UV-Curable Paints for Commercial Aircraft Exteriors

By Richard W. Baird

The Boeing Company assessed the feasibility of developing and implementing UV-curable paints for decorative and non-decorative use on aircraft exteriors. Pigmented and non-pigmented urethane-based sample submissions were tested to our requirements for finish quality and engineering performance, with results approaching those of qualified thermally cured exterior urethanes. Pathways were identified for development of a full intermix tint line for application of complex livery artwork and a non-decorative clearcoat for protective use.

FIGURE 1

One of the new Boeing corporate liveries—representative of the trend toward more complexity and, consequently, more masking cycles.

Potential opportunities were identified for using very fast-curing exterior aircraft paints for the purpose of reducing paint process cycle time and improving finish quality and durability for the airline customer. We determined that the greatest time-saving benefit would be realized with ultraviolet(UV)-curable pigmented and clear paints applied to areas of the airplane receiving complex livery artwork and areas requiring special-purpose coatings that would impose significant delays on the process flow unless the cure time was very short. (An example of the latter is heat-resistant coatings for exhaust duct areas.) A list of engineering and appearance requirements was generated based on the existing requirements for presently qualified exterior paints and included additional requirements specific to UV-curable coatings.

Two formulators were identified who had the resources and motivation to develop UV-curable paints for aircraft exterior use. A close collaboration was set up between these formulators and their raw material suppliers, as well as with the UV-cure equipment suppliers, in order to facilitate the development process. A gated development path leading ultimately to use of the UV-curable paints in production was put in place. At each development step, the business case for proceeding to the next phase was assessed before continuing to the next.

Presently, we are close to qualifiable formulas for clear and pigmented paint and a cure process for it. The next step will be an initial scale-up to verify the feasibility of setting up a tint line to cover the required color gamut and to assess the feasibility of curing large sections of aircraft surface.

Why UV Cure?

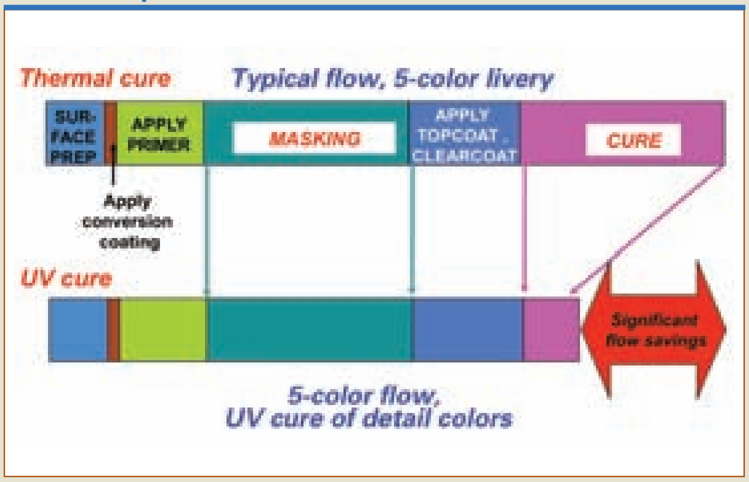
There are multiple drivers for implementing UV-curable exterior aircraft paints. As production rates for the more popular Boeing airplane models reach unprecedented highs, it has become more urgent than ever to streamline the production flow to support these increases. This urgency is highest at the final exterior finishing step—at the end of the build process where inventory holding costs are highest and where delays are most likely to disrupt delivery schedules. Adding to this urgency is the recent trend toward more elaborate airline liveries (Figure 1) involving up to five or more colors, each of which requires a full masking/application/cure cycle to apply.

For exterior finishing, the best opportunity for flow time reduction is in the curing step for topcoats and clearcoats. A high-level analysis of the flow for a five-color livery scheme (Figure 2) suggests that significant savings could be realized by using paint with faster cure time. The largest flow-time reduction would be achieved with paints with near-instantaneous cure (i.e., with UV-curable paints). Additionally, since UV cure is accomplished without significant heat generation, other work can progress while paint is curing, unlike the case for thermally cured paint. Yet even more flow-time savings is realized because after the UV cure the paint is fully cured and in fly-away condition.

In addition to detail livery colors, there is also a need for non-decorative pigmented paint and clear paint with specialty properties that can be applied

Figure 2

Potential process flow reduction with UV cure



and rapidly cured to minimize impact on the overall flow time.

UV-curable paints have the added benefit of helping reduce emissions of volatile organic compounds since they are typically formulated with up to 100% solids.

Requirements for UV-Curable Aircraft Exterior Paint System

A number of requirements must be satisfied in order to achieve the most benefit from a UV-curable exterior paint system. Together these requirements present a significant formulation and process-integration challenge similar to the one faced by the automotive industry—but with several added challenges unique to commercial airplane finishing.

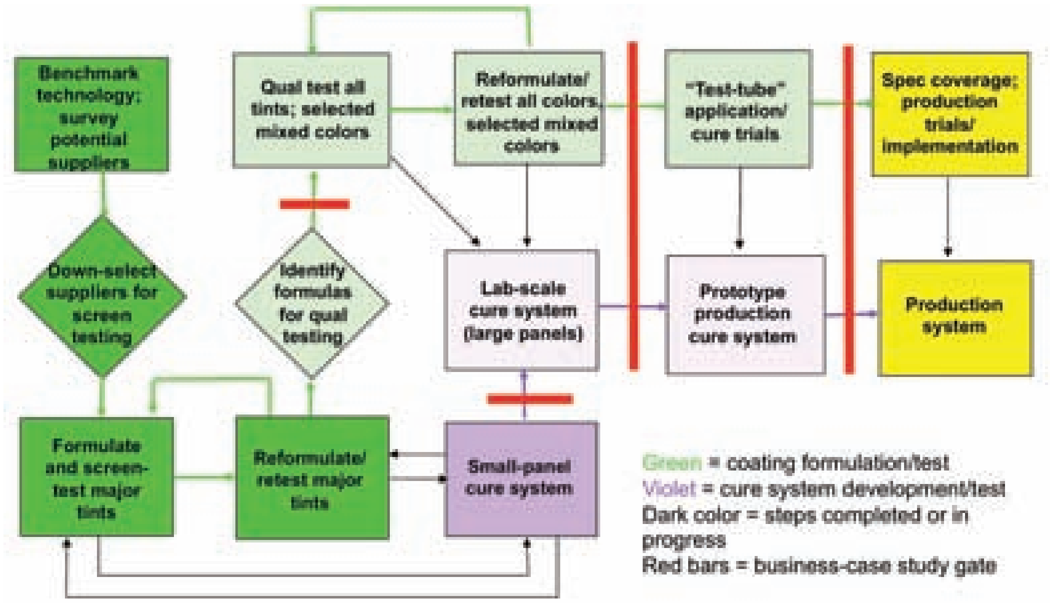
Challenges Include:

The ability to reproduce the entire Boeing-Approved Color (BAC) gamut. In practice, this means formulating the paint as a set of intermix tints that can be combined to generate all the unique BAC colors. Most of the complexity of new livery artwork is in the colors applied after the main "body wrap" colors, and these livery colors cover a broad gamut. Thus, to obtain the full benefit as a decorative paint system, an intermix tint line is required with at least a dozen tint bases, similar to what is presently implemented with thermally curable paints. Formulating each color individually would probably be prohibitive. This requirement poses significant challenges for the photoinitiator package (e.g., it must have a broadband response since there is no part of the UV spectrum useful for curing that is not blocked by one or more pigment absorption peaks). Non-decorative application, however, is another story. Since only a few standard colors are required (e.g., BAC 707 Gray) it makes little sense to go to the expense of setting up a tint line. This is also the case for most military scenarios.

Spray properties close to thermally curable paints. For optimum finish quality and shop-friendliness, the paint must have a spraying viscosity similar to that of thermally curable formulas, and similar "leveling" power (ability to form a smooth film) and resistance to runs and sags. The closer the spray behavior

Figure 3

Development flowchart



is to conventional paint, the shorter the learning curve will be for the painters, and reworks will be minimized. A typical approach is to formulate the paint with high room-temperature viscosity, then heat the paint to lower the viscosity to a sprayable range. Leveling and sag resistance are then controlled by the rate of viscosity recovery as the paint film cools on the surface.

"Hang time" requirement. The room-temperature viscosity must be high enough to support a film about 0.002" or more in thickness (for adequate opacity), applied in a single coat on a vertical surface for a period long enough to allow time for technicians to return to the wet film with the curing lamps. Use of thixotrope additives is typically needed to extend the "hang time" to an acceptable length while retaining good leveling. Without these additives, the paint would either continue to "level" slowly (finally developing sags after an interval typically too short to allow time to return with the cure system) or level incompletely (leaving an unacceptably rough, "orange-peely" finish).

Cure process requirements. Equipment complexity, weight, cost and power consumption must be minimized. Ozone generation must be minimized or prevented to obtain the maximum environmental benefit. The equipment must be safe to use, portable and light enough to operate on a movable paint platform. The paint must be sensitive enough and the UV intensity high enough to enable a sufficiently high coverage rate of the cure lamps over the painted surface to maximize the flow-time savings and offset the higher equipment costs associated with UV cure. There is also a fire safety requirement calling for explosion-proof (NFPA Class-I, Div-1) operation to enable curing in the paint hangar. These factors tend to favor a one-bulb, UV-A cure system that is either intrinsically safe or can be enclosed in a positive-pressure inert-gas envelope.

Overspray cure requirement. Since it is impossible to channel 100% of overspray droplets into the paint hangar air exhaust, every surface of the hangar eventually gets coated with a fine layer of overspray droplets. This is not a problem with thermally cured paints; the droplets merely harden where they land. With UV-curable paint the overspray droplets will remain wet indefinitely, which is clearly unacceptable. A secondary cure process ("dual-cure") is the typical approach—where the overspray droplets eventually harden enough via a secondary cure mechanism to minimize safety concerns (typically within 12 to 24 hours). This secondary mechanism does not require UV exposure and can proceed in the dark.

Engineering and appearance requirements. In addition to the requirements listed above, the paint formula must satisfy all the engineering and appearance requirements established for thermally cured paint.

UV-Curable Paint Development—a Gated Process

The development process followed the flow as depicted in Figure 3. It is a series of development phases connected by gates. At each gate, the test results are assessed and a business case analysis is performed to support the decision to proceed to the next phase. The development phases are as follows:

Identifying formulators. We began the development process by canvassing the industry for formulators who had the resources and interest in providing a UV-curable exterior paint system for us. The canvassing process revealed two formulators, hereafter denoted as "A" and "B," who began the process of formulating and submitting liquid and cured samples for us to test. The samples were submitted as both clear and pigmented formulas. To begin the development, several tints were selected that were deemed to be representative of the extremes of the color gamut required. This would facilitate development of a photoinitiator package capable of working with the full range of pigment absorptions.

Iterative screen testing of submissions. To expedite the test process, a battery of screen tests was employed that was a subset of the full-qualification test battery included in the paint specification. The test battery is listed in Table 1. There followed several iterative cycles of testing; reporting of results to the formulators; and submission of reworked formulations until we tested formulations that were close to satisfying the screen test requirements. As anticipated, the greatest challenges have been in achieving adequate surface and through-cure with a single bulb, and achieving adequate colorfastness for certain pigments without overcoating the color coat with a clearcoat. Results to date, however, suggest ways to meet these requirements through adjustments to the paint formula and the cure process.

Qualification testing and incorporation into the specification. Once we obtain a formula satisfying the screen test requirements, it will be sent through the entire qualification test battery. For decorative paints, the number of colors submitted will increase to the full number required for the tint line. We anticipate several more iterative cycles of testing and re-submission as the suite of tints are adjusted to best work together as a tint line (e.g., adjustments to the photoinitiator package, pigment loading, thixotropes and other additives, as well as residual adjustments to reactive diluent and oligomer components).

Concurrent cure system development. Concurrent to formulating the paint, we evaluated several approaches to the cure process. To satisfy our safety and process-engineering requirements, we focused on a one-bulb, UV-A process. We adopted conventional UV lamp technology due to its technical maturity. While LED-based curing would be ideal for our application and is well-established for curing printing-ink films, it still lacks technical maturity at the performance levels required to cure paint films at the coverage rates we require. This technology is developing rapidly, and we expect it to become a viable option for large-scale aerospace paint curing in the very near future.

Delivery of the UV to the painted surface could be accomplished either by UV lamp fixtures installed throughout the hangar and surrounding the airplane (including

Table 1

Criteria used to screen test samples

Property	Target
Spray temperature	Optimized for Boeing paint process
"Hang" time	
Cure dosage	
Cure intensity	
Overspray cure (tack-free)	
60 deg Gloss	Equal or better than qualified paint
Pencil-scratch hardness*	
Leveling	
Fluid resistance—MEK, IPA, 100 rubs	
Fluid resistance—Skydrol®, 30 days*	
Scribe adhesion (tape-pull)*	
Droplet jet test*	
Impact resistance (Gardner)*	
Thermal shock*	
Weatherometer (500 kj) deltaE**	
Weatherometer delta gloss	

* Values over abraded undercoat. ** Per SAE JI960 protocol.

floor units for the underside) or by scanning a lamp system over the surface. The former scheme, while conceptually simple (just throw a switch to effect the cure) and fast (all painted areas exposed simultaneously), was rejected as prohibitively costly and unsafe due to stray UV radiation. Also, since the hangar would be off-limits during cure, no simultaneous operations could proceed.

Thus, we adopted the idea of scanning the UV lamps over the painted surface (as is done in the automotive industry) except that, in our case, the lamp array is moving, not the painted surface. Thus, the actual effective cure time would be the time required to "paint" the surface with the required dosage per unit area of UV. This overall cure time is dependent not only on UV intensity and paint sensitivity, but also on the time required to set up and maneuver the cure lamps over the entire painted surface.

Once a basic cure method was chosen, its development was dovetailed with that of the paint formulas. To obtain adequate through-cure in the least exposure time and with the lowest UV intensity, the oligomeric resin, reactive diluent and photoinitiator package all need to be optimized for the intensity and spectral output of the curing lamp system. During the course of the screen test program we identified an optimal UV-A intensity range and dosage range for obtaining through-cure with maximized coverage rate (i.e., minimized cure time) for the paint formulas being developed.

Scale-up to curing large test substrates. When we obtain a qualifiable paint formula and associated cure process at the lab-bench scale, the next step is to scale-up to a lab system capable of curing large substrates in a manner simulating the "push-broom" coverage process expected on the airplane.

Scale-up to application and cure on simulated airplane sections. The next development phase is to scale-up to a production-prototype cure system that is explosion-proof and capable of operation on a paint platform. This prototype will be evaluated in simulations of representative aircraft painting scenarios, and any residual issues with cure system or paints addressed. Scrapped fuselage sections will be used for these trials, which will be conducted in the paint hangar with the painters who would be painting customer airplanes.

Production trials on customer airplanes. Finally, if all continues to proceed nominally we will move to a net-configuration cure system and production trials on customer airplanes chosen in the same manner as for any new coating or marking system.

As each phase of development is completed, we will conduct a business case study for proceeding to the next step. Presently, we are assessing the best path for qualification testing. Once one or more paints pass the qualification-test battery, we will revisit the business case to determine where to target an initial implementation. The follow-on development phases (large-scale lab testing, "test-tube" trials and production trials) will then be planned accordingly. Conceivably, at any point the business case may not close, at which point the results will be documented for possible re-evaluation in the future as technology improves (e.g., LED curing).

However, even in the event of a decision to terminate the effort, we anticipate that the unique application and cure testing resources put in place for the development effort can be utilized in other ways. An example of this would be to provide testing services in support of contract research and development work assigned to our labs.

A Collaborative Effort

As described above, development of a successful UV-curable paint formula must be dovetailed with the development of a curing system for it. To facilitate this process, both paint formulators worked closely with a cure-system developer and raw-material suppliers, as well as with the end-user. Meetings between the various stakeholders were held to manage the development process; in particular, to ensure that resources and expertise were most effectively deployed.

Conclusions

The technology is still some time away from a working UV-curable coating and curing system for the aircraft exterior, but we are optimistic that a useful niche can be found for this technology that supports the planned production rate increases for commercial aircraft at Boeing.

—Richard W. Baird is a process development engineer for exterior coatings and marking systems at The Boeing Company in Seattle, Wash.