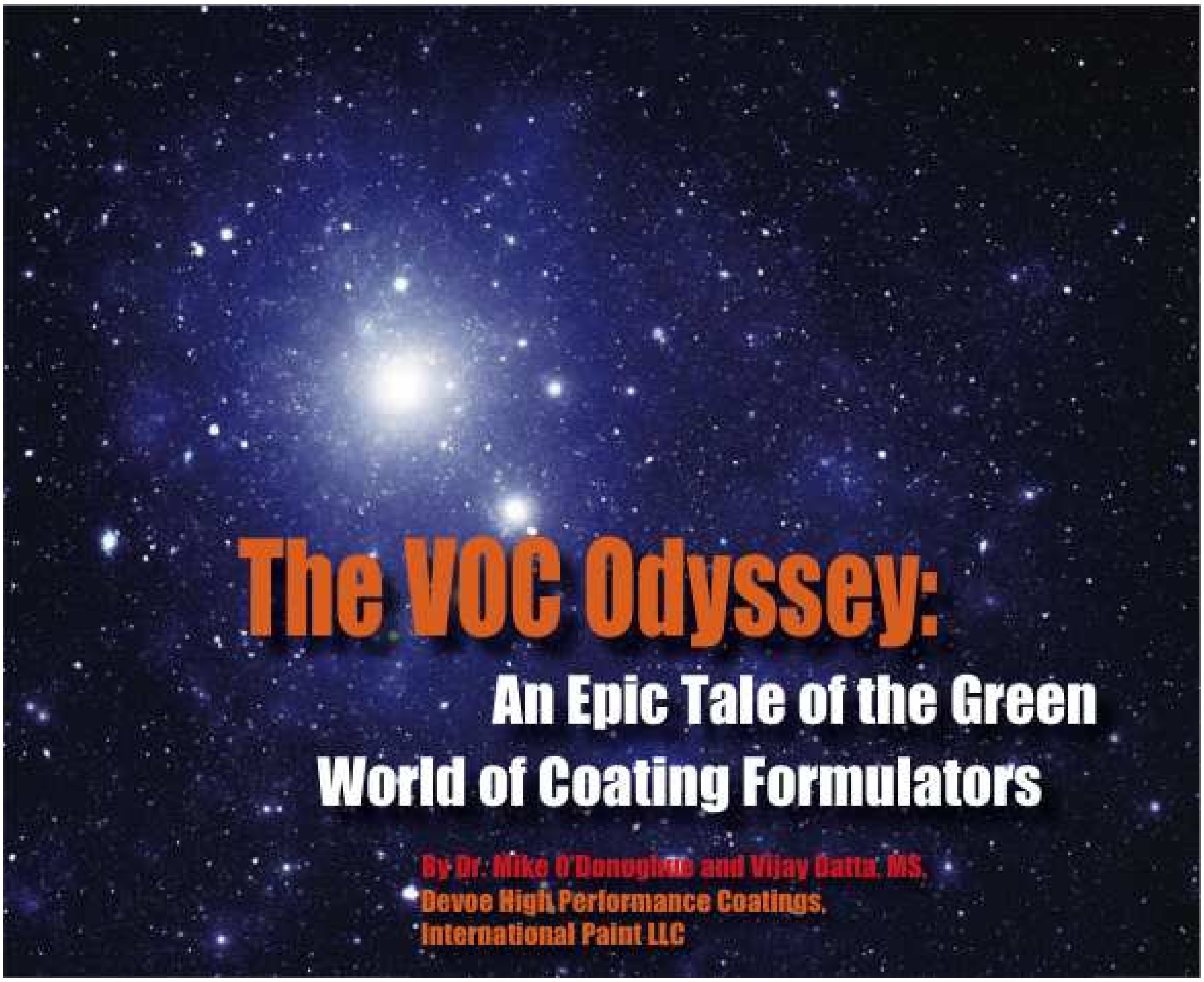



So there you are in the laboratory, a coatings formulator in the modern age, pondering an exciting challenge in the realm of protective coatings, where a real sense of scientific wonder often prevails. The crucial task at hand? One that's been around in one form or another since the late 1980s to the present. You must address head on the sometimes perplexing regulatory position of volatile organic compounds (VOCs); produce high performance coatings that are easy and safe to apply; keep the costs down without detracting from in-service performance; do your stint for the environment in particular and the planet at large by complying with VOC regulations without inadvertently introducing something worse; strengthen your company; and delight your customers. No mean feat in creative problem solving. After all, what innovative design goals could be more stimulating or rewarding? Headline stuff in molecular engineering: Get a Green "A" Grade.

At the heart of the matter are VOCs, which are hydrophobic or hydrophilic compounds, either of a manmade or natural source, that participate in atmospheric photochemical reactions and thus contribute to atmospheric pollution. Most of them are considered to be hazardous air pollutants (HAPS). VOCs emitted from activities in the paint and coatings industries accounts for a significant amount of the total VOCs emitted by manmade activities. For instance, in the U.S. in 2007, solvent utilization (of which the manufacture and use of VOC-emitting paints and coatings are a substantial subset) accounted for 23% of all VOC emissions from manmade sources.[1]

Air quality issues are front and center in society nowadays. In the presence of sunlight, VOCs have the ability to react with nitrogen oxides; form ground level ozone; contribute to smog formation; and thus have a deleterious effect on both our health and the environment. Small wonder that, even without the hot topic of climate change in North America and the European Union (EU), solvent emission regulations are always subject to new proposals, change, and ever-increasing stringency. In July 2006, for instance, the South

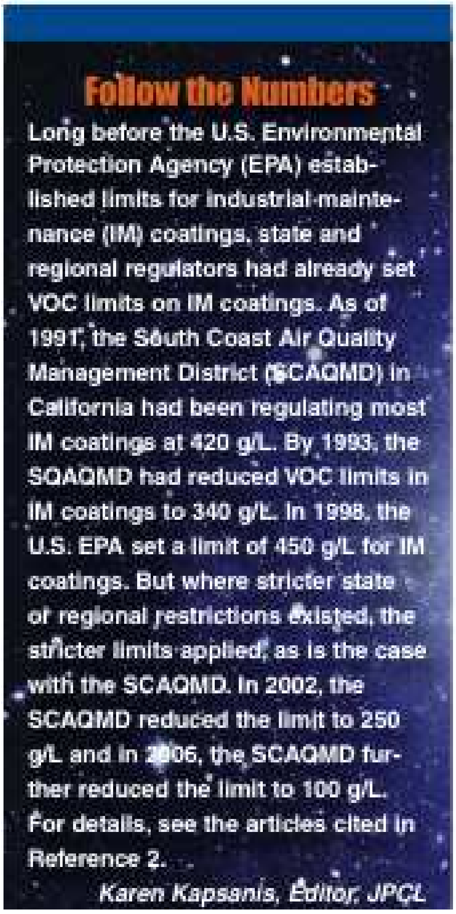
Coast Air Quality Management District (SCAQMD) in California lowered VOC limits for industrial maintenance coatings to 100g/L. A decade earlier, the SCAQMD levels were 340 g/L.[2] Meanwhile, in 1998, the U.S. Environmental Protection Agency had set a national limit of 420 g/L. (See sidebar on this page.) So coating formulators have their work cut out.

**Trauma Here; Transcendence There…**

Sure, you are aware that an adversarial relationship between regulators and the coatings industry has surfaced from time to time. But while it might be objected that tackling VOC emissions through coercive policies has been a blessing for coatings manufacturers, few would dispute that those policies have been anything short of revolutionary or have generated a new paradigm in the coatings industry. Admittedly, compliance with VOC regulations has brought a measure of travail. Smaller coatings manufacturers have been subject to attrition: many have succumbed or vanished, or have been swallowed up by larger fish in the coatings sea. Resin restrictions have led to certain coating types having all but disappeared. Coating application, aesthetics, and performance have at times been negatively impacted in one way or another. Add to this the reality that capital costs increase considerably due to VOC compliance in the coatings manufacturing process.

Notwithstanding the above, with enforced VOC regulatory compliance holding court, there is, in fact, a transcendent bright side in the way coatings are now formulated. There has been a litany of substantial developments and occasional breakthroughs with respect to the creation of new and customized resin technologies, exempt solvents, reactive diluents, additives, and corrosion inhibitors.[39] The resulting cost effectiveness of new, improved, and innovative coatings has often led to notable life cycle increases for facility owners. All good.

Advances and adaptations in waterborne, solvent-free, powder, and radiation-cured coatings are mainstream nowadays. While solvent-borne coatings are often considered superior to waterborne technologies, this is not always the case and has been described as myth in the case of waterborne epoxy technology.[10,11] Table 1 shows the merits and shortcomings of some new approaches to VOC reduction.


**Follow the Numbers**

Long before the U.S. Environmental Protection Agency (EPA) established limits for industrial maintenance (IM) coatings, state and regional regulators had already set VOC limits on IM coatings. As of 1991, the South Coast Air Quality Management District (SCAQMD) in California had been regulating most IM coatings at 420 g/L. By 1993, the SQAQMD had reduced VOC limits in IM coatings to 340 g/L. In 1998, the U.S. EPA set a limit of 450 g/L for IM coatings. But where stricter state or regional restrictions existed, the stricter limits applied, as is the case with the SCAQMD. In 2002, the SCAQMD reduced the limit to 250 g/L and in 2006, the SCAQMD further reduced the limit to 100 g/L. For details, see the articles cited in Reference 2.

*Karen Kapsanis, Editor, JPCL*

**Table 1: Merits and Shortcomings of New and Traditional Coating Technologies**

| Technology | Merits | Shortcomings |
|---|---|---|
| **Waterborne** | Low VOC<br>Easy color change<br>Easy cleaning with water<br>Versatile for application over complex surfaces<br>Application versatility (multiple techniques)<br>Suitable for shop and field application<br>Low flammability | Slow drying<br>Humidity-dependent drying<br>Reduced performance<br>Fair to moderate gloss and distinctness of image<br>High surface energy (low tolerance for oily and dirty substrates)<br>Flash rusting |
| **High-solids** | Ambient or thermal cure<br>Low solvent costs<br>Easy color change<br>Full range of gloss<br>Application versatility (multiple techniques)<br>Versatile for application over complex surfaces<br>Reasonably easy touch-up<br>High film build capability | Reduced flow and leveling<br>Reduced distinctness of image<br>Two-pack or thermal cure (no lacquer)<br>High cost/wet gallon<br>Flammability concerns |
| **Traditional solvent-borne** | Wide range of suitable application techniques<br>Easy touch-up and repair<br>Applicable to ambient, thermal and lacquer cure<br>Extremely fast cure<br>Suitable for application over complex surfaces<br>Suitable for high-speed continuous production lines<br>Excellent control of evaporation rate<br>Good tolerance for marginal surface quality<br>Low capitalization costs<br>Suitable for shop and field application<br>Full range of gloss and color<br>High aesthetics | Low to moderate film build capacity<br>Relatively high cost ($/dry mil)<br>High VOC emissions (unless using exempt solvents)<br>Clean up is easy but expensive<br>Flammability concerns |

*(Courtesy of C.H. Hare)*

Application technologies have undergone diversification and streamlining. Such changes are exemplified in the development of HVLP, air-assisted airless, and new generation, heated plural-component equipment that facilitate application of one-coat, thick-film coatings and short-pot life, solvent-free coatings.[12] Moreover, working in concert, progressive coatings and equipment manufacturers have made welcome progress in the indirectly VOC-prescribed requirement to optimize coating performance, optimize application technologies, innovate, and minimize or even eliminate solvent usage.

A snapshot of advances in the tactical approach to VOC reduction in the world of industrial coatings is the primary thrust of this paper. An overview of four formulation strategies is provided: waterborne technology (single-component and two-component coatings); solvent-free and high-solids coatings; those coatings formulated with exempt solvents; and additional miscellaneous strategies. While powerful strides have recently been made on many more fronts than the above three, formulators' contributions to VOC compliance from their work on pigments, additives, tint systems, thermal spray, powder coatings, and radiation-cured coatings will be discussed in a future paper.

## FORMULATION STRATEGY 1
### Waterborne Single Component

Popular wisdom has shown that it is not an insuperable problem for the coating formulator to ramp up the performance of any coating system while simultaneously being eco-effective by lowering the coating's VOC levels. But it is technically challenging for the formulator from the chemistry vantage point. Nowhere is this more true than in the pursuit of matching solvent-borne coating performance with that of waterborne technologies. That said, some outstanding innovation from waterborne latex raw suppliers is notable. Ordinarily, single-component waterborne latexes with VOCs in the 100 to 200 g/L range possess inferior performance profiles in medium- to heavy-duty industrial service (chemical and salt-laden) environments. But now, novel technology has come to the fore from different waterborne resin manufacturers. The result? Proprietary direct-to-metal (DTM) acrylic latexes not only have <100 g/L of VOCs but also possess increased gloss, barrier properties, corrosion resistance, and hardness, as well as the ability to withstand freeze-thaw cycles.[1316]

How have these advances been achieved? In one case, through the formation of “composite particles,” where a controlled adsorption of latex particles onto a pigment has been engineered to take place.[13] Novel chemistry causes latex particles to associate with pigment surfaces in the wet applied coating and give rise to a dry film where the pigments are uniformly encapsulated by latex particles; the film then cures by a self--cross linking oxidative cure mechanism (Fig. 1).

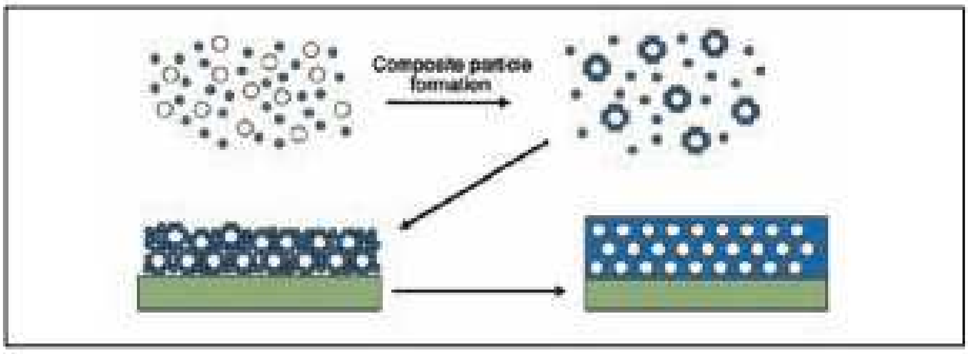



*Fig. 1: Formation of latex polymer-pigment composites and their effect on the film formation mechanism of latex paints.[13] Courtesy of Dow Coating Materials (formerly Rohm and Haas Company)*

Elegant and creative chemistry from the formulator yields micro- to nano-sized “composite particles” that afford substantial film property enhancements compared to conventional single-component acrylic latexes in which the latex or pigment particles may be over-aggregated (Fig. 2). Essentially, as water begins to evaporate from the applied film, the latex binder appears to cocoon each pigment particle and act as a spacer between pigment particles in the drying film.[16] In a conventional single-component waterborne coating, the pigments often agglomerate. In contrast, in a new technology single-component analogue that forms composite particles, the result is a dry coating film in which the pigment is more optimally dispersed and capable of far higher in-service industrial performance.

Accelerated laboratory tests using electrochemical impedance spectroscopy (EIS) show that single-component waterborne coatings that contain composite particles have improved barrier performance. Such coatings have been placed in aggressive ISO 12944 C4 industrial environments (Fig. 3). As expected, the superior durability of this technology is also aided by the polymer’s high molecular weight.

With VOC levels below 100 g/L, a new generation class of styrene acrylic waterborne coatings possesses good adhesion, early humidity resistance, and corrosion protection and durability comparable to the same properties in high-quality solvent-borne alkyds and polyurethane coatings.[15] Although used as DTM primers, more commonly, the new generation water-bornes are primarily used as high-quality finishes (Figs. 4a and 4b).

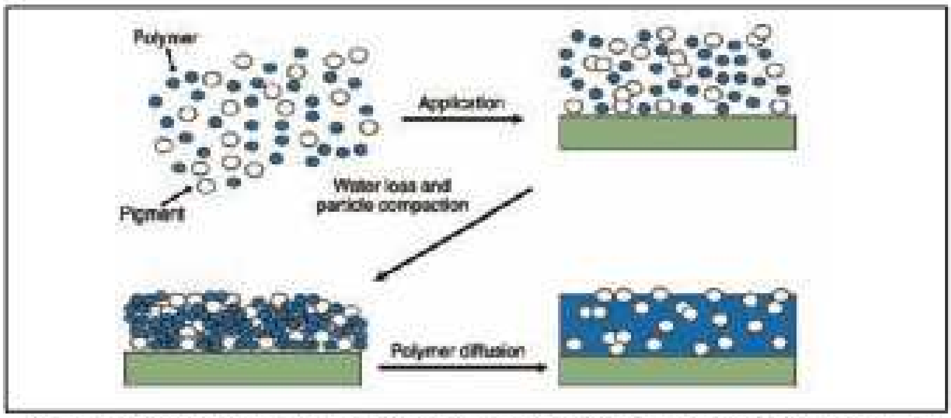



*Fig. 2: Film Formation for a Typical Latex Paint.[13] Courtesy of Dow Coating Materials (formerly Rohm and Haas Company)*


*Fig. 3: ISO 12944 - a comprehensive corrosion protection standard. Examples: atmospheres; moderate sulphur dioxide levels; production areas with high humidit chemical processing plants. C5-I: Industrial areas with high humidities and aggr Marine, offshore, coastal areas with high salinity.*

Granted, the familiar waterborne styrene acrylic coatings have been around for more than a decade and have performed well in harsh conditions (Fig. 5a and 5b, p. 30). In recent times, however, they have undergone such rapid advances using nano-particle technology and creativity in resin formulation that coatings incorporating such technology have performance profiles now suited to more aggressive service environments. A key criterion for enhanced coating performance is the subtle effect of particle size. The latter dramatically affects coating durability.

*Fig. 5a (above): Thermal generation plant (fueled by natural gas). Steel overated with an acrylic latex. 5b (below): The coating 15 years later, maintenance free, at same location: the structure is open to a seacoast environment. Courtesy of Frank Bird, Glidden Paints and Peter Roberts, Devoe Coatings*

Novel approaches in styrenated acrylic latex polymer design include the following.[15]

- Formulating to ensure that the monomers used produce nano-sized emulsion particles with dialed-in heterogeneity that combines both hard and soft polymer chains in the very same particle. Monomers typically include styrene, butyl acrylate, butyl methacrylate, methyl methacrylate, and 2-ethyl hexyl acrylate.
- Self-cross linking between additives and the polymer.

Unlike alkyds and two-component polyurethanes—with their inherent technology limitations to achieve VOCs below 100 g/L without compromising performance characteristics—new generation styrenated acrylics offer far fewer limitations.

**Waterborne Two-Component Epoxies**

Epoxy resin technology has come a long way since its development in the 1940s by a chemist working at Devoe & Raynolds.[17] Today, epoxy coatings formulated from a wide spectrum of curing agents frequently provide unrivalled anticorrosive performance and the lowest life cycle costs. This is especially true with respect to tank and vessel linings.

Most high-performance, ambient-cure epoxy coatings are primarily solvent-borne, and to a lesser extent, solvent-free. Given that certain solvents have been known to pose potential health, safety, and environmental hazards, two-component, waterborne coatings are steadily gaining acceptance as formulators innovate in the realm of waterborne binders.

Historically, although they were introduced in the late 1960s, waterborne epoxy coatings have suffered from limited acceptance due to largely inferior performance compared to their solvent-borne counterparts. Challenges arise because epoxy resins are hydrophobic and require water-sensitive surfactants to facilitate dispersion in the most ubiquitous solvent on earth—water; moreover, curing agents are invariably water--soluble amines and are often salted with an acid to enhance water solubility.

Overcoming these deficiencies, certain resin formulators developed a water-borne epoxy dispersion and amine curing agent that uses proprietary non-anionic surfactants pre-reacted to the epoxy backbone.[10] While obtaining VOC levels below 100 g/L, this novel technique yields faster dry time, faster hardness development, and better corrosion resistance than the solvent-borne benchmark.

Although by no means exhaustive, the preferred approach to formulating waterborne epoxies involves the following three primary aspects.

- Stoichiometry: basically this aspect is the ratio of amine hydrogen to epoxy in a formulation. Generally, two-component waterborne epoxy coatings are formulated at a stoichiometric ratio of 1:1 to achieve the best balance of performance attributes. Table 2 illustrates, however, the effect on coating properties with a deliberate excess of either epoxy resin or curing agent.

- Pot Life: new generation waterborne epoxy coatings do not suffer from shortcomings of earlier waterborne epoxies in which the end of the pot life cannot be determined. (See Table 3 for influences on the pot life.) New generation waterborne epoxy coatings require no induction period and, labeled as a Type 5 System in Fig. 6a, use liquid emulsions and hydrophobic amine adduct curing agents to give fast dry, DTM, low-VOC properties.[18]

**Table 2: Epoxy to Amine Ratio Affects on Performance**

| Increasing the epoxy relative to curing agent gives improved: | Increasing the curing agent relative to epoxy gives improved: |
| --- | --- |
| • Pot life<br>• Acid resistance<br>• Water resistance<br>• Humidity resistance<br>• Corrosion resistance | • Cure rate<br>• Gloss<br>• Adhesion<br>• Solvent resistance<br>• Stain resistance |

*(Courtesy of M.J. Watkins)*

**Table 3: Factors Affecting Pot Life**

| As the variable below increases... | Pot life... |
| --- | --- |
| Epoxy/curing agent ratio | Increases |
| Acid addition to curing agent | Increases |
| Temperature | Decreases |
| Catalyst level | Decreases |
| Initial viscosity | Decreases |
| Solids | Decreases |

*(Courtesy of M.J. Watkins)*

- Coalescence: complete coalescence is the distinctive characteristic in the new generation coatings versus earlier types. Formulators have been able to fully coalesce epoxy resin particles plus curing agent particles in a continuous aqueous phase (Fig. 6a). In marked contrast, incomplete coalescence typifies earlier two-component waterborne epoxies (Fig. 6b).

The chemistry of two-component waterborne epoxies is far more complex than the snapshot presented

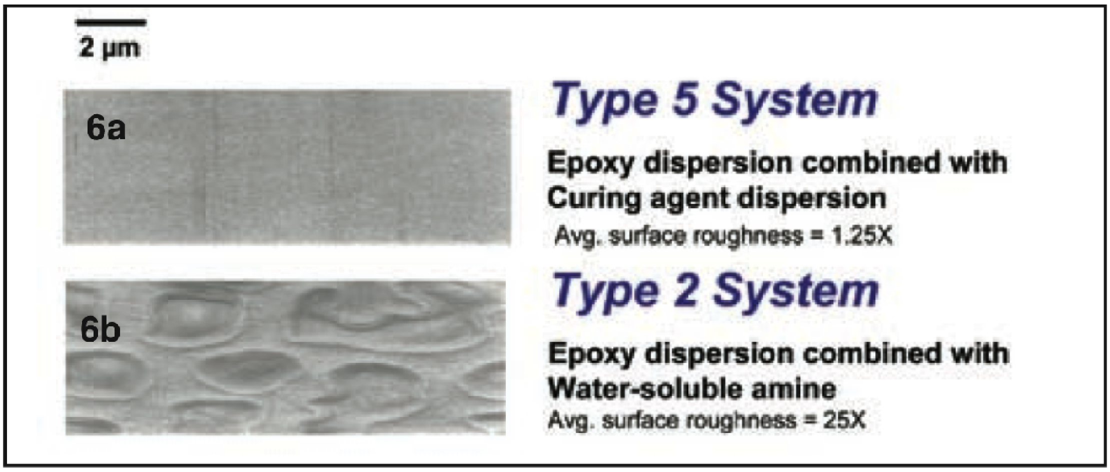



*Fig. 6a and b: Coalescence Comparison of Waterborne epoxy Type 5 and 2 Systems. Courtesy of Michael J. Watkins et al, Hexion Specialty Chemicals[11]*

here. Hence, the reader is encouraged to plumb the depths of Watkins et al. for a complete treatise.[11]

**Waterborne Two-Component Urethanes**

Not to be outdone, formulators have forged ahead in the realm of waterborne polyurethanes. For the past 40 years, two-component polyurethanes have largely been the de facto long-lasting finish coats of choice and one of the largest polymer classes used in the coating industry.[19] A polyol cross-linked with an aliphatic isocyanate provides highly durable, gloss- and color-retentive finish coats that, since the mid 1960s, have mushroomed in growth not only in the world of coatings but in other areas such as foams, sealants, adhesives, and flooring materials. Until recently, these coatings have been available in solventborne formulations only.

Due to the well-known sensitivity of the isocyanate group (NCO) to the OH moiety in water (and moisture), for years, little effort was spent developing a waterborne, two-component aliphatic urethane. The formulation landscape has altered dramatically. Now, extensive research has culminated in the advent of waterborne aliphatic urethane coatings based on polyester or polyacrylic as the polyol and HDI trimer as the curing agent.[20] Early formulation attempts required vigorous agitation in a controlled aqueous medium for full compatibility of isocyanate and OH groups, but recent developments of more hydrophilic resin components have made it easier to use this technology and overcome the natural shenanigan tendencies of some active little molecules! As opposed to their solvent-borne counter parts, stochiometeric ratios of NCO: OH are kept quite high to compensate for the side reaction with water. Normally, these new waterborne aliphatic urethane coatings are used as thin films because overbuilding them causes gas formation (that pesky $CO_2$ molecule) to unleash poor aesthetic finishes.

On a practical note, it is noteworthy that advances in two-component waterborne epoxy and polyurethane systems are forging ahead and such coatings have been used for many years on rail cars.[21] This technology also finds very promising use in flooring and OEM applications. Coatings made from the new generation of waterborne polyurethane resins are typically below 50 g/L.

A helpful suggestion would be to ensure sufficient training is provided for applicators and facility owners on the proper use of two-component waterborne coatings. For example, inclement weather conditions (rain and relative humidity) invariably have a greater deleterious effect on the application of waterborne coating than on solvent-bornes. Furthermore, spray equipment cleaning also has challenges given that only water--miscible solvents should be used to clean spray gear for waterborne coatings.

**Formulation Strategy 2: VOC Exempt Solvents[7]**

Coatings are often formulated with solvents that are VOC exempt. The EPA defines exempt compounds as “organic compounds that are not considered volatile organic compounds due to negligible photochemical reactivity” (40 CFR Part 59.401; a list of exempt solvents is found in 40 CFR 51.100). The selection of these solvents is rather limited. Of particular interest to the formulator are parachlorobenzotrifluoride (PCBTF), acetone, tertButyl Acetate (TBAc), and more recently, tarksone (some examples are included in Table 4; Fig. 7). On the one hand, these solvents can allow the continued use of traditional coating systems without unduly exceeding VOC limits. On the other hand, they have drawbacks that may not offer the same useful properties as nonexempt solvents.

**Table 4: Currently Exempt Solvents**

| | Solvency | Evaporation | Cost |
|---|---|---|---|
| Acetone | Excellent | Fast | Low |
| Methyl Acetate | Very Good | Fast | Moderate |
| Parachlorobenzotrifluoride | Good | Moderate | High |
| Volatile Methyl Cyclosiloxane | Very Poor | Slow | Very High |

*Courtesy of C.H. Hare*

### Solvent System Design and Release

The use of the exempt solvents acetone, PCBTF, or tertButyl Acetate (TBAc) with nonexempt solvent tails that contribute flow and leveling characteristics is a strategy that delivers fast dry systems at low VOC with little or no effect on the pot life. Solvent release from a traditional coating film is typically 60–80% evaporational and 20–40% diffusional. In contrast, solvent release from a solvent-borne, low-VOC coating film is 0–30% evaporational and 70–100% diffusional.

### Acetone

A strong and polar solvent, acetone is a low boiler that possesses little photochemical reactivity, has excellent solvency, and is inexpensive.

Unfortunately, acetone is hydrophilic and water miscible, and, as a result, can cause all sorts of maladies, from cooling the surface of coatings and promoting blushing, to causing poor application and leveling of a coating due to the latter drying too fast. Indeed, it is widely recognized that the major weaknesses of acetone are its fast evaporation rate, low flash point, and fire hazard.

In the case of epoxy coatings, acetone can associate with amine curing agents to form ketimines, upset the cure reaction, and increase dry times. For this reason, acetone would be employed in the epoxy base component as opposed to the curing agent. So to lower the VOC of high-performance coatings, a satisfactory solvent system design strategy for binder systems will often consist of acetone blended with parachlorobenzotrifluoride (PCBTF) or tarksone, with or without a high-boiling VOC solvent.

### Parachlorobenzotrifluoride (PCBTF)

This relatively non-polar chlorinated hydrocarbon solvent is a medium boiler and one of the “best friends” of the coating formulator.[22] It is hydrophobic, VOC exempt, and neither an ozonedepleting substance (ODS) nor a hazardous air pollutant (HAP). With a broad-spectrum solvency, PCBTF possesses a compact and planar shape and diffuses more readily from coating films and certainly not as fast as acetone. Unlike acetone, PCBTF is not reactive with any amines in two-component epoxies, and is invariably un-reactive in most coating systems.

With zincs, highmolecularweight epoxies, moisturecured urethanes, and polyurethane finishes, the use of PCBTF affords the coating formulator the means to reduce VOCs to less than 250 g/L without fear of reactivity with other coating constituents or decomposing in a dehy-drochlorination reaction.

In the field, the coating applicator benefits by being able to thin coatings with this nonexempt solvent and thus achieve usable film viscosity and excellent spray characteristics, and in doing so, maintain full compliance with VOC regulations.

On the negative side, PCBTF can impart odor/taste-related problems to potable water coatings. Additionally, in an age in which cost reduction is deemed a priority, the cost of PCBTF is high and can severely impact the attractiveness of coatings that use high levels of PCBTF to yield VOC levels that approach 100 g/L.

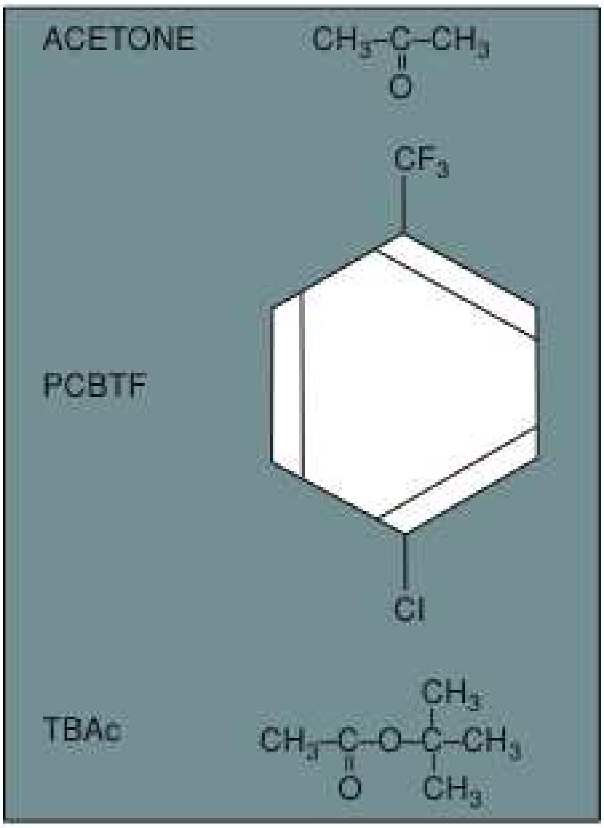



Fig. 7: Structural formulas for VOC-exempt solvents

### Tertiary Butyl Acetate (TBAc)

With an evaporation rate similar to toluene, TBAc is a VOCexempt solvent due to its limited reaction to form smog and its low environmental and health impact. A versatile solvent for the coatings formulator, TBAc resists aminolysis, hydrolysis, and acidolysis and is used in a variety of generic coating types, including polyurethane finishes and two-component epoxies.[23] Interestingly, TBAc may be successfully used to replace xylene in new-generation epoxy coatings. Limitations for TBAc are that it is not a particularly strong solvent for high-molecular-weight epoxy resins and it has a rather low flash point.

### Tarksone (A Blend of Solvents)

Synonymous with outstanding performance in water immersion, solution-polymerized vinyl-based coating systems (VYHH and VMCH) may well be set to return to the protective coatings scene, having largely disappeared from the map in the past two decades because of stringent VOC regulations.[24] The coating formulator blends an environmentally friendly biomass alcohol that is both non-HAPS and non-VOC (from wood-related products) with acetone in the vinyl formulation. Acetone is considered to be an ideal, non-polluting solvent for vinyl coating systems. The resulting vinyl film has a VOC content less than 100 g/L.

A potential downside is the cost associated with the blended biomass solvent, because a relatively large amount must be employed in the vinyl formulation to both achieve the desired VOC levels of the coating and raise its flash point to about 120 F. That said, PCBTF and TBAc are somewhat more expensive solvents.

In a nutshell, exempt solvents afford an improved VOC air quality strategy

- by replacing solvents with high atmospheric reactivity,
- with minimal effect upon coating performance or ease of application, and
- by assisting application in the field without running afoul of VOC regulations.

## FORMULATING STRATEGY 3: SOLVENTFREE COATINGS (100% SOLIDS BY VOLUME)

For decades, solvent-free epoxies and urethanes have been a particularly effective means to produce zero- or low-VOC, high-performance chemically curing coatings. The basic approach in formulating them is to use low molecular weight and low viscosity liquid resins, being mindful to create a careful balance between mono- and difunctional materials. This approach strikes a balance among flexibility, impact resistance, and abrasion resistance in contrast to hardness and chemical resistance. Additionally, both monofunctional and difunctional epoxy diluents may be employed in epoxy systems to further reduce viscosity for low VOC.[4]

Why are modern solvent-free coatings becoming even more popular? Aside from their low VOC attributes, they can have a number of advantages, some of which were outlined by Dromgool in a well-balanced review of the plusses and minuses of solvent free epoxies. The advantages that Dromgool identified for solvent-free epoxies when used as tank linings included: “They are usually a one-coat lining system; they can be applied at high film builds; there is no risk of solvent entrapment; some will tolerate early immersion; they can save much time and labor; and they combine the generally excellent adhesion of epoxies to prepared steel substrates with a hard, tile-like finish. In addition, they have minimal occupational health and safety (OH&S) issues, including no worker exposure to solvents (no lower explosive limit, or LEL), and no release of solvent when changing from liquid to solid.”[25, 26]

Fig. 8: One-coat solvent-free advanced hybrid epoxy in crude oil storage tank
Courtesy of Darryl Corbin, Envirolne, High Performance Coatings and Linings

While no one disputes the key advantages of solvent-free epoxy coatings, the approach of using low molecular weight resins has resin toxicity implications not as prevalent with higher molecular weight resins. Furthermore, there are performance disadvantages, too, because the judicious use of solid epoxy novolac resins in a multi-coat solvented coating can usually produce better chemical resistance (due to a more tightly cross-linked polymer structure) and hence better chemical resistance than a solvent-free system.

For many solvent-free epoxy coatings, one negative is the extended dry times, but having said that, there have been significant advances that largely overcome this dry time deficiency. Some proactive coating manufacturers have long since formulated ultra-high build solvent-free epoxies that can be applied in one--coat applications from 15–150 mils DFT that are cured in hours for fast turnarounds[27] (Fig. 8). The key to success most often lies in the domain of the curing agent. For example, phenalkamines—curing agents derived from cashew nut shells—afford the formulator very fast, low-temperature, and all-season curing coatings along with substantial VOC reductions as low as zero VOC.[28] Benefits include the following.

- Low viscosity (<1,000 cps)
- 100% solids
- Non-brittle
- Compatible with all resins
- All-season cure
- Non-blushing
- Workable pot life

The phenalkamines are also considered “green in terms of $CO_2$ consumption,” as the shell-derived CNSL (cashew nut shell liquid) is obtained from a renewable natural source.[28]

In the relentless pursuit of excellence, it cannot be overemphasized that the use of solvent-free coatings of any generic type has been one of the major contributions of coating formulators in addressing VOC regulations.

## FORMULATING STRATEGY 4: MISCELLANEOUS

Additional strategies to meet low-VOC regulations involve gaining traction with new coating technologies per se. Among them, two new approaches merit serious consideration.

### Polysiloxanes

In polysiloxane technology, inorganic silicon-epoxy hybrid or silicon-acrylic hybrid polymers have been developed to combine the excellent properties of both organic and inorganic moieties in a new class of polymers.[29] The low viscosity siloxane polymers can be formulated to achieve durable and very low-VOC, two component coatings systems.

### Polyaspartics

More recently, a second approach is the development of polyaspartic ester technology. Giving rise to rapid curing and rapid return to service capabilities, polyaspartic coatings possess performance comparable to conventional aliphatic polyurethanes and do not employ the polyols of urethane finishes. A new dimension in high-solids and low-VOC, rapid-cure finish coats has been spearheaded by the formulator where polyaspartic coatings can be applied in thick films, in a single coat, without sacrificing quality and cure times.[19]

All in all, looking back at the excellent strategies described to address VOC compliance, coating formulators have turned out to be eco-contributors in a world of eco-centricity. Without a doubt, they have earned their bread and butter!

## CONCLUSIONS

Coating formulators have demonstrated ingenuity in complying with stringent VOC regulations while keeping the same standard of high performance.

Significant research and development in recent years has shown that two component waterborne epoxies can deliver comparable performance to solvent-borne epoxies, and that novel single component waterborne coatings possess outstanding corrosion resistance and aesthetic properties.

VOC regulations should not be deemed adversarial. The overarching brighter side of VOC regulations has brought out the best from coating formulators in providing owners with life cycle extension benefits; applicators with a lower number of applied coats; and all parties a quicker return to service, sometimes in a single coat.


## SPECIAL ACKNOWLEDGEMENT

The work of Dr. O'Donoghue's personal friend Clive H. Hare has been used extensively herein. The protective coatings industry will forever be indebted to Clive for his exemplary contribution. For those of us who have walked with Clive through the mysterious fields of protective coatings, who could ask for a better guide?

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