3-Dimensional UV Radiometers:
A New Way To See Ultraviolet Light

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ABSTRACT

The UV industry continues to mature and gain sophistication in both materials and production equipment. The logical follow-on to the maturation process is the emergence of more sophisticated diagnostic tools supporting UV processing. The 3-Dimensional Radiometer (3DR) is the first diagnostic UV tool that allows UV line operators to 'see' and correct UV shadows on complex parts.

This paper will review UV cure theory and introduce a 3-dimensional radiometers as a diagnostic tool for UV line set-up and operation.

INTRODUCTION

UV coatings are an exciting advent in the coatings industry based on a technology that provides sophisticated scientific diagnostic tools to resolve phantom production problems that may plague and often go unresolved with conventional coatings technologies. UV processing involves a simple equipment add-on to preexisting finishing lines or may be the centerpiece of a major process upgrade. UV technology uses liquid coatings that are free of solvents, which by industry consensus, are termed Zero V.O.C., 100% solids or UV curable coatings.[1, 2]

Fig. 1. Before: A thermoplastic automotive 3DR before UV exposure.

Fig. 2. After UV exposure the 3dr indicates UV distribution over the surface. Note the effect UV blocking film had on the 3DR indicator underneath.

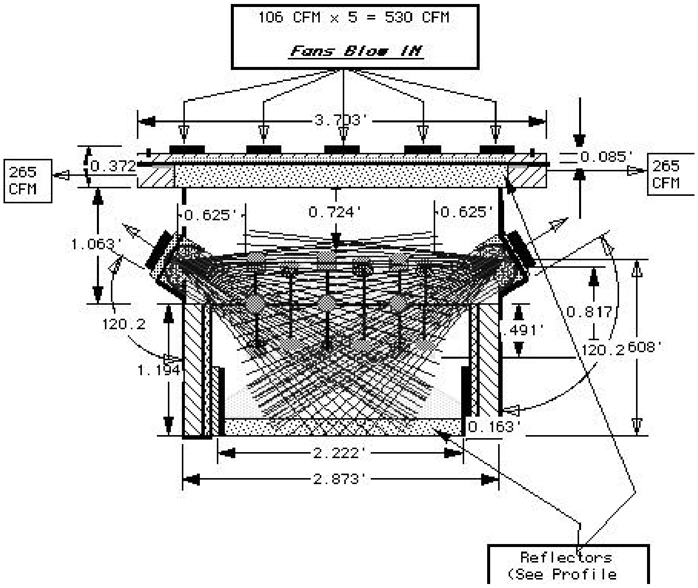

Fig.3. A vector ray trace drawing depicting UV distribution within a curing chamber.

UV CURING - HOW IT WORKS

Ultraviolet (UV) processing incorporates UV light energy to initiate a desired chemical reaction. In effect UV energy 'powers' the chemical reaction that converts a UV curable coating from a liquid to a solid state. This happens in a matter of seconds with NO flash-off or drying time.

UV occurs naturally in sunlight. Natural sunlight is comprised, in part, of infrared (Heat), visible, and UV light. For the purposes of this paper we will focus on aspects pertaining to UV.

Plants naturally use UV light to power the chemical reaction known as photosynthesis. Plants derive their energy directly from UV wavelengths - the same wavelengths used in industrial UV curing.

What is UV? UV light is the region of light, which is just beyond the blue end of the visible spectrum for humans. The UV band (260-400nm) is divided into three primary bands designated UVA (400-320nm), UVB (280-320nm) and UVC (260-280nm). Natural UV is comprised mainly of UVA with a minor UVB component. UVB and UVC cause 'sunburns' to human eyes and skin. It is important to note that UV is readily absorbed by most transparent materials and not readily reflective. This is the reason why one cannot receive a tan through glass.

The actual mechanisms of UV curing are based on advanced mathematical equations in quantum mechanics. These exercises are beyond the scope of this paper. However, the curing process may be described without the supporting mathematics. The UV curing process consists of three interlaced facets: A) Coating Composition (coating vendor); B) UV Source/Equipment (Equipment Integrator), and; C) Curing (UV Line Operator).

A. UV COATING COMPOSITION

All UV curable coatings are comprised of the following components:

1. **Photoinitiator**s – Absorb UV light and start the reaction;
2. **Acrylic Resins** - Acrylate functionality is conducive to UV Polymerization;
   Monomers - Small molecular weight acrylates. Contribute to physical characteristics such as hardness, softness, elasticity and etc.
   Oligomers - Are large molecular weight acrylated materials such as urethanes, polyesters, silicones and etc. that impart their characteristic properties to the cured coating.
3. **Additives** - Control properties such as aesthetics (gloss, 'feel', etc.); surface properties, and; adhesion to substrate properties.

The coating formulator designs the coating to meet the customer's needs. Communication between the finisher and coating vendor is critical during the formulation phase of a new coating. Once it is evident that a satisfactory coating is feasible, equipment for curing should be selected along with an equipment integrator. Alternatively bids could be solicited from integrators for equipment installation. Equipment integration may take up to 12-24 weeks depending on integrator scheduling. While equipment integration is pending, formulation work may be continued to finalize or further improve upon initially agreed upon coating performance properties.

A formal description of the formulation target objectives for coating characteristics and properties is strongly recommended by this author in order to clearly define project goals, objectives, roles and responsibilities. Such a document not only facilitates formulation of a successful coating but also concretely identifies the rolls and responsibilities of all parties involved as an implementation team.

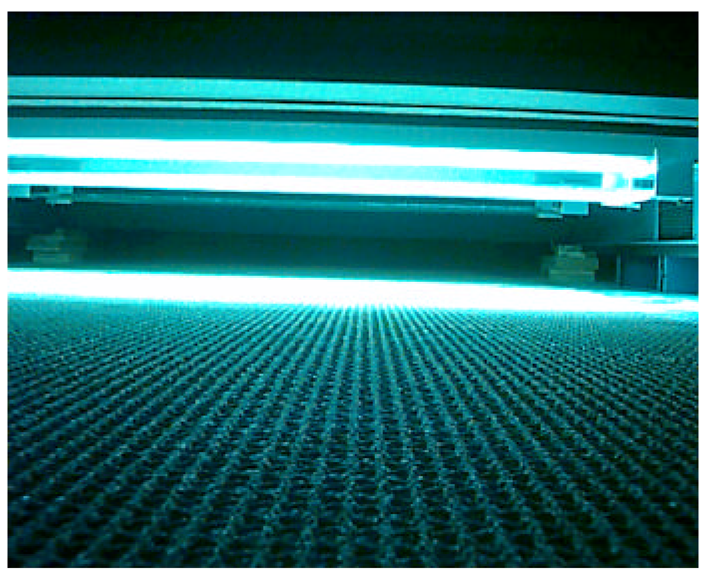

Fig. 4. A typical 2-D or flat-line curing system. This view taken from conveyor belt level shows the actual cure area illuminated by the UV source.

B. EQUIPMENT FACTORS

Reflective surfaces are used to reflect and redirect UV energy in curing chambers much like infrared energy is in conventional IR ovens. However, not all materials reflect UV very well. There are in essence two types of 'mirrors': First and second surface.

Second surface mirrors are most commonly used and familiar to the reader: silver backed, glass mirrors. In general, glass is opaque to ultraviolet and infrared radiation. Therefore, second surface reflectors such as silver-backed glass mirrors generally do not reflect UV light very well. This is due to the fact that UV light must pass through the glass layer (first surface) which absorbs a majority of UV energy before it even reaches the reflective silver backing (second surface). Whereas first surface reflectors such as metal foils or polished metal surfaces make excellent UV reflectors. It is vital to select reflective materials that reflect and not absorb critical UV wavelengths required for UV cure (Table 1).[3]

TABLE 1. REFLECTIVE FACTORS VARIOUS SUBSTANCES [4]

MATERIAL	% REFLECTANCE
ALUMINUM, ETCHED	88
ALUMINUM, POLISHED	73-95 [A.S.]
ALUMINUM FOIL	73
CHROMIUM	45
NICKEL	38
STAINLESS STEEL	20-30
SILVER	22
TIN PLATED STEEL	28
PLASTER, WHITE (WALLS)	40-60
WHITE PAPER	25
WHITE COTTON	30
WHITE OIL PAINTS	5-20
PORCELAIN, WHITE ENAMEL	5
GLASS	4
WATER PAINTS	10-30

Measured at 254 nm, at normal incidence.
Reflectance increases rapidly at angles Greater than 75%
[Source: American Ultraviolet Co., Lebanon, Indiana]

Approximately 50-70% of UV energy from industrial UV sources is directly attributed to reflection and redirection by the reflective surfaces behind the UV bulb. For this reason, it is vitally important to conduct weekly cleaning and inspection of ALL UV reflective surfaces i.e. UV source and curing chamber. Such reflective surfaces are best replaced at a minimum of once a year to assure peak reflective characteristics. Otherwise, this will manifest a change in UV curing characteristics within the curing chamber. Such an unmonitored change will cause a phantom curing problem. Over time, UV radiation slowly oxidizes reflective surfaces. Though the surfaces may appear to be highly reflective to the human eye, they may no longer reflect the wavelengths critical for UV cure. It is advisable to design "slide-in/slide-out" reflectors for easy maintenance and replacement. Such surfaces should never be riveted in place.

The commercialization of highly efficient and safe chemistry coupled with proper selection of materials in the construction of UV curing chambers minimizes or eliminates line-of sight curing altogether. This is accomplished by positioning the reflective material to utilize secondary and tertiary reflection of UV energy to non-line-of-sight areas (from the UV source) on the target part.

The installation of UV equipment is accomplished either as an entirely new finishing line or as a retrofit to a pre-existing line. In either case, the most critical the function of the integrator is to:

1. Design and install the requisite equipment, or;
2. Act as a general contractor facilitating the installation and integration of equipment from various manufacturers.

The latter scenario is most preferable as each sub-system manufacturer (UV system, coating application equipment, conveyance, air handling, etc.) should be held by contract to guarantee performance of their sub-system.

A formal description of target objectives, responsibilities, services and guarantees is strongly recommended by this author to clearly define project goals and objectives. Such a document not only facilitates formulation of a successful coating but also defines roll responsibilities of all parties involved as an implementation team. Additionally, this would allow the finishing line owner to have the project bid on competitively.

C. CURING

When a UV curable coating is exposed to UV light the following happens in this order:

1. The Photoinitiator absorbs UV and breaks-up into "free radicals". A minimum of 1.5 to 2 eV are required to put a molecule into an excited electronic state capable of generating free radicals which initiate polymerization.

Experimentally, it has been observed that UV cure can be initiated with as little as 0.005 J/cm2 (320-390nm). This was done by the author using a UVICURE Plus Radiometer (EIT, Inc. Sterling, VA) The significance of this reading is that it is the average natural sunlight UV dosage for Miami, Florida at noon (Table 2).[5, 6]

In comparison, using the same radiometer on an industrial 2-dimentional (2-D), or flat-line, UV curing system a UV dosage of 2.026 J/cm^2 was typical. UV dosages of greater than 7.4 J/cm2 have been observed and measured by the author on industrial 3-dimensional systems in the field.

SOURCE	UV (J/cm^2)	REL. MIAMI, FL[5]
Miami, Florida	0.005	1
Typical Flat Line	2.026	405
3-D Lines	7.4	1,480

Table 2. A comparison of UV between a flat line, a 3-D line and natural sunlight.

2. Free radicals initiate a chain reaction in which the acrylic sites (functional sites) bond together or polymerize. Free radicals are extremely energetic molecules capable of producing extremely fast chemical reactions. These reactions can be as slow as 1 second to as fast as $1.0X10^{-11}$ S. (0.00000000001 second) can! Acrylates are intentionally inhibited, or controlled from premature reaction by the addition of stabilizers, which, in the presence of oxygen scavenge and neutralize any free radicals that may form during handling or storage.[7]

In the absence of oxygen, photopolymerization has been reported to be 17.5 times faster than in the presence of oxygen. The efficiency of photoinitiators has advanced to the point that multiple free radicals can be generated from one molecule. Advances in curing efficiency along with the incorporation of reflective techniques in curing chamber design have effectively eliminated "line-of-sight" cure. [8]

Of special note, UV curing is hampered by the presence of non-reactive components in the coating usually added by production line personnel. In the case of zero V.O.C. UV curable paints and coatings, non-reactive diluents (solvents, alcohol, oils and water and etc.) decrease or confound the near instantaneous mechanism of UV curing. Any such component(s) that do not flash-off and remain in the system will cause at least one or a combination of the following:

A. Retarded/inhibited cure rates;

B. Finish flaws, or;

C. Autoignition of solvent (UV lamp operate well above the Autoignition temperature of solvents).

Rather than using non-reactive diluents as viscosity controls, novel methods have been developed that control viscosity without significantly hampering energy transitions vital to the UV cure mechanism. This novel technology also provides for superior film properties over conventional paint and coatings. [9, 10]

3. As the available reactive acrylic sights are consumed during cure, the chain reaction shuts-down. Once the reactive acrylate sites are consumed, the only remaining reactive sights are on the photoinitiator molecules themselves, which then recombine. The photoinitiators are ultimately trapped within the polymer, which forms around them.

Acrylated photoinitiators are a class of material that acts as both acrylic resin and photoinitiator. This allows the photoinitiator to not only initiate the reaction but to actually participate in the cure and become part of the solid polymer. Such materials have applications in the biomedical arena.

Fig. 6. A Metal 3DR before UV (Left) and After UV. Note the dark and even change in color.

Fig. 5. Above: The 3DR indicated not only a contour irradiance issue but also a UV shadow issue for this part. Note the areas that vary directly with the contour. This indicates the top lamp on this flat line operation was not operating properly – perhaps the part was run before the lamp reached full operating intensity. Additionally, some foreign object cast a shadow on this part during cure.

Ultimately it is the responsibility of the line owners to train their line operators to ensure proper day-to-day adjustment and operation of their production and curing equipment. In addition to weekly routine cleaning and maintenance procedures, positioning of UV lights and proper irradiation of production parts must be confirmed as a preemptive quality assuring measure. In addition to conventional UV radiometers which will provide a quantitative indication of UV energy in the curing chamber, the use of a "3-Dimentional radiometer" (3DR) which acts as an indicator of UV irradiation is strongly recommended. The 3DR will allow for immediate identification of UV shadows or misdirected UV light sources.

3-DIMENTIONAL RADIOMETERS

Ultimately, UV cure is contingent on proper lamp positioning to irradiate coated parts. There is little the coating formulator or the equipment integrator can do if production parts are not properly irradiated with UV light. 3DR's provide a means for on-line confirmation of irradiance integrity. A representative production part coated with a proprietary photochromic coating, which changes color with exposure to UV. The part thus becomes a reusable, 3-dimensional, visual indicator of UV irradiation. The 3DR facilitate proper lamp set-up, which is critical for 2-dimensional and especially 3-dimensional UV lines.

In the case of 3-dimensional UV processing, lamp set-up is performed with the UV sources turned off. (The UV wavelengths required for cure are invisible to human eyes, and damaging to unprotected eyes and skin. Industrial UV lights produce large amounts of visible light that should not be used as an 'indicator' of or for UV light.) First, a 'target part' is positioned in the cure zone, as it would normally be found in production. Then, UV sources are positioned and directed at the 'target' part with the line operators using their best guess in directing the lights onto the part. When it is safe to do so, the UV curing chamber lamps are powered up, and test parts are coated and run to test lamp positioning. If an area on the part feels under-cured, the line operator must power down the UV lights, allow the chamber to cool, re-enter and re-adjust the UV lamps to correct for the under-cured area. Then another test part is run. This cycle is repeated until satisfactory lamp positioning results in satisfactory cure is achieved. This process is costly in terms of time and labor and generation of scrap parts and material.

For the first time, UV shadows and hot spots due to improper lamp positioning can be immediately identified and corrected. Described as a "UV litmus test", 3DRs revert to their original color allowing for years of reusability.

Fig. 7. This test part would present a challenge to position UV lamps. The top photo shows the part prior to UV exposure. The bottom photo reveals UV Distribution on the surface. Note the UV shadows on this part appear as pink areas.

In the case of 2-dimensional UV processing, or flat-lines (Fig. 4), the flat surface nearest the lamp(s) usually does not experience cure problems (Fig 6.). However, sides, lead and trailing edges or contours are often presumed to acquire adequate irradiation for cure. The typical presumption is that if there is enough UV to cure the top surface, there should be enough UV to cure the adjacent contours, sides and edges. This presumption is incorrect and may lead to falsely concluding that the coating is at fault. This may spur a reformulation where a simple lamp adjustment (or cleaning) may be all that is required. If 2-D line operators had access to a 3DR, they would quickly be able to differentiate between cure problems due to under irradiated areas versus coating failure.

Conventional radiometers provide information on UV energy at a single sensor point on the radiometer. This is typically a circular sensor less than 0.5 In. in diameter. Beyond the sensor's detection area, no further information is available on UV energy. Such radiometers are excellent in quantifying UV energy - one point at a time.

Fig. 8. This depiction of a severely burned part shows how the 3DR indicates hot-spots. The center of the hot spot reverts to original color while the hot spot itself is surrounded with an extreme color transition.

THEORY OF 3DRS OPERATION

An ideal UV radiometer would be identical in size and shape to the actual production part. Such a UV radiometer would allow the operator to 'see' UV distribution over the entire part providing immediate visual identification and location of UV "shadows" (Fig. 7.) or "hot spots". Further, such a tool will allow on-line confirmation, diagnostic and quality assurance of part irradiation integrity. 3DRs allow for immediate indication that any lamp(s) may have moved out of position, a reflector may require cleaning/replacement, or some other unattended factor is effecting part irradiation (Fig. 5.).

In the absence of UV light, 3DRs possess a pale coloration the intensity of which is dependent on the concentration of the UV indicating component. 3DRs change color on exposure to UV light and so indicate UV irradiance over the surface of the part. The rate of change, color and return to original color are controlled by selection of the UV indicating component. This application is similar to and familiar to most readers in the form of corrective lenses (glasses) that change color on exposure to sunlight. The greater the UV exposure the darker the color transition.

Infrared (IR) hot spots, which normally coincide, with UV hot spots, cause the center of the hot spot to revert to the original ground state color. While the surrounding fringe area of the hot spot is demarked with very dark blue (Fig. 8.). 3DR's revert to their original color in minutes making them a highly reusable and cost effective production and quality assurance tool for UV processing lines.

Application: Where's the UV?

Line-of-sight cure afforded a straightforward diagnostic approach to determining UV cure problems. The elimination of line-of-sight cure requires a sophisticated diagnostic tool to resolve cure issues. Prior to 3DRs, vector ray tracings provided the closest means by which to visualize reflection patterns within the cure chamber in determining surface irradiation with UV (Fig. 3).

Simply passing the 3DR's through the UV cure chamber will indicate UV distribution on the part surface. (Care should be taken not to coat the 3DR with the production UV coating first.) As the 3DR is made from a production part, it provides a non-invasive measurement that preserves all factors influencing cure normally found in production. The 3DR provide a qualitative indication of UV irradiation where conventional radiometers provide quantitative UV information. This allows evaluation of irradiation without the need for UV lights operating at full intensity. This then further eliminates cool down time and speeds the set-up cycle.

3DRs indicate UV exposure regardless of the UV equipment's manufacturer. "Instant on" systems, microwave type as well as electrode-arc systems are suitable for 3DR use. Typically, electrode-arc systems are not turned off during breaks or shift changes; rather they are idled at low power to extend lamp life. This allows UV line operators to confirm the integrity of part irradiation not only at the initial lamp configuration but even prior to start of the shift and during production breaks.

CONCLUSION

3-Dimensional radiometers have been described as reusable, "UV Litmus test" parts for quick targeting and troubleshooting of UV light sources. Operators of UV processing lines must monitor and maintain sufficient levels of UV to achieve satisfactory cure. Determining UV exposure has been limited to radiometers with single point-source detectors that provide information only at the detector's point of measurement. Conventional radiometers are not capable of producing information outside of the sensor area. 3-dimentional radiometers made from actual production parts are utilized as reusable "UV Litmus Test" parts, which are passed through the UV cure chamber. The part's surface changes color with UV exposure. Inspection of the test part allows UV line operators to "see" UV light exposure variations on the part's surface, thus making it a powerful and valuable diagnostic tool for UV line operators.

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ABOUT THE AUTHOR

Andrew A. Sokol has been involved in the UV/EB industry for over 12 years. His experience base in both UV equipment and chemistry spans both the public and governmental sectors. Mr. Sokol has been awarded two US letters patent in the area of UV technology. He has additional patents, both domestic and foreign, pending in the area of UV/EB Technology.

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