

EFSEN 

UV & EB TECHNOLOGY

USING INTEGRATING SPHERE TECHNOLOGY FOR UNIFORM UV CURING

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Summary

We evaluate a novel approach to UV curing of three-dimensional object using an adaptation of integrating spheres. We investigated these parameters:

1. Uniformity of irradiance
2. Stability of irradiance
3. Repeatability of dose
4. Thermal effects

We found the uniformity of irradiance is excellent, although it is difficult to quantize. The irradiance is very stable from exposure to exposure, varying <1%. The delivered dose is also very stable and repeatable, again varying <1%.

Objects exposed to UV in the chamber were uniformly heated compared to direct exposure tests where localized overheating was common at the same average delivered dose.

Introduction

Integrating sphere technology has recently been applied to UV curing applications. This paper describes an evaluation of the technology for UV curing using a commercially available system from Vela Technologies, Inc., San Diego, CA, USA.

Integrating sphere technology was developed to diffuse light in order to measure light power regardless of the spatial distribution. It has since become a standard instrument in photometry and radiometry. Until recently, the technology has seen limited use in industrial and production applications.

An integrating sphere uses multiple diffuse reflections of light incident on the sphere inner surface to homogenize the light over the entire surface (Figure 1). This results in uniform irradiance at all points on the interior surfaces of the integrating sphere.

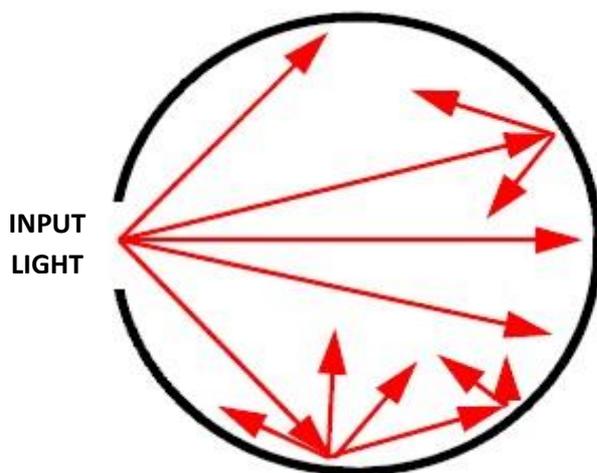


Figure 1. Basic integrating sphere.

This has been applied to UV curing by recognizing that uniform irradiance on the interior *surface* of the sphere creates uniform irradiance at all points within the *volume* of the sphere. Thus, an object placed inside an integrating sphere will be exposed to uniform radiation on all its surfaces facing the sphere wall (within certain limits of approximation).

For UV curing applications, the “sphere” is actually a rectangular cuboid (or simply a “rectangular box”) and is referred to as a chamber. However, the underlying integrating sphere equations still apply to such a chamber with planar rather than spherical walls.

The experiments described here evaluate the uniformity, irradiance stability and dose control performance of an integrating-sphere based curing chamber available from Vela Technologies, Inc. We further examine the thermal effects on a real-world part requiring three dimensional curing.

Benefits

The integrating sphere for UV curing applications is a hollow chamber having diffusely reflecting inner surfaces. Light from a UV source is coupled to the chamber via one or more ports in the chamber wall, and objects to be cured are placed inside. Multiple diffuse reflections from the chamber walls lead to uniform irradiance on the chamber walls.

The result is a spatial integration of the light source geometric information, completely decoupling the light field inside the chamber from the lamp geometry. All points within the interior volume of the integrating sphere then have the same irradiance. This has several specific benefits for UV curing:

- *Uniformity of irradiance.* All surfaces to be cured receive the same irradiance.
- *Three-dimensional exposure.* Irradiance is the same on all surfaces, not just those facing the lamp. Objects do not need to be rotated or moved.
- *Radiant exposure is decoupled from light source.* The lamp can be smaller than the treated object. Multiple parts can be exposed using a single lamp.
- *Tighter process control.* The irradiance is known at all points inside the integrating sphere, so the exposure can be monitored in real time.

Limitations

This technology has the following disadvantages:

- *Lower irradiance than conventional focused systems.* Applications requiring very high intensity are generally not well suited for integrating sphere curing because the input radiant flux is spread over a large area.
- *Object size limitation.* The larger the object inside a chamber, relative to the chamber size, the poorer the uniformity.

These limitations in many cases are outweighed by the advantages listed above.

Applications to UV Curing

This technology is successfully being used for curing coatings and adhesives. In most cases, it is integrated with automated production machines. Here are some examples:

Catheter/guidewire coating. A customer needed to increase production rate and reduce operating costs for existing arterial catheter and guidewire products. They successfully converted to an integrating sphere curing chamber using 2 electrodeless UV lamps to cure 10 parts at once (~1200mm long each) within 30 seconds with zero cure-related scrap. UV bulb replacement cycle changed from 10 bulb changes every 2 weeks to 2 bulb changes every 6 months.

Urinary catheter coating. Another customer needed to increase production throughput substantially to meet per-unit cost requirement. Their 12-catheter curing system rotated the catheters in front of a bank of 6 arc lamps, resulting in a high down time due to the number of lamps and moving parts. They installed an integrating sphere curing system and are now curing 144 catheters at one time using two 500 W/in electrodeless lamps. Cure time is less than one minute.

Adhesive curing. A customer's product contained several UV cured adhesive joints. These were cured one joint at a time by placing the uncured parts on a conveyor running in the focal plane of a 300 W/in arc lamp, requiring 4 passes as the part assembly progressed. By converting to the integrating sphere technology, they are now curing all four adhesive joints on two separate parts – eight adhesives joints total – at one time, with a single 30 second exposure.

Test Objectives and Setup

Our testing focused on these questions:

- Uniformity of irradiance: Is it really uniform?
- Irradiance stability: Does the irradiance vary with time and from exposure to exposure?
- Dose control: How repeatable is the dose, in J/cm², on exposed parts?
- Thermal effects: Do the parts experience more or less heat than conventional direct irradiation?

The following sections describe the test setup used and experiments to answer those questions.

Equipment

Chamber. The chamber used here is a VelaCure™ system (P/N 523-1100) from Vela Technologies, Inc., San Diego, CA, UVA (see Figure 2). It is a laboratory-use curing system, designed for six catheters or guidewires. The chamber interior dimensions are 560H x 254W x 457D (mm). The main elements of the VelaCure system are the chamber, shutter, controller and UV lamp. Parts are loaded manually on this particular unit; however, the system includes automatic control of the lamp and exposure parameters via a touchscreen display.

Parts may be suspended from a manually-loaded rack as shown in Figure 3 (urinary catheters shown). The rack is then placed over an opening in the chamber top; a safety door closes over the rack, preventing UV escaping the chamber.

Pressing the RUN button on the touchscreen control unit causes the shutter to open, letting UV into the chamber and beginning the cure cycle (the lamp is normally always on). Once the target exposure (or “dose,” in J/cm²) is reached, the shutter is closed and the parts may be removed.

The VelaCure chamber also has a holder for attaching an EIT Power Puck radiometer to measure the chamber irradiance.



Figure 2. VelaCure system used in these experiments. Right, detail of parts rack and safety lid. Photos courtesy Vela Technologies.

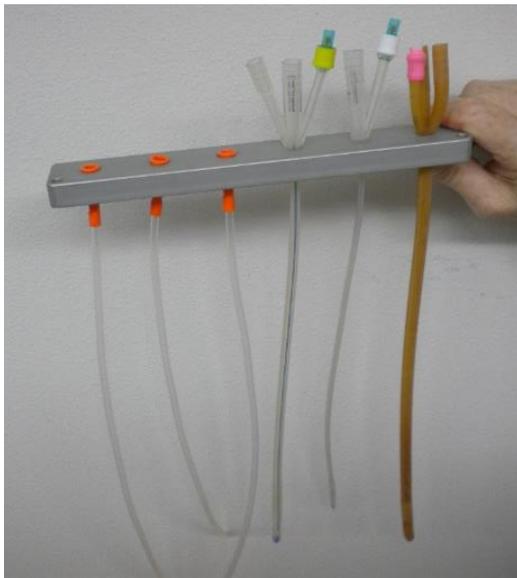


Figure 3. Parts rack loaded with various urinary catheters.

Lamp. A Heraeus Fusion F300 lamp system with an H-bulb and standard reflector was used as the UV light source. This is mounted on the VelaCure chamber with the shutter between the two. The VelaCure control unit controls all lamp functions. The lamp is left continually on in the test reported here, but it may be cycled on and off automatically with each exposure to save energy.

Diagnostics. All radiometric measurements were performed with either a Power Puck II Profiler Mid Range or a MicroCure radiometer from EIT. We recorded UVA values only (defined as 320 – 390 nm by EIT).

Two types of UV sensitive color-changing strips from Con-Trol-Cure, Inc. were used to visualize uniformity on the chamber walls and object surfaces. Both are paper strips that change color in proportion to incident irradiance, providing a visual reference for relative exposure. The first type has five exposure zones on it, each zone having decreasing sensitivity to incident UV (“5-zone strip”). The second type has only one color-changing zone (“single-zone strip”). By placing these on an object inside the chamber (or even on the chamber interior walls), we get a relative measure of the incident irradiance. After exposure, strips from different locations are compared to determine if the color change is the same for each zone on the strips, giving a relative indication of chamber uniformity.

Uniformity

One of the promises of this technology is uniform, 3-dimensional exposure of multiple objects at the same time. This section describes tests to evaluate the irradiance uniformity on the chamber walls as well as on parts in the chamber.

Testing of uniformity was divided into three efforts:

1. Uniformity on chamber walls. If the chamber is truly acting as an integrating sphere, then the irradiance on each wall should be the same.
2. Uniformity on single part. We next measured the uniformity of UV incident on the surface of a single part placed inside the chamber.
3. Uniformity on multiple parts. Finally, we suspended various parts inside the chamber and exposed them together. This is how parts are normally processed through the VelaCure chambers in production.

We'll describe and discuss each test separately.

Uniformity on chamber walls. Five-zone color strips were placed on each chamber wall except the rear and exposed together (Figure 4). The power puck radiometer was used to record the absolute irradiance. This should provide a relative measure of irradiance uniformity on the chamber walls.

The uniformity with multiple objects suspended in the chamber is very good. Figure 5 shows the 5-zone test strips that were placed on each of the five of the chamber's six walls and exposed, along with the Power Puck radiometer value during that exposure. The radiometer was on the right wall. To get the irradiance within the strip's sensitivity range, we only opened the shutter 20%, meaning the chamber irradiance was approximately 20% of its maximum value. All strips were exposed together for 5 seconds. Recall that the



Figure 4. Location of test strips on chamber walls. Only the top, bottom and right strips are visible. The top strip is actually on the hinged lid, shown open in the photo; the right strip is next to the radiometer port on the right wall.

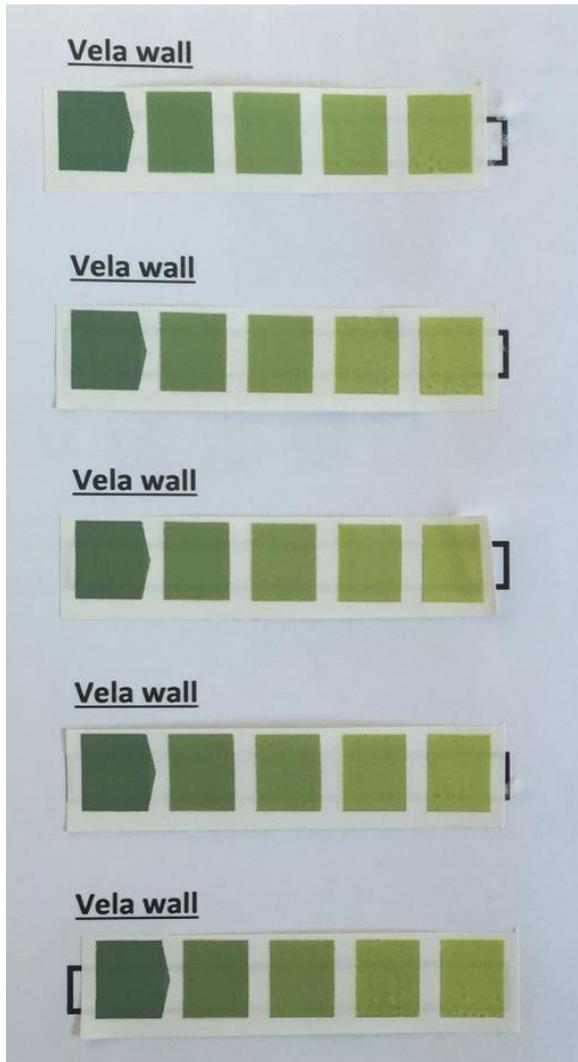


Figure 5. Chamber wall uniformity results. Compare each zone of one strip with the same zone of the others. Strip sensitivity decreases from left to right. From top: chamber top, front, right, left and bottom wall.

color-change sensitivity of each zone decreases from left to right in the figure, so any zone should be compared only to the corresponding zone on other strips.

There is no detectible difference in color change of the strips when comparing correlated zones. All of the color changes correspond to 150 – 200 mJ/cm² according to the comparison chart supplied with the strips. The radiometer reading is 101 mJ/cm², quite a bit less than the color chart indicates. The difference could be due to the larger field of view and of the flat test strips (the puck sits outside the chamber, and so has a restricted field of view. However, because there is no data on the strip's angular responsivity, and the color chart is not intended as a calibration tool, we do not place much value on the color chart dose estimate.

Uniformity on single part. We placed an aluminum pipe on the chamber floor with MicroCure radiometers attached to the pipe outer surface – one at the top and one at the bottom of the pipe. This provides a calibrated measure of irradiance uniformity on the pipe surface. See Figure 6.

In a variation (Figure 7), we covered the exterior of the pipe with single-zone and 5-zone paper to get a relative measure of irradiance on the entire surface in a single exposure.



Figure 6. Pipe on floor with radiometer attached.

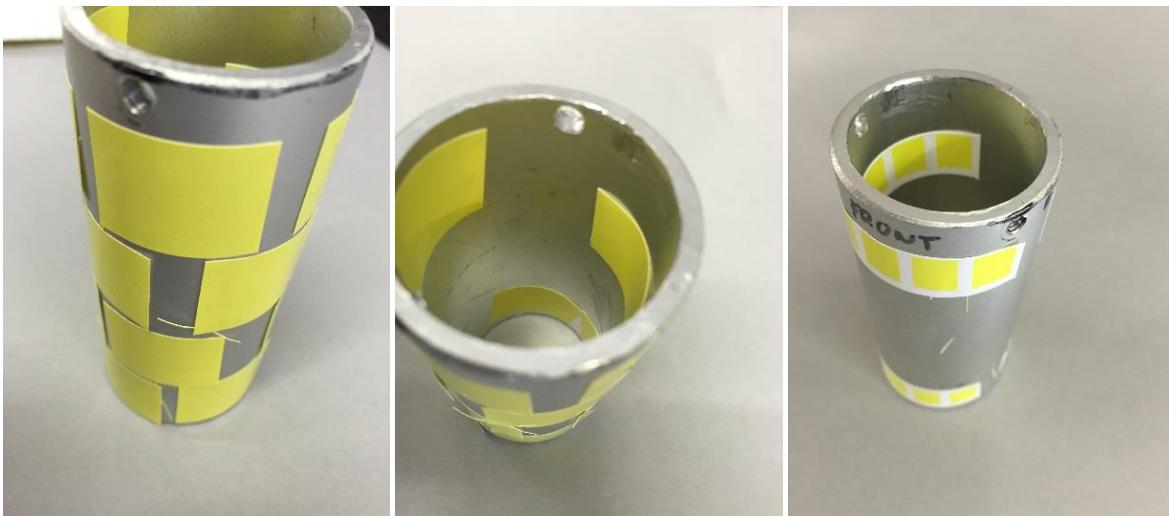


Figure 7. Pipe prepared with color strips inside and out for self-shadowing test. Left and middle show location of single-zone strips on outer and inner diameter; right photo shows 5-zone strips (also mounted on the rear of the pipe but not visible).

Table 1 shows the radiometer readings on the pipe surface using a MicroCure radiometer. The irradiance is very uniform. Note that the radiometer on the bottom of the pipe is quite close to the chamber floor while the top radiometer is ~80 mm above the floor (as shown in Figure 7). Yet the readings are identical, indicating that proximity to a chamber wall and the subsequent change in field of view does not affect the surface irradiance measured on the part.

The chamber irradiance as reported by the power puck is 20% lower than the irradiance measured by the MicroCure. This is due to the difference in instrument readings, as well as the fact that the Power Puck is located on the exterior of the chamber, peering inside through a 25mm hole. This places the Power Puck sensors ~10mm away from the chamber inner wall. We speculate the difference in reported irradiance is due to this field of view limitation as well as the difference in instrument readings.

Table 1. Irradiance on pipe surface placed on chamber floor. Shutter open 20%, target dose 500 mJ/cm².

Sensor location above floor (mm)	Irradiance (mW/cm ² UVA)	
	Part (MicroCure)	Chamber (Power Puck)
10	29	23
80	29	

Figure 8 shows the single-zone color papers that were affixed to the pipe surface (pre-exposure locations shown in Figure 7 above). In this test, the pipe was centered between the chamber left and right walls; it was ~100mm from the front wall and ~350mm from the rear wall. Once again, the exposure is very uniform over the entire cylindrical surface of the pipe.

Note that the inner surface receives ~50% less irradiance due to self-shadowing. However, using conventional line-of-sight irradiation from the lamp onto the pipe OD would not irradiate the ID at all.

Exposed 5-zone strips are shown in Figure 9. The first two outside strips were on the OD front and rear near the top, respectively; the bottom two outside strips were on the OD front and rear near the bottom, respectively. The first inside strip was on the ID near the top, while the second inside strip was on ID near the bottom. This provides greater resolution on the irradiance distribution.

Again, by comparing appropriate zones, it is evident the irradiance is quite uniform on both the inner and outer surfaces. Using the color-comparison chart provided with the strips, we see the outside receives 100 – 150 mJ/cm² while the inside receives 70 – 100 mJ/cm².

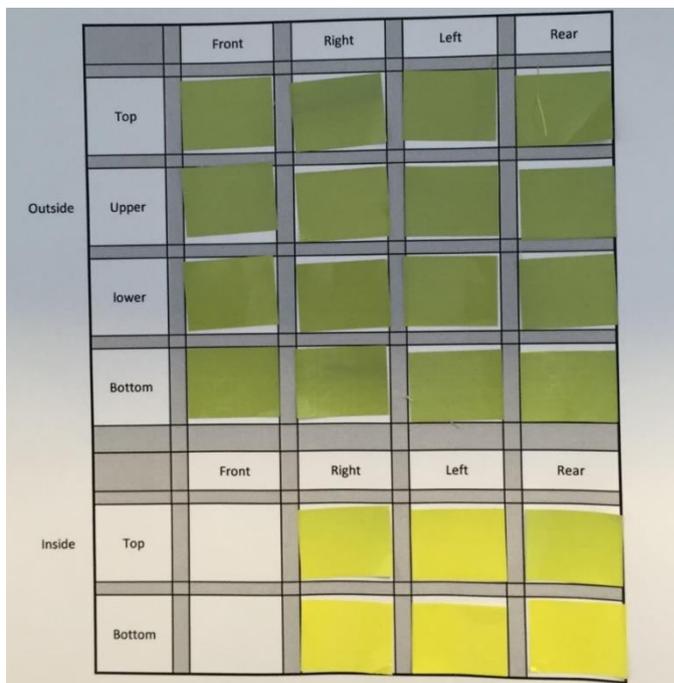


Figure 8. Single-zone color strips from pipe surface after exposure. Axial location on pipe is indicated in row headers; azimuthal location is in column headers. Shutter open 20%, 2.7 second exposure.

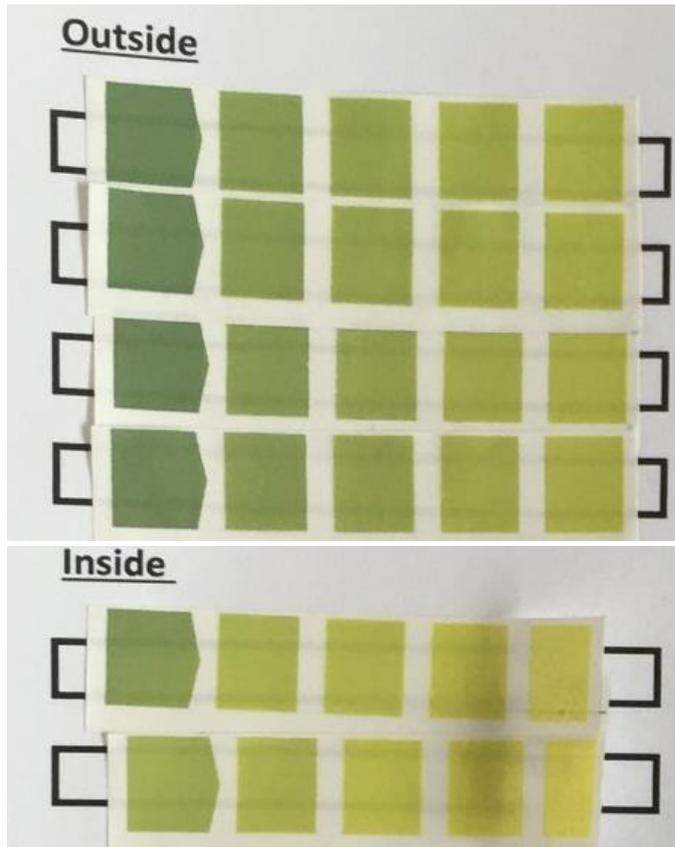


Figure 9. Five-zone strips from pipe-on-floor test. "Outside" strips were on pipe OD; "inside" strips were on pipe ID. Outside: 1st & 2nd strips are top front and rear, respectively; 3rd & 4th strips are bottom front and rear, respectively. Inside: top strip is top inside, bottom strip is bottom inside.

Uniformity on multiple parts. For this test, we suspended three different parts inside the chamber using the parts rack. Figure 10 shows the setup. The parts used were a urinary catheter (clear), a black plastic car dashboard part and the aluminum pipe from previous tests.

The results are remarkable. Figure 11 shows the exposed strips. In each case, the exposed colors correlate with 70 – 100 mJ/cm² except the last aluminum pipe and last dashboard strip which correlate with 50 – 75 mJ/cm². The former was on the inner surface of the pipe; the latter was on the inside (concave) surface of the dashboard part. Note that the "Vela wall" strip is almost indistinguishable from the others.

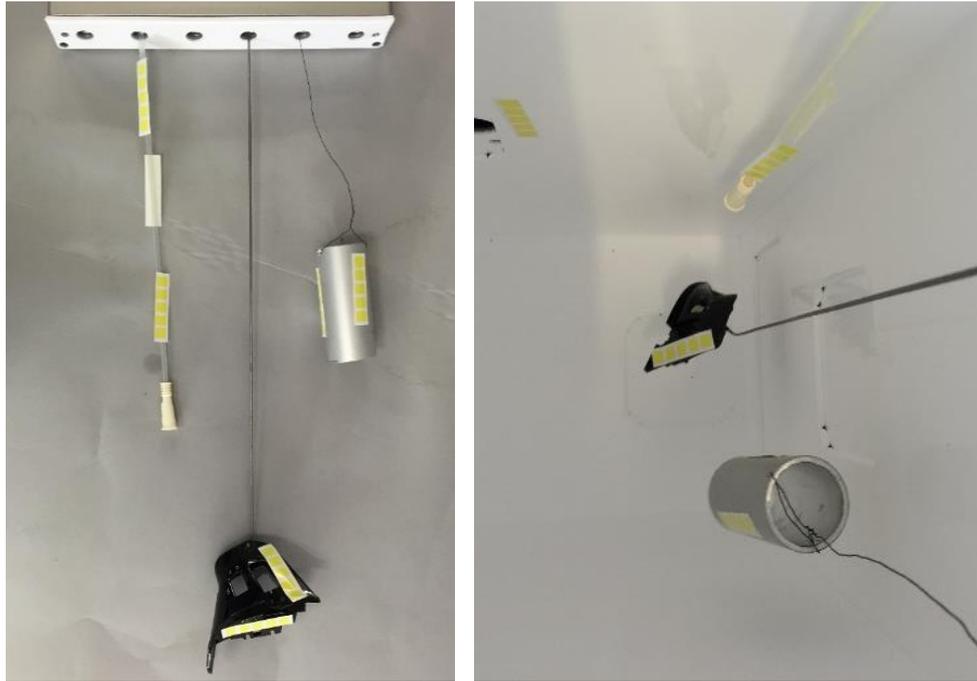


Figure 10. Left photos shows the parts on rack prior to insertion into chamber: a urinary catheter, a car dashboard part and an aluminum pipe. Right, view looking down into chamber with parts suspected inside. The radiometer port is the hole (dark spot) on the left top (chamber right wall) with a 5-zone color strip nearby. Shutter 20% open, target dose 100 mJ/cm².

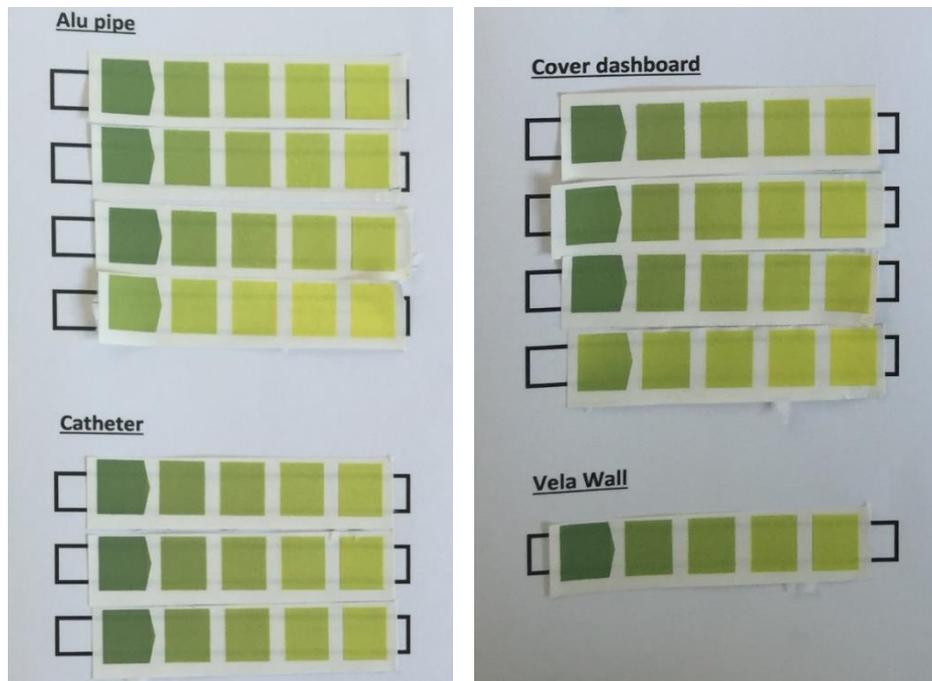


Figure 11. Exposure strips from parts in Figure 10. "Alu pipe" – lower strip was on pipe ID. "Catheter" – top, bottom strip face chamber rear wall, middle strip faced chamber front. "Dashboard" – bottom strip was on inside having the most restricted field of view. "Vela wall" – on right wall near radiometer port.

Uniformity conclusions. Based on these tests, we find that:

1. Chamber walls have uniform irradiance.
2. Single and multiple parts placed inside the chamber experience very high uniformity of irradiation.
3. Heavily shadowed regions such as the aluminum pipe inner surface or dashboard concave surface still received sufficient irradiance for UV curing applications, with a 25 – 50% reduction in irradiance, all depending on geometry.

Irradiance stability

Having shown the chamber irradiance is uniform, we wanted to test the stability with time. Because the chamber is simply an assembly of diffuse reflecting walls, one would expect the time-dependent irradiance to follow that of the lamp used.

To investigate this, we recorded the chamber irradiance using the profiling Power Puck radiometer during repeated exposures. This profiling radiometer records the irradiance vs. time at a sampling rate of 1024 samples/sec or one sample every 977 μ sec.

Repeated exposures. We performed a set of tests with the VelaCure controller set in "dose mode" to evaluate stability and repeatability of irradiance during exposures typically used for production. In this case, we ran the VelaCure system in dose mode. Each exposure lasts \sim 30 seconds; the time between exposures was \sim 30 seconds as well. The lamp was on continuously and exposures were controlled by opening and closing the shutter.

Results are shown in Figure 12 with values of each exposure given in Table 2; Figure 13 shows the average irradiance of each exposure. Once again, the irradiance is stable during each exposure. Overall, all 10 exposures averaged 139.4 ± 0.359 mW/cm² ($\pm 0.26\%$). We believe the irradiance variation within each exposure is due to lamp output variation, but did not attempt to verify this.

Stability conclusions. Chamber irradiance is very repeatable, within 1 mW/cm² in the condition tested.

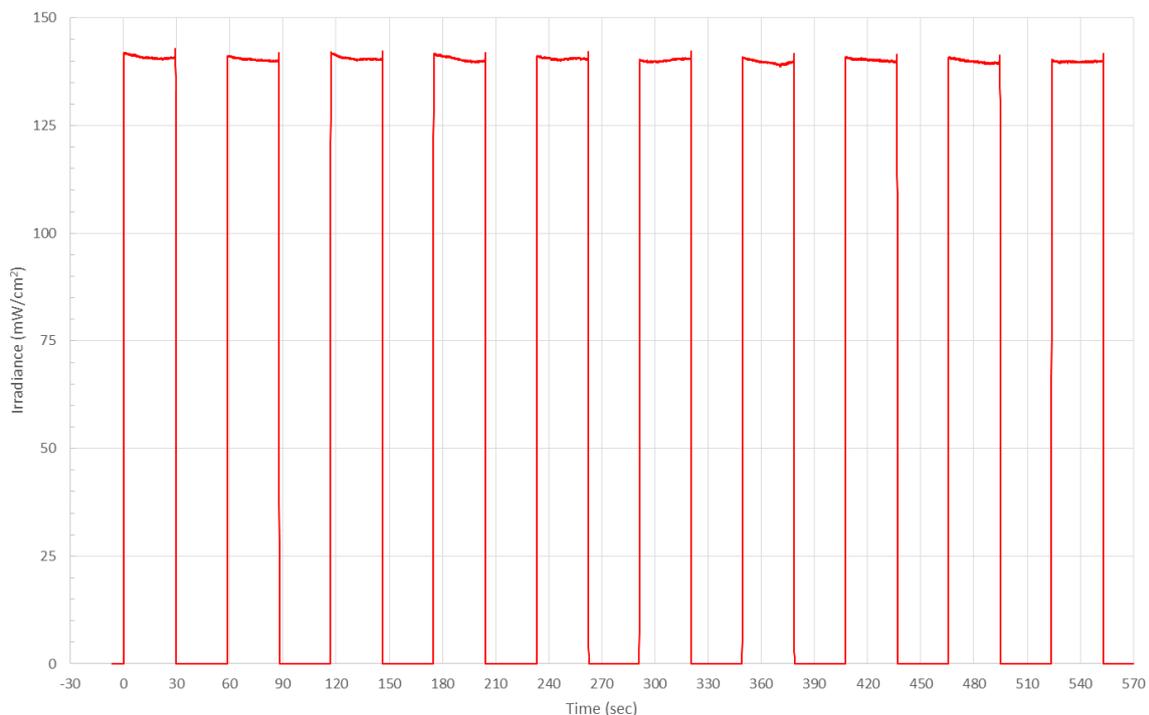


Figure 12. Sample of repeated exposures with \sim 30 second exposures followed by \sim 30 second off.

Table 2. Time-averaged irradiance of each repeated exposure.

Irradiance (mW/cm ²)											
1	2	3	4	5	6	7	8	9	10	Avg.	σ
140.0	139.4	139.7	139.6	139.6	139.2	138.9	139.3	139.0	138.9	139.4	3.59×10^{-3}

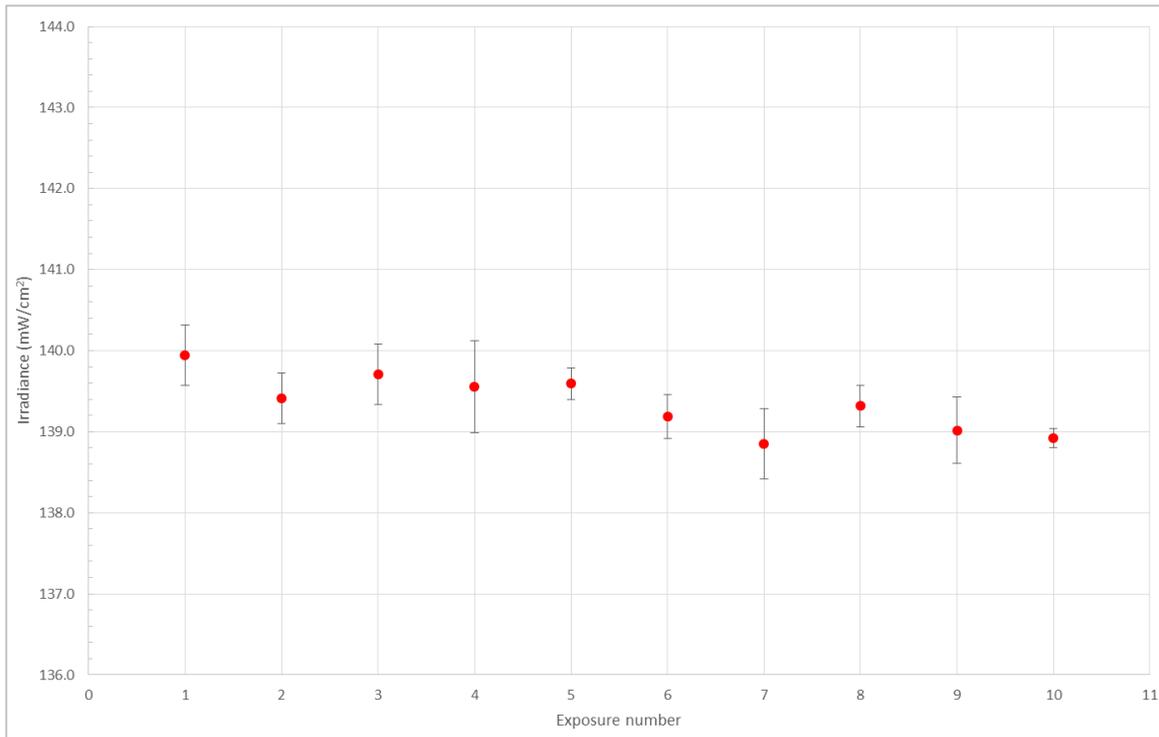


Figure 13. Time-averaged irradiance for each exposure. Error bars are one standard deviation.

Dose Control

One of the more intriguing features of the VelaCure systems is what is called “dose control.” Recall that a part exposed to UV starting at time t_1 and ending at time t_2 receives a dose given by the irradiance on the part integrated over the exposure time. However, as shown above, irradiance on the part is the same as irradiance on the chamber wall due to chamber uniformity. Therefore, the dose received by the part is:

$$H = \int_{t_1}^{t_2} E_{part} dt = \int_{t_1}^{t_2} E_{wall} dt \quad (J/cm^2)$$

So, by measuring the irradiance at any point on the chamber wall during an exposure, the dose delivered to all of the parts inside the chamber can be calculated in real time. Once the calculated dose reaches a user-set target value, the controller automatically stops the exposure.

(Note: Dose is sometimes referred to as “fluence” or “energy;” all are typically used to mean energy received per unit surface area. “Exposure” in this paper refers to irradiating a part, not the dose received.)

The result is that variations in irradiance over time and from exposure to exposure can be automatically compensated using feedback control to give the required dose in all applications and on all parts. A further benefit is that the same chamber configuration can be used for a variety of parts.

Dose repeatability. We evaluated the chamber performance when in dose control mode using the “repeated exposure” tests above and calculating the dose for each exposure. The target dose was 4.1 J/cm². The time-dependent dose is shown in Figure 14 (along with irradiance for clarity); total dose per exposure is shown in Figure 15. The dose averages 4.12 ±0.014 J/cm² (±0.341%) over all exposures.

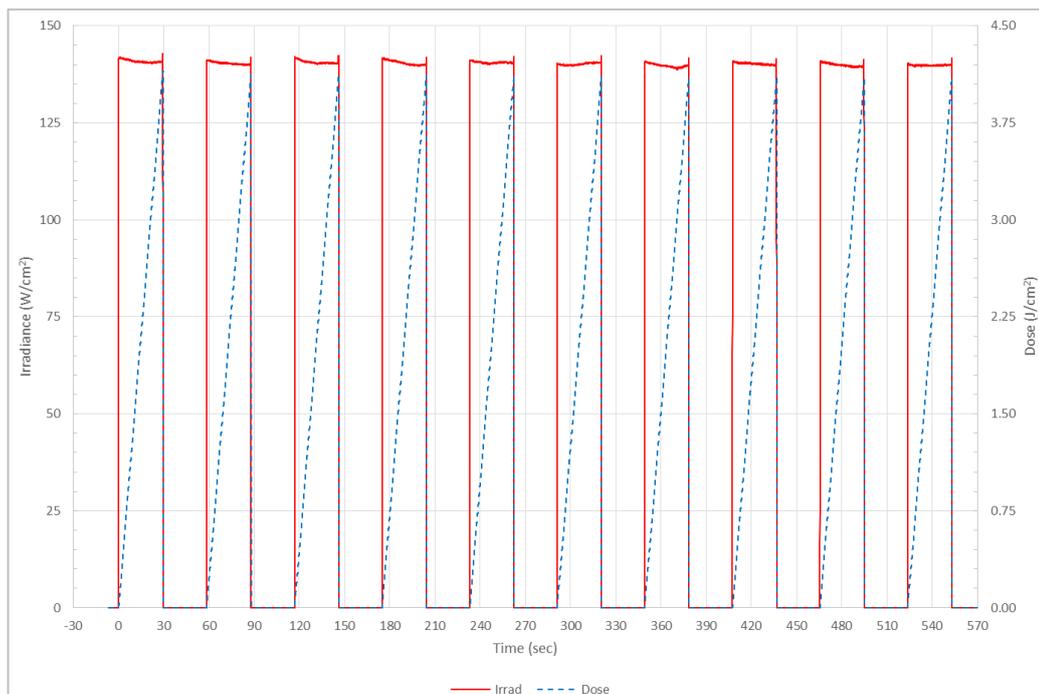


Figure 14. Dose and irradiance together. Dose calculation is reset to zero after each exposure.

Effect of parts on dose control. We wanted to know if delivered dose was consistent as the number of objects inside the chamber varied. To do this, we kept the target dose constant while exposing from 0 to 6 identical urinary catheters and measured the dose (integral of irradiance) using the profiling radiometer.

Results are shown in Figure 16. The irradiance changes as the number of parts inside increases, as discussed above: each added part causes the irradiance to drop due to increased light absorption. To keep the dose constant as parts are added and the irradiance drops, the VelaCure system automatically increases the exposure time. The net result is a constant dose delivered to all parts inside the chamber.

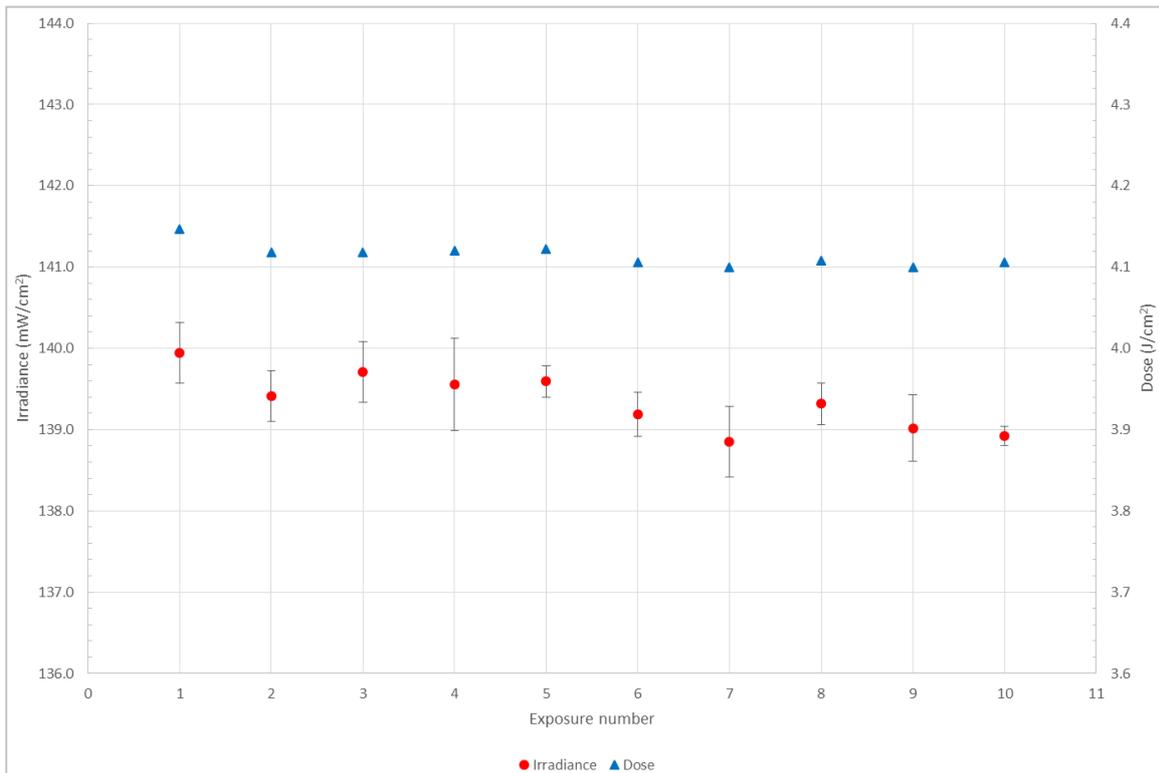


Figure 15. Calculated dose value for each exposure of Figure 12.

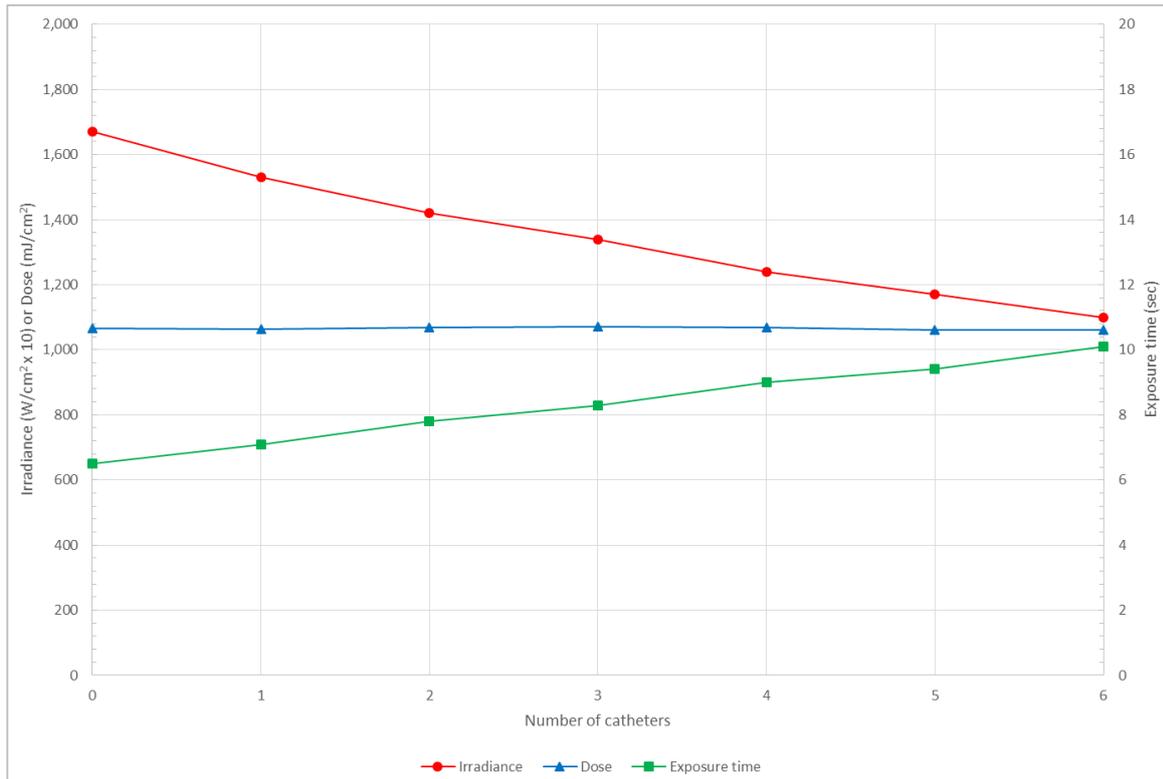


Figure 16. Delivered dose vs. number of parts inside the chamber with dose control active.

Dose control conclusions. The system tested exhibited very good control of dose delivered to exposed parts.

Thermal Effects

Parts heat up during exposure due to absorbed UV, visible and infrared radiation. Uniformly irradiated parts should therefore heat up uniformly.

We tested this by exposing a complex-shaped black plastic part using both the VelaCure chamber and using a conventional direct-exposure method – a 120W/cm electrodeless UV lamp mounted over a conveyor belt. For the direct-exposure method, we measured the dose, by stopping a conveyor when PowerPuckII filter was direct under the UV lamp, however in an excess distance of 25mm from the focus point. We had 1300mW/cm² for about 7 seconds, exposing the unit to 9,1J/cm². We then placed the same part in Vela, and exposed it via Dose Control mode to 9,1J/cm² (duration about 150seconds)

The results are shown in Figure 17. The directly irradiated part partially melted during the exposure. The part exposed in the VelaCure chamber showed no damage with the given dose.



Figure 17. Complex parts exposed to the same dose. Left, direct exposure of 9,1J/cm². Right, VelaCure exposed at 9,1 J/cm².

Conclusions

We evaluated an integrating-sphere based UV curing chamber from Vela Technologies, Inc. Our performance criteria were irradiance uniformity, repeatability of irradiance, consistency of delivered dose and reduction of localized heating. In all cases, we found this technology performs exceptionally when applied to three-dimensional UV curing.

Acknowledgements

We would like to thank Vela Technologies for use of the VelaCure system and technical support during testing.