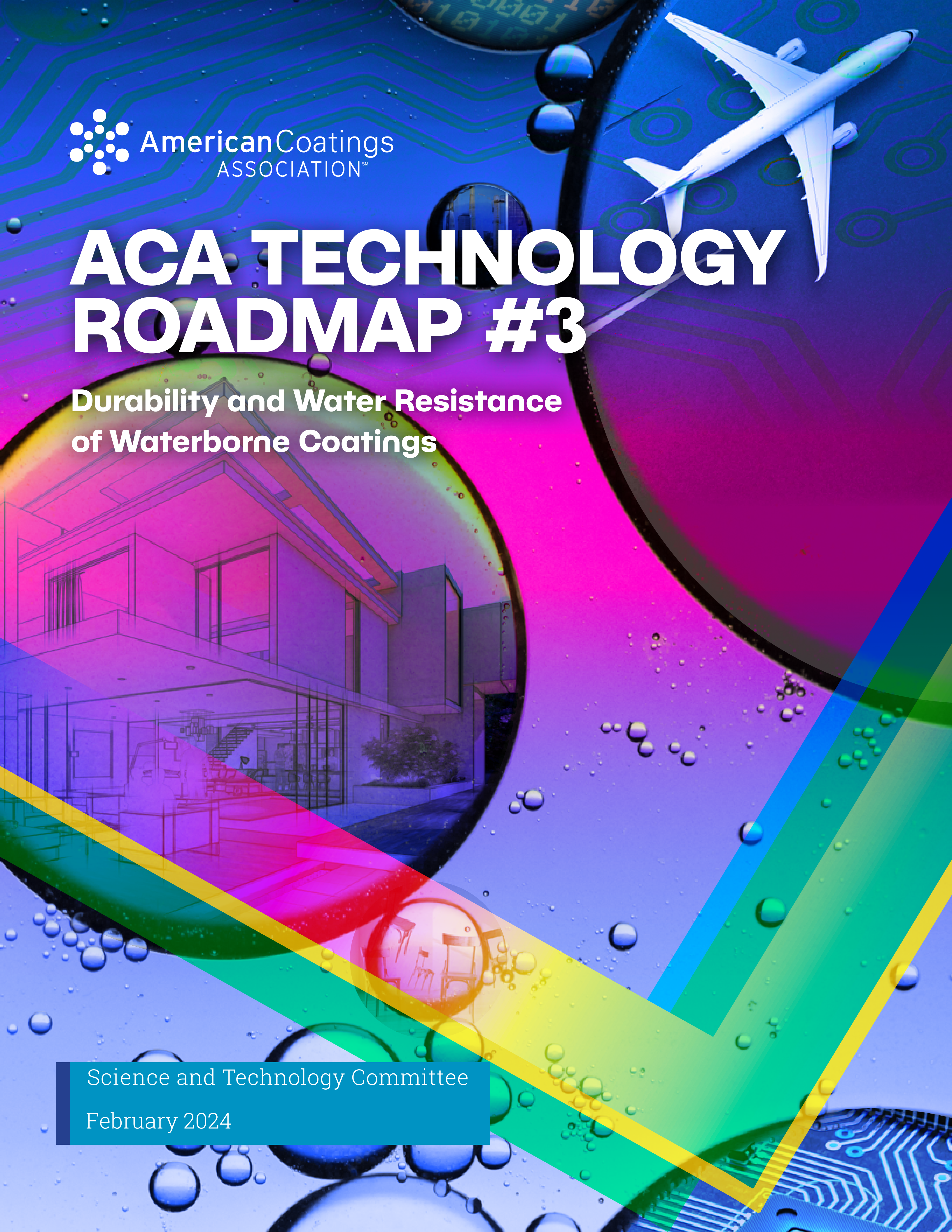

AmericanCoatings ASSOCIATION℠

ACA TECHNOLOGY ROADMAP #3

Durability and Water Resistance of Waterborne Coatings

Science and Technology Committee

February 2024

EXECUTIVE SUMMARY

The American Coatings Association (ACA)[1] is developing a series of future-looking Technology Roadmaps. Potential topics were identified through a rigorous, industry-led process. Technology Roadmap #3 addresses the topic of durability and water resistance of waterborne coatings.

Each ACA Technology Roadmap identifies "open-innovation" research that supports both near- and long-term needs of the coatings industry. ACA Technology Roadmaps are not intended to promote or advance any product, practice, solution, or technology. Contributors were cautioned not to disclose any confidential business information. Where future collaboration is recommended, it is intended to comport with antitrust rules and be guided by legal counsel.

The growing focus on sustainability and the ever-tightening restrictions on volatile organic compounds (VOCs) have prompted increased reliance and use of waterborne coatings. This ACA Technology Roadmap considers research areas related to improving the performance, durability, and water resistance of waterborne coatings. Waterborne paints and coatings are used extensively across architectural and industrial applications. While there is an increasing demand for waterborne coatings, a number of challenges and difficulties remain regarding the formulation and ever-growing performance requirements of waterborne coatings.

Through a series of expert interviews and subsequent consensus-building discussions, the following recommendations endeavor to guide forward-looking research efforts by the coatings industry to address current challenges facing waterborne coatings:

1. Improved test methods – Non-destructive test methods, seasonal tests, in-the-field "open time" indicators, and weathering tests that better predict real-world performance are all needed. Industry committees could foster their development.
2. Higher crosslink density – Research into more highly crosslinked and two-component (2K) waterborne systems is needed. A conference session or symposium on these topics could help facilitate that.
3. Greater system robustness – This is achieved through novel resins, additives, surfactants, dispersants, and pigments to address "open time," freeze-thaw stability, "flash rust," and adhesion. Organizing conference sessions and symposia on these topics could help that come into focus.
4. Improved packaging for waterborne coatings – This could be a topic for a conference session or symposium.
5. Training on proper surface preparation and waterborne coating storage, handling, and application. Coordination with applicator trade groups, such as contract painters, could provide training opportunities.

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[1] The American Coatings Association (ACA) is a voluntary, nonprofit trade association working to advance the needs of the paint and coatings industry and the professionals who work in it. The organization represents paint and coatings manufacturers, raw materials suppliers, distributors, and technical professionals. ACA serves as an advocate and ally for members on legislative, regulatory, and judicial issues, and provides forums for the advancement and promotion of the industry through educational and professional development services.

6. Awareness – Sharing current success stories would help, and could be featured in trade publications, especially when the story is verified independently.
7. Updated product specifications – More durable waterborne systems may not fit current specifications. Encouraging the updating of specifications to specify performance rather than a specific chemistry or type of system would be helpful.

Background on the ACA Technology Roadmap Project

ACA, through its Science and Technology Committee, is developing a series of ACA Technology Roadmaps that endeavor to build technical consensus on industry-wide "open innovation" research that supports both near- and long-term needs of the coatings industry. A rigorous, multi-step analysis was undertaken to identify potential topics, the result of which is included in Appendix A.

Once a topic is selected for development from the list, ACA staff and a diverse set of industry leaders – through a consensus-based process – identify research that has the potential to advance industry sustainability and growth by informing manufacturers, raw materials suppliers, academic institutions, government research laboratories, and other research organizations.

First and foremost, the ACA Technology Roadmaps are not intended to promote or advance any product, practice, solution, or technology over or to the exclusion of others, nor restrain in any fashion the individual competitive efforts of any company. Rather, they are intended to drive innovation and competition by broadly sharing identified technological needs of the industry. All ACA Technology Roadmaps are available to the public on the ACA website.

Subsequent actions may include targeted technical discussions, such as industry-academia workshops, dedicated conference sessions, or fostering the development of new test methods. Further, the process used to develop this content was carefully established to ensure contributors were cautioned not to disclose any confidential business information, research plans, or competitively sensitive information. Where further collaborative action among companies is recommended, it is intended to be with the consultation of legal counsel to ensure compliance with antitrust laws and other applicable regulations and laws.

This is the third ACA Technology Roadmap. ACA Technology Roadmap #1 (August 2022)[2] examines the industry's challenges in sustained use of critical materials for formulating both existing and emerging products and provides a detailed discussion of the project's aims, benefits, and execution. ACA Technology Roadmap #2 (January 2023)[3] examines the trend toward lightweighting, which often involves the coating of novel substrates.

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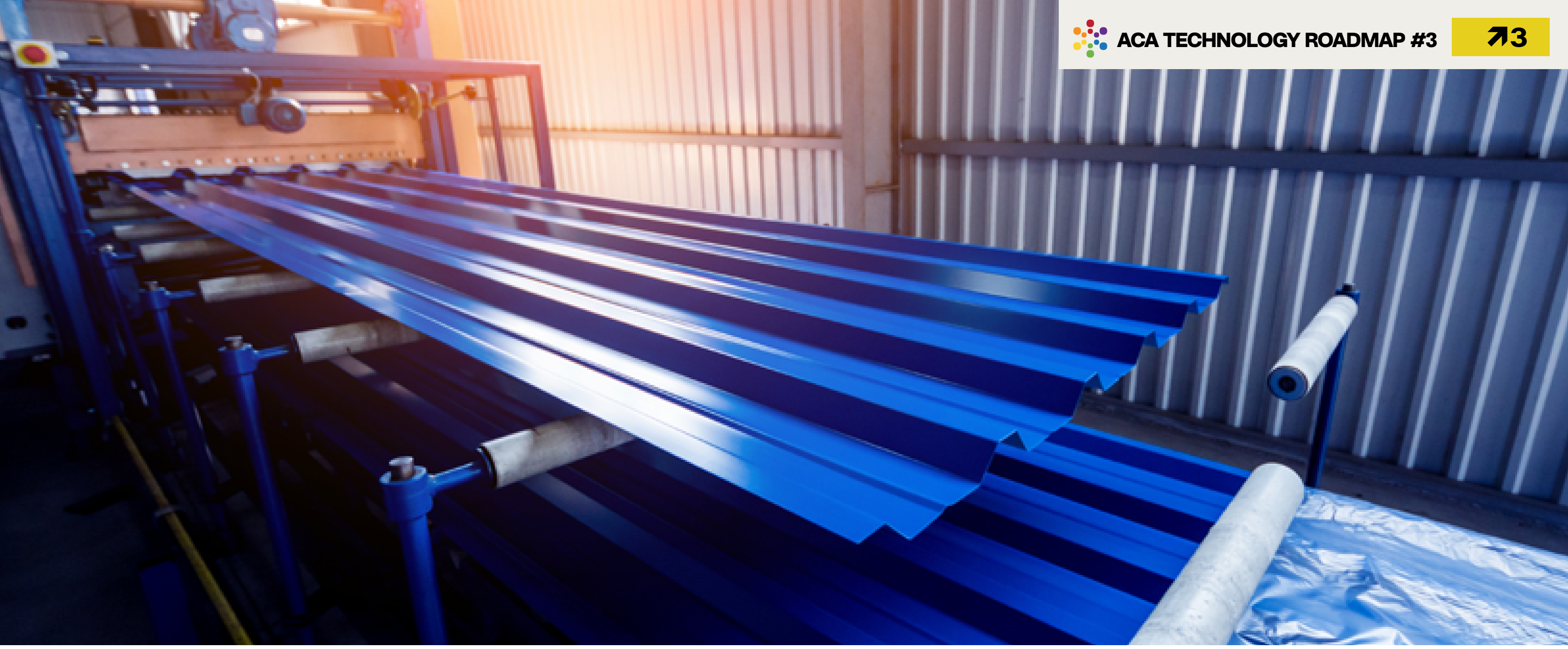
[2] Available at https://www.paint.org/wp-content/uploads/2022/08/ACA-Technology-Roadmap-1.pdf

[3] Available at https://www.paint.org/wp-content/uploads/2023/02/tech-roadmap-2.pdf.



ACA TECHNOLOGY ROADMAP #3: DURABILITY AND WATER RESISTANCE OF WATERBORNE COATINGS

Introduction and Scope

This ACA Technology Roadmap, "Durability and Water Resistance of Waterborne Systems," highlights how the growing focus on sustainability, rising use of green building standards, and tightening restrictions on volatile organic compounds (VOCs) have prompted an increased reliance on waterborne coatings. These factors are creating a demand for improving the performance and durability of waterborne coatings, as well as advancing the resin and additive technologies used in the formulations. To further support sustainability goals, waterborne coatings not only beautify the substrate but also protect it. This further helps to reduce raw material consumption in both rebuilding the substrate and developing more coatings. Although waterborne coatings are used extensively, technical challenges remain, including the need for improved durability.

To help inform and shape the conception of ACA Technology Roadmap #3, the article "Waterborne Industrial Coatings: Regulatory Changes Slowly Driving Shift to Waterborne" by Cynthia Challener in *CoatingsTech* magazine (Vol. 14, No. 10, October 2017)[4] was consulted during the industry survey and interview phases of development. Some key observations from the article include the following:

- Furniture – North America tends to use one-component (1K) waterborne coating systems, while Europe uses more two-component (2K) waterborne coatings. Shops that use equipment for which mixing takes place in the spray gun are generally best suited to using 2K coatings. For outdoor furniture, waterborne ultra-violet-protective coatings can be used.

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[4] Available at https://www.paint.org/coatingstech-magazine/articles/waterborne-industrial-coatings-regulatory-changes-slowly-driving-shift-waterborne/.

- Architectural – Waterborne coatings have been widely used in the architectural segment for many years. Acrylic resins are the most used resin type.
- Flooring – The flooring industry has unique challenges. Ben Smith (Flowcrete Americas) is cited, "Resin versatility is especially important in the flooring industry, particularly with respect to the ability to develop customized coatings with specific properties." For example, in the electronics sector or where explosive gases/powders are used, flooring needs to dissipate static electricity. As another example, flooring in the aviation industry must withstand hydraulic fluids.
- Automotive refinish – This sector typically uses acrylic resins.
- Industrial – This sector includes coil coating, electrical insulation, industrial finishes, automobile interiors, and office machine exteriors. Regulations in Europe already require the use of waterborne liquid coatings for industrial applications. For certain industrial substrates, polymeric resins need to withstand harsh outdoor environments. The standard suite of polymeric resins today includes acrylic emulsions, styrene acrylics, polyurethane dispersions, epoxy polymers, and hybrids (e.g., urethane-alkyd hybrids).

According to the 2017 article, novel crosslinking chemistries and advances in resin synthesis may be needed to improve durability. As Jeff Johnson (Axalta) noted,

> Resin technology is a key contributor to product performance and is one of the most valuable assets of a coatings company. While the fundamental building blocks of resin synthesis have not changed, advances in catalyst technology have created opportunities to create novel polymer architectures that have dramatically widened the range of coating performance available from water-based resins. Controlled polymer architecture also provides a means to reduce surfactant levels and to reduce the use of other water-soluble components used during polymer synthesis, resulting in improved application robustness through better spray atomization along with improved durability.

Current Uses of Waterborne Coatings

Waterborne coatings are known for low-VOC content, ease of use, cleanup and disposal, and their safety during handling, storage, and transportation. Waterborne coatings are widely used across various industry sectors due to their environmentally friendly and performance characteristics. These industry sectors include:

- Adhesives
- Aerospace
- Architectural
- Automotive original equipment manufacturing (OEM)
- Automotive refinishing
- Cans
- Coils
- Construction
- Electronics
- Energy storage
- Fabrics

- Fiber sizing
- Floors
- General industrial equipment and materials
- Inkjet inks
- Leather
- Marine vessels and structures
- Oil and gas
- Packaging
- Paper
- Printing inks
- Protective
- Sealants
- Wood and furniture

The variety of waterborne coatings and applications across various industry sectors using them continues to grow. Waterborne coatings are the standard choice for architectural coatings, accounting for around 80% of household paints sold today.[5] They are extensively used by professional painters and Do-It-Yourself (DIY) consumers for both interior and exterior applications, and commonly used on walls, ceilings, trim, and other surfaces in residential, commercial, and institutional buildings to enhance aesthetics and provide long-term protection.

Waterborne architectural products include primers, paints, lacquers, varnishes, and stains. These provide durability; mechanical resistance; stain resistance and repellency; water and chemical resistance; scrub, scuff and burnish resistance; and increase hiding on many substrates. In addition to low-odor and easy cleanup, the simple application processes allow less-skilled labor to apply coatings. The low-VOC and odor characteristics enable use of waterborne coatings in schools, hospitals, other sensitive institutions and confined spaces.

Wood is a common substrate for waterborne coatings. Both DIY consumers and OEMs apply waterborne systems to furniture, windows, trims, cabinetry, joinery, doors, flooring, and decking. Waterborne systems provide long-term protection against ultraviolet (UV) rays, moisture, stains (including water, smoke, tannin, and grease), and mechanical abrasion without hiding the natural beauty of the wood. Waterborne coatings include primers, clear finishes, topcoats, sealers, and stains.

Industrial waterborne coatings are mostly used in light-to-medium general industrial applications although they are increasingly used in high-performance areas due to novel resins and additives that contribute those properties. They are applied to machinery, roadways, equipment, appliances, plastics, concrete, masonry, and other industrial surfaces. High-performance waterborne resins and additives offer resistance to mechanical wear, corrosion, chemicals, and moisture, thereby making them suitable for certain heavy-duty applications and demanding environments.

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5 Paint Quality Institute, as quoted in *PCI* Magazine (February 6, 2019), "Study Expects Moderate Growth in Architectural Coatings Market" available at https://www.pcimag.com/articles/105700-study-expects-moderate-growth-in-architectural-coatings-market.

The packaging industry applies waterborne coatings, inks, and adhesives to rigid containers and flexible packaging, including food-contact surfaces. These waterborne coatings provide a barrier to water, oil, and chemicals. They also protect against abrasion, display label information (including security features), and even provide tactile sensory effects such as "soft feels." Beyond packaging, waterborne inks are used for inkjet printing, screen printing, gravure printing, and flexographic printing.

In recent years, automotive applications (both OEM and refinishing) have included waterborne coatings as primers, monolayer topcoats, basecoats, and clearcoats. They provide adhesion, protection, and aesthetic value. Global variations are evident across how waterborne coatings are formulated, used, and regulated.

The exteriors of marine vessels and structures are typically coated with solvent-based and 100% solids systems due to stringent performance requirements. Waterborne systems are used extensively in interior cabins and less-harsh-exposure areas on ships. In recent years, however, high-performance waterborne coatings are being used for exterior and interior protective marine applications on ships, structures, bridges, pipelines, mines, water/waste treatment facilities, power plants, and offshore rigs to protect against corrosion, fouling, chemicals, and degradation in harsh environments.

Polymeric Resins Used in Waterborne Systems

Waterborne systems incorporate various types of polymeric resins to achieve the desired performance characteristics, as follows:

- Waterborne acrylic resins are commonly used due to their adhesion, durability, and weather resistance. Self-crosslinking acrylic resins provide especially good gloss retention as well as chemical, stain, and UV-ray resistance. Acrylic resins are versatile and can be formulated to achieve many different finishes for a wide variety of applications.
- Waterborne polyurethane dispersion resins offer durability through weathering, corrosion and resistance to UV rays, as well as chemical and abrasion resistance. They are used in coatings where high-performance properties are required, such as automotive, industrial, and wood finishes. They adhere well to challenging substrates and can be formulated to achieve a balance of hardness and elasticity. Also, they can be combined with other resin types to enhance performance.
- Waterborne epoxy coatings offer film integrity that can withstand harsh environments. They offer strong adhesion, chemical resistance, and corrosion protection. Accordingly, they are commonly included in metal, concrete, and flooring coatings.
- Waterborne alkyd resins serve as binders in coatings that require hardness, blocking resistance, gloss, yellowing resistance, outdoor durability, multi-substrate adhesion, with the characteristic flow and leveling that painters are seeking. They are found in architectural paints and primers for trims, cabinets, and doors. They can be formulated to meet semi-gloss to high-gloss enamel requirements.
- Waterborne vinyl acetate ethylene resins are used for industrial, architectural and consumer applications on various substrates, such as drywall, wood, cellulosic concrete, vinyl, aluminum, and masonry. They resist water and are low odor. They are used for waterproofing coatings, wood adhesives, and engineered fabrics. They can be combined with acrylic monomers to increase durability and avoid yellowing.

- Waterborne styrene-acrylic resins combine the properties of styrene and acrylics to offer adhesion, durability, and water resistance. They are used in architectural coatings, wood finishes, and industrial coatings.
- Waterborne polyvinylidene chloride resins provide barrier properties against moisture and gases, such as oxygen. They are commonly used in the packaging industry to provide high-performance barrier coatings or films. They also are used to impart flame retardance, and for protective and anti-corrosion applications.
- Waterborne polyvinylidene fluoride resins are known for their superior durability, weatherability, chemical resistance and corrosion resistance. They are used as topcoats in original equipment manufacturer-applied and field-applied architectural and protective coatings, as well as other high-performance environments.
- Waterborne silicone resins offer heat resistance, weatherability, dielectric properties, and water resistance and repellency. They, too, are used in high-performance applications.

Raw material suppliers often blend resins to build unique combinations (hybrids), plus additives, to achieve the performance demanded by a specific application and environment. Recent technological advances allow raw material suppliers to use plant-based, bio-based, recycled, and recyclable materials to manufacture resin monomers, thereby increasing sustainability.

Current Challenges for Waterborne Coatings

While waterborne coating systems have certain strengths, several challenges and opportunities for improvement remain. These are associated with waterborne formulation, application, and performance, including film formation, dry time, "open time," "flash rust," adhesion, hydrophilicity, and freeze/thaw stability during transport and storage.

Waterborne films encounter challenges in forming a strong barrier and repelling water, primarily due to the inherent hydrophilic characteristics of the resins and/or dispersants used. Hydrophilicity may also be affected by additives, surfactants, and pigments. Managing the hydrophilic properties of waterborne coatings is important to prevent excessive water absorption by the "dry" film and resultant blistering, which can lead to decreased durability and other performance issues. Acrylics and alkyds have lower crosslinking density and, consequently, offer less barrier performance than other resins. Highly crosslinked resins, with reactive components like isocyanates, additional challenges arise, such as the reactivity of the isocyanate group with water. Innovations in formulation chemistry may be needed to achieve desired performance. The formulation of waterborne systems often requires more complex chemistry and may involve additional processing steps.

Waterborne coatings, such as epoxy and polyurethane, provide stronger barriers. Formulating waterborne coatings to prevent the trapping of water during drying is crucial to avoid film defects. High humidity levels affect film formation, drying time, and adhesion, while low temperatures prolong curing times. When both are encountered, durable film formation is especially difficult. Poor film formation compromises overall performance and is a challenge to overcome.

At the other extreme, high heat and low humidity lead to the rapid evaporation of water, especially in low-VOC formulations, which impacts the coating's workability and application quality. "Open time" – the time during which the coating remains workable – is another consideration and challenge. Balancing the need for extended "open time" with durable film formation is especially important for areas with dry and hot climates, such the deserts in the southwestern United States.

Waterborne coatings can be susceptible to “flash rust” or “flash corrosion,” especially if the substrate preparation is inadequate. If a surface is wet for a long time prior to painting (for example, in high humidity at low temperature), a waterborne system does not allow the surface to dry, which can lead to “flash rust” of the metal substrate. The presence of dirt and acidic pollutants on the surface can also contribute to “flash rust.” Proper surface cleaning and pre-treatment, therefore, are crucial to mitigate this challenge.

Substrate surface properties present challenges for the durability of waterborne systems. Some waterborne coatings may be incompatible with certain types of substrates, and some substrate surfaces may require additional preparation or priming to ensure proper adhesion and compatibility. Especially challenging for waterborne coating adhesion are substrate surfaces that are damp, dirty, oily, or greasy. Unsurprisingly, waterborne coatings often necessitate thorough surface preparations. To prepare a surface, blasting or sanding might be required. Such preparatory steps add to the project’s cost.

Achieving a uniform coating thickness is challenging for some waterborne systems due to high viscosity and rheological properties. Special application techniques and additive packages may be needed to achieve the desired film thickness, rheological responses, and coverage.

Microbes, such as mold and mildew, can thrive in waterborne systems. To improve the storage shelf life and the dry film’s longevity, antimicrobial compounds are often added. Proper application of biocides and fungicides in formulations as well as suitable storage and handling procedures are important to maintain the quality and stability of waterborne coatings.

Ensuring freeze-thaw stability and addressing transportation and storage concerns is important for waterborne coatings. Field applications require the waterborne coating to withstand seasonal changes (i.e., late fall/winter/early spring), which expose the coating to fluctuating temperatures and humidity. Achieving good film formation with no cracking under these conditions remains challenging for waterborne coatings. Waterborne resins with improved freeze-thaw resistance or which require less, or no use of glycol are desired to prevent performance issues.

Proper defoaming, surface tension control, and surface wetting can also be challenging for waterborne coatings. Proper use of defoamers or surfactants to reduce surface tension can eliminate entrained air bubbles (also referred to as foams), which can cause pinholes in the coating during drying. Correct use of surface additives for flow and leveling and substrate wetting minimizes coatings defects. Determining the correct amount and use of additives can help achieve the desired waterborne coating performance.

Recommendations for Waterborne Coatings

Regulations play a significant role in incentivizing change, as demonstrated by the industry response to the low-VOC coatings rules in California (especially by the South Coast Air Quality Management District), Europe, and China. Regulatory restrictions spurred innovation to develop new, low-VOC coatings, many of which are waterborne.

Beyond regulation, perhaps the largest challenge for waterborne systems in certain applications is gaining professional and public acceptance of their performance, including durability. Previous experience may bias the selection of today's improved coatings. Sharing current success stories would help, as would independent verification of waterborne system performance.

New users and applicators need to be properly trained in best practices for surface preparation, storing, and applying waterborne systems. Training could address challenges such as how waterborne systems tend to dry quickly with a short "open time" or recoat window. The interplay of temperature, humidity, and drying time could be included in the training. Another focus could be on how the addition of water to thin the coating on-site could create instability in the system and impact the final appearance and performance of the coating.

To convince users of a waterborne coating's durability, the exact performance requirements of the user's end application need to be fully understood. Furthermore, understanding the factors that influence consumer choice is important for adoption of waterborne systems. Trade journal and magazine articles, as well as trade conferences and symposia, could be avenues to disseminate the latest technological advances in waterborne coatings durability.

Product specifications may need to be updated or revised to accommodate the latest waterborne systems. Some specifications were written decades ago, and some users say they cannot adopt the newest technology on their site or application because it is not written into specifications. Specifiers may not currently appreciate the performance capabilities of the latest waterborne coatings. As specifiers become more comfortable with new waterborne products and their performance, they may be able to write them into the specification. When not included in a specification, it is difficult to pursue the new technology and conduct long-term performance and durability studies. One solution is to re-draft specifications for performance (including durability) rather than a specific chemistry or type of system.

Although performance of waterborne systems has improved greatly, opportunities for further advancements remain. The opportunities can be divided into the following categories: improved test methods, higher crosslink density, greater system robustness, and developing improved training materials on optimal handling and substrate preparation to maximize performance.

All coating systems, including waterborne, require improved test methods to investigate the chemistry that occurs at the interface between the coating and its substrate. Failures often occur at the interface, and it can be difficult to determine the source of failure without complete removal of the coating.

Suggested areas for test method development include:

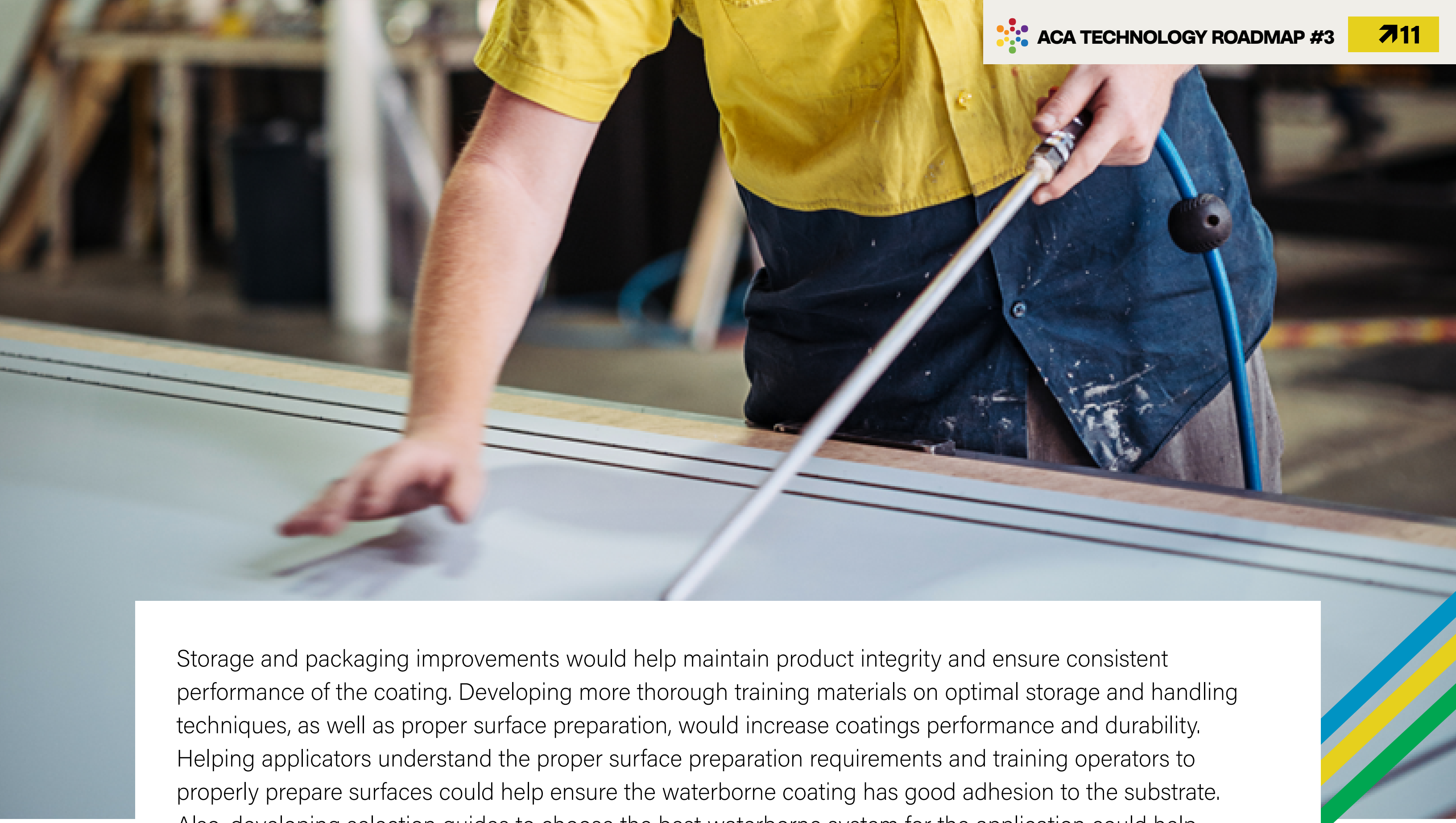
- Developing non-destructive tests to allow investigators to better understand when a coating is close to failure. Such tests could provide opportunities to repair the coating prior to irreversible or unanticipated failure.
- Developing methods to better understand waterborne film formation under different environmental conditions, which would help formulators write better guidance for applicators. For example, a waterborne paint applied in the spring had excellent performance; however, when the same paint was applied in the late fall, early failures were observed.
- Improving weathering test methods would aid waterborne systems. Accelerated weathering test methods do not correlate well with real-life, outdoor exposure conditions, especially for coatings used in harsh climates. In addition, more accurate tests would shorten the timeline to commercialization.
- Laboratory tests are often insufficient to predict actual performance in the field. Developing in-field methods to detect approaching end of "open time" would assist contractors that apply waterborne systems.

Today's waterborne systems generally have low crosslink density and are one-component (1K) systems, which often prevents their use for highly corrosive and extreme environments; more highly crosslinked and/or two-component (2K) waterborne systems are needed for these applications. Waterborne systems, however, can be more challenging to formulate due to the inherent water sensitivity of some components. For example, as mentioned previously, waterborne polyurethane systems are challenging due to inherent reactivity of isocyanate with water. Compensating with additional isocyanate increases the crosslinking yet adds costs.

Often, greater system robustness is achieved through novel resins or additives. Surfactants and dispersants, which are added to create stable waterborne systems, may contribute to water sensitivity and lower durability. Advancements in polymeric resins could enhance the performance of waterborne systems, and the selection and compatibility of additives in waterborne systems play critical roles in the performance of waterborne systems. A few areas for research were mentioned by the experts interviewed:

- New additives that improve "open time" in hot, and dry climates.
- A new polymer that could hold onto water longer and then release the water after a point to extend "open time."
- Surfactants that, after drying, do not lead to crack formation or water-sensitive areas.
- Additives or new resins that improve waterborne freeze-thaw stability. These could either prevent freezing or allow the paint to be used after freezing and thawing.
- New additives that allow waterborne systems to adhere to poorly prepared (e.g., greasy, dirty, moist) surfaces.

Collaboration between binder and additive manufacturers is essential for developing effective formulations. To reiterate, such collaboration is intended to drive innovation and competition and should be carried out with the consultation of legal counsel to ensure compliance with antitrust laws and other applicable regulations and laws.



Storage and packaging improvements would help maintain product integrity and ensure consistent performance of the coating. Developing more thorough training materials on optimal storage and handling techniques, as well as proper surface preparation, would increase coatings performance and durability. Helping applicators understand the proper surface preparation requirements and training operators to properly prepare surfaces could help ensure the waterborne coating has good adhesion to the substrate. Also, developing selection guides to choose the best waterborne system for the application could help prevent early failures if an inappropriate system was chosen.

The following takeaways may help guide future research efforts by the coatings industry to address industry-wide challenges to increase the durability and water resistance of waterborne systems.

1. Improved test methods – Non-destructive test methods, seasonal tests, in-the-field "open time" indicators, and weathering tests that better predict real-world performance are all needed. Industry committees could foster their development.
2. Higher crosslink density – Research into more highly crosslinked and two-component (2K) waterborne systems is needed. Conference sessions or symposia on these topics could help facilitate discussions.
3. Greater system robustness – This is achieved through novel resins, additives, surfactants, dispersants, and pigments to address "open time," freeze-thaw stability, "flash rust," and adhesion. Organizing conference sessions and symposia on these topics could help that come into focus.
4. Improved packaging for waterborne coatings – This could be a topic for a conference session or symposium.
5. Training on proper surface preparation and waterborne coating storage, handling, and application. Coordination with applicator trade groups, such as contract painters, could provide training opportunities.
6. Awareness – Sharing current success stories would help, and could be featured in trade publications, especially when the story is verified independently.
7. Updated product specifications – More durable waterborne systems may not fit current specifications. Encouraging the updating of specifications to specify performance rather than a specific chemistry or type of system would be helpful.

Continued focus on this topic in trade journals, conferences and seminars could help achieve industry-wide advances.

APPENDIX A

ACA Technology Roadmap Project – Development of Topics

ACA's Science and Technology Committee initially considered a wide assortment of "research themes" to elaborate upon in subsequent, targeted discussion aimed at creating ACA Technology Roadmaps. Discussions eventually identified several broad categories and related subcategories, which allowed for organizing and prioritizing the effort. These are highlighted below, and those marked in bold text are the consensus areas for initial focus. Content in italicized text will be considered in the future.

1. Materials (i.e., availability, safety, performance)
    - **a. Sustained use of critical materials** [completed as ACA Technology Roadmap #1][6]
    - *b. Renewable, reduced carbon footprint (bio-based materials, substantiation of life cycle)*
    - **c. Reducing regulatory uncertainties – technical/testing methods**
2. Formulation (i.e., dispersion/use/performance in coatings)
    - **a. Dispersibility (understanding colloidal stability, nanomaterials, pigments, etc.)**
    - *b. Speeding up development process (predictive modeling/artificial intelligence/machine learning, automation/high throughput/accelerated testing)*
    - **c. Initial visual appearance and performance impacted by film formation, dampening, flow and maintenance of appearance**
    - *d. Wet-state preservation and supply-chain impacts (ties into sustained use of critical materials)*
3. Application (i.e., substrate/flow/cure)
    - **a. Coatings challenges presented by lightweighting and new/mixed substrates (i.e., substrate change over time and substrate-surface interaction)** [completed as ACA Technology Roadmap #2][7]
    - *b. Waterborne systems (broader application robustness)*
    - **c. Kinetics control (curing, drying for technologies)**
    - *d. Improved transfer efficiency (application-related equipment)*
    - *e. Predicting end-use performance with lab testing (i.e., modeling)*
4. End use and product
    - *a. Predicting lifetime performance (i.e., accelerated testing, predictive modeling, sensors)*
    - **b. Durability and water resistance of waterborne systems**
    - *c. Enhanced physical properties (including durability, scratch, mar, flexibility, toughness, mechanical, etching, chemical resistance)*
    - *d. Improved adhesion on all substrates and under all conditions*
    - *e. Improved environmental durability (i.e., weathering, color stability, UV and other natural exposures) and maintenance of appearance (aesthetics of color, sheen, etc.)*
    - **f. Improved corrosion and infrastructure protection**
    - **g. Enhancing value of coatings through non-traditional attributes (functional coatings)**
5. End of life
    - **a. Improved recyclability of unused product, applied film, and the package**
    - *b. Better evaluation tools for assessing full-system impacts (i.e., "cradle-to-cradle" and "eco-footprint" methodology and other predictive models for "end of life")*

[6] Available at https://www.paint.org/wp-content/uploads/2023/02/tech-roadmap-2.pdf.

[7] Available at https://www.paint.org/wp-content/uploads/2023/02/tech-roadmap-2.pdf.