the BP temperature setpoint. Very little difference – only 2-3 °C – is observed between the BP and IBP sensors in this test.

The IBP mounted to the specimen box can easily dissipate heat through the box wall to the ambient environment. This is a critical consideration for performing weathering tests with plastic specimens that cannot effectively remove heat like the BP and IBP on standoffs – they will see temperatures significantly hotter than programmed setpoints. Additional UV fluorescent temperature results were presented in [7].

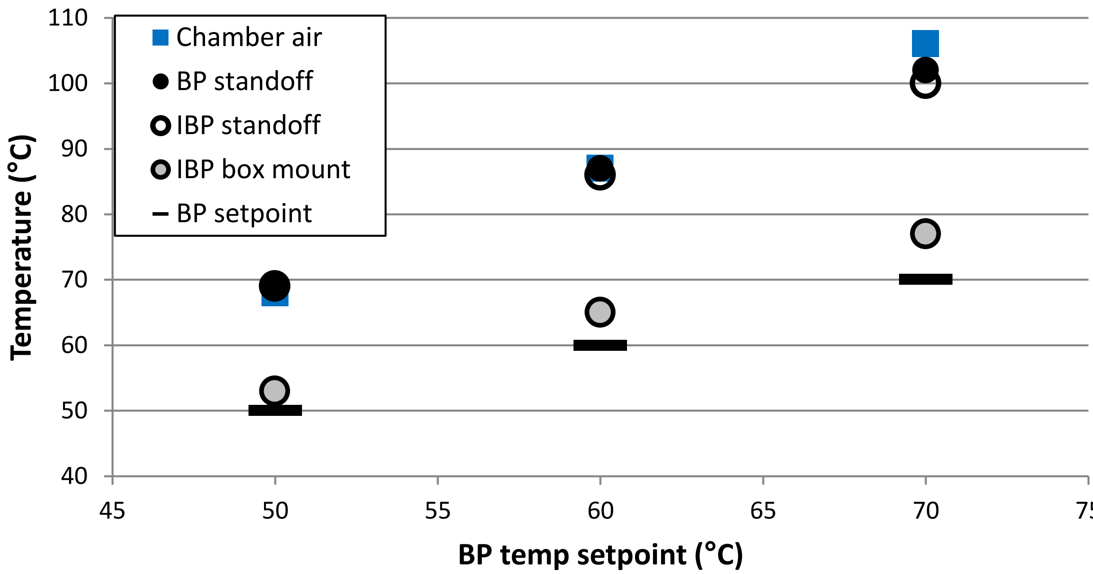

Figure 9. Average temperatures recorded for chamber air (blue squares), BP on standoffs (black circles), IBP on standoffs (open circles), and IBP mounted to specimen box (gray circles) for BP temperature setpoints of 50 °C, 60 °C, and 70 °C.

Discussion

Black Panel Selection for UV Fluorescent Testing

As mentioned previously, an uninsulated black panel temperature sensor is virtually always specified for UV fluorescent testing, regardless of whether the test is conducted on an insulating specimen like a plastic, or a conductive specimen like a painted metal. However, the results of the previous section show that black panel control often results in much higher specimen temperatures than may be desired for testing plastics. Testing conducted using both polymeric and metallic test specimens, controlling with both insulated and uninsulated black panels, provides some helpful information in selecting the proper control type.

The results from this test (Fig. 11) are striking. The two datasets at left present specimen temperatures for a typical 2D flat panel configuration; far left with a BP and second from the left with an IBP. For a plastic specimen under standard black panel control, the measured temperature exceeds the setpoint by almost 10 °C. This could have a profound impact on test results from an insulating polymeric specimen, especially a material that is not designed or intended for high-temperature applications. When using the IBP, however, the temperature is reduced to a value much closer to the programmed setpoint. If one is performing a test with the intent that specimen temperature should be the setpoint, the insulated black panel is the clear choice for polymers. For a painted metal specimen, the BP option provides specimen surface temperature a few degrees higher than programmed setpoint; IBP runs a few degrees cooler. The selection here is at the user's discretion; BP might be the preferred option for consistency with historical results.

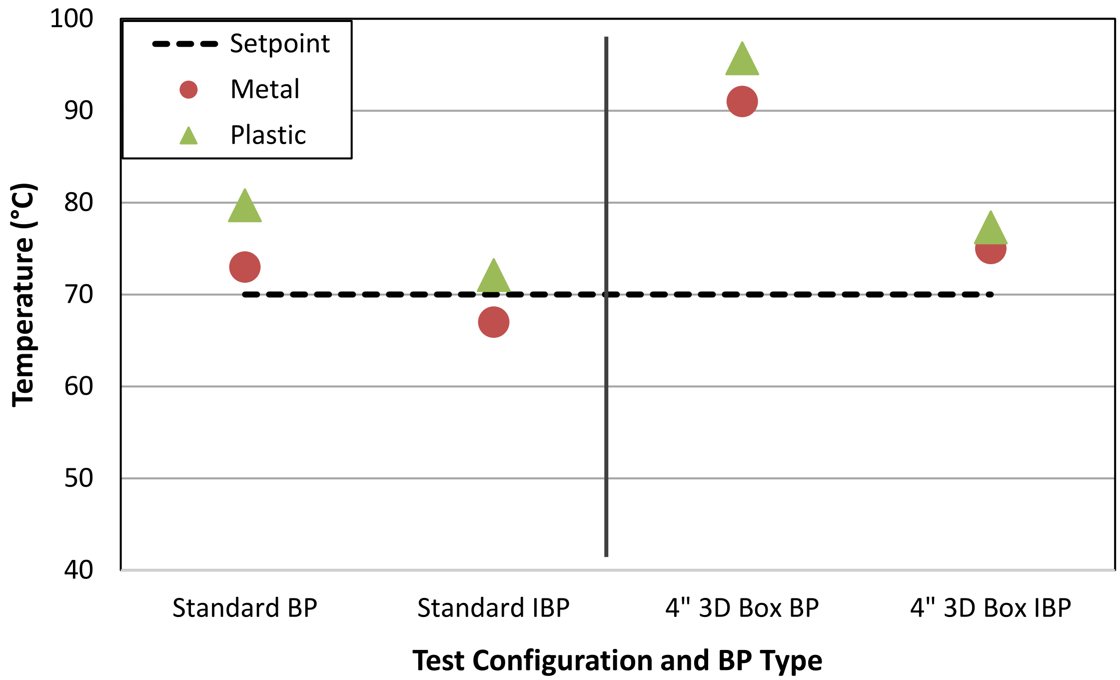

Figure 10. Average surface temperatures recorded for metal (red circles) and plastic (green triangles) specimens for testing at a temperature setpoint of 70 °C. Test includes standard 2D (left) and 3D (right) configurations, each with a BP (1st and 3rd datasets) and an IBP (2nd and 4th datasets).

The two datasets at right show specimen temperatures recorded for a 4” (100 cm) deep three-dimensional box configuration. Second from right uses a BP, and far right with an IBP. Here, the results are similar for the plastic and the metal specimens. Testing with a conventional uninsulated black panel generates specimen temperatures that greatly exceed setpoint values – more than 20 °C difference for both types of materials. Testing instead with an IBP reduces temperatures substantially, with both a manageable 5 °C above programmed setpoint.

The recommendations from these results are clear. For optimal matching of specimen temperature to programmed test setpoint, one should select:

- Uninsulated black panel for flat, conducting metal specimens
- Insulated black panel for flat, insulating plastic specimens
- Insulated black for any specimens tested in 3D boxes

Insulated Black Panel and Black Standard Compared

The terms “insulated black panel” and “black standard” are often used interchangeably, since a “black standard” is indeed a type of insulated black panel. However, these terms are not identical. ISO 4892-1 provides a clear, detailed definition of the construction of a black standard, while ASTM G155 uses the term “insulated black panel” but refers back to ISO 4892-1. The “insulated black panel” used in a UV fluorescent tester does not meet the requirements for construction of a black standard – although it is a black panel with insulation, there are several differences in construction, most notably that the temperature-sensitive element is located on the irradiated side of the black plate.

Use of the UV fluorescent-style insulated black panel is still permitted according to ISO 4892-1:

> *Black surface thermometers which differ in construction from that specified above are permitted as long as the temperature indicated by the alternative construction is within ±1.0 °C of that of the specified construction at steady-state temperature and irradiance settings in the programmed test cycle.*

The data presented in Fig. 12 demonstrate that the UV fluorescent insulated black panel meets this requirement. A test was performed under irradiation with a 60 °C (uninsulated black panel) setpoint. Temperature measurements collected from a black standard thermometer and by the UV fluorescent-style insulated black panel are nearly identical.

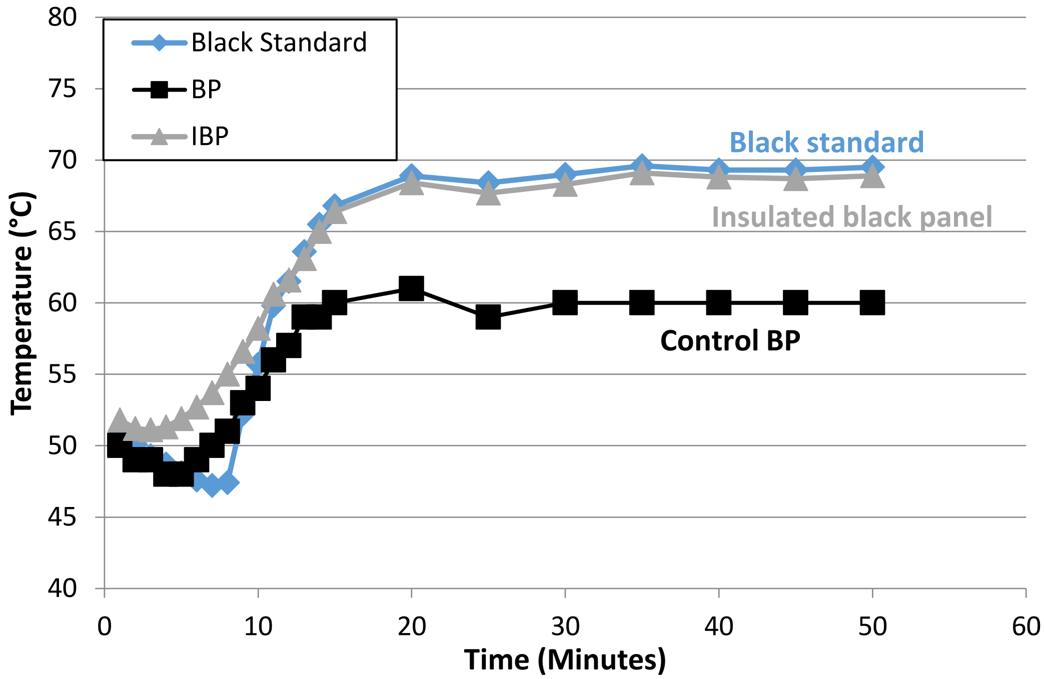

Figure 11. Temperature for a UV fluorescent test at 60 °C black panel control temperature (black squares), with recorded data from a black standard (blue diamonds) and insulated black panel (gray triangles).

Summary and Recommendation

Black panel temperature control is critical in accelerated weathering testing of polymeric materials. Experimental results demonstrate that specimen temperatures in a UV fluorescent tester significantly exceed the programmed black panel temperature setpoint, a value often thought to be representative of the hottest temperature in the test chamber. Plastic specimens are found to reach higher temperatures than metal test specimens, anywhere from 10-20 °C hotter than nominal test setpoints. These differentials can impact significantly test results and may result in damage to or melting of plastic specimens. This effect can be even more pronounced in testing using three-dimensional specimens.

Results presented using an insulated black panel temperature sensor in a UV fluorescent device demonstrate that such control provides surface temperatures for 2D plastic specimens that are much closer to the tester's programmed setpoint than those from traditional uninsulated black panel sensors. Furthermore, insulated black panel control provides more reasonable specimen temperature for both metallic and polymeric test substrates. Therefore insulated black panels should be recommended for all UV fluorescent tests involving plastic materials and/or three-dimensional specimen mounting. Further work will evaluate how the selection of a black panel or black standard in xenon arc testing affects temperatures of metal and plastic test materials, and whether a similar materials-based recommendation is appropriate.

References

1) ISO 4892-1:2016, *Plastics — Methods of exposure to laboratory light sources — Part 1: General guidance*

2) ASTM G151-19 *Standard Practice for Exposing Materials in Accelerated Test Devices that Use Laboratory Light Sources*

3) ISO 4892-2:2013, *Plastics — Methods of exposure to laboratory light sources — Part 2: Xenon-arc lamps*

4) ISO 16474-2:2013, *Paints and varnishes — Methods of exposure to laboratory light sources — Part 2: Xenon-arc lamps*

5) ASTM G155-21 *Standard Practice for Operating Xenon Arc Lamp Apparatus for Exposure of Materials*

6) SAE J2527, *Performance Based Standard for Accelerated Exposure of Automotive Exterior Materials Using a Controlled Irradiance Xenon-Arc Apparatus* (2017)

7) Francis, A. *et al.*, "Temperature control during fluorescent UV weathering testing of plastic materials," *8th European Weathering Symposium: Natural and Artificial Aging of Polymers*, Thomas Reichert Ed. (2017)