Ultra-Weatherable Fluoropolymer Coatings for Bridges

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ABSTRACT:

Fluoropolymer topcoats have been used on bridges in Japan for more than 25 years. Based on data from field applications and laboratory testing, these topcoats can have an effective life exceeding 50 years. The use of fluorourethane topcoats can substantially reduce life cycle costs for coatings on steel and concrete bridges. Fluoropolymer topcoats are now required in Japan on large steel bridges like the Akashi Straits Bridge, the world's longest suspension bridge.

INTRODUCTION

Coatings are used on steel bridges primarily to prevent corrosion and subsequent loss of structural properties. The development and widespread use of zinc rich primers beginning in the 1970's has resulted in substantial improvement of corrosion resistance of the typical bridge coating system. Many bridges using zinc rich primers have been in service for more than 30 years without exhibiting corrosion. Topcoats and other coats are used primarily to prevent the transmission of corrosion initiators like chloride, oxygen, and moisture.

Coatings are also used to maintain the appearance of bridges. In some cases, for example, the Golden Gate Bridge, the appearance of the coating system is integral to the image and history of the bridge. On many bridges, non-traditional colors are being used to make them more attractive to the public. Unfortunately, the performance of topcoats has generally not matched that of zinc rich primers. Most of the topcoats in use today will usually begin to chalk, fade, peel, and crack well before the end of the life of the primer system. Conventional topcoats may even erode completely, exposing middle coat and primer. This not only damages the appearance of the bridge, but can also initiate corrosion.

In the early 1980's, a new type of coating resin was developed in Japan. This new resin was able to combine properties characteristic of fluoropolymers (weatherability, corrosion resistance) with those of polyurethanes (reactivity, ease of application, solubility). These resins, generically known as fluoroethylene vinyl ether (FEVE) resins, enabled the development of fluorourethane topcoats whose life can exceed 50 years while still retaining color and gloss. These FEVE topcoats therefore match the long term performance of zinc rich primers, offering the possibility of significant improvements in coating system durability. Reductions in coating life cycle costs result, as the need for recoating is reduced. Associated costs like those for diverting traffic during recoating operations are cut as well. Environmental effects, for example, the emission of solvents, are also lessened as repainting frequency is decreased.

STRUCTURE OF FEVE RESINS

FEVE resins derive their weatherability and durability from two sources: the strength of their chemical bonds, and the structure of the polymer.

The carbon-fluorine bond is one of the strongest known. The presence of fluorine also increases the strength of carbon-carbon bonds found in the FEVE polymer. In each case, the bond strengths are such that ultraviolet (UV) radiation is not energetic enough to break the bonds. Attack of chemical bonds in coatings by UV radiation in sunlight is the primary means of degradation for conventional topcoats. This pathway cannot occur in FEVE based coatings. The structure of the FEVE polymer also influences its weatherability. As shown below in Figure 1, the FEVE molecule consists of alternating fluorinated units and vinyl ether units. The fluorinated units with their strong chemical bonds are able to protect the less robust vinyl ether units from degradation by UV light.

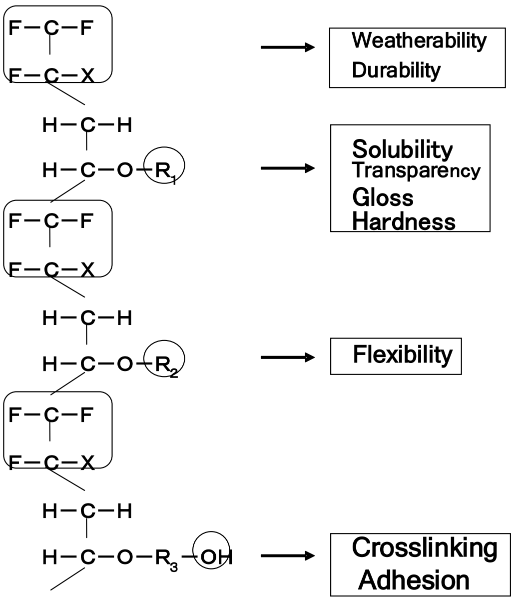

Figure 1-Chemical Structure of FEVE Resin

It can also be seen in Figure 1 that the vinyl ether segments influence the properties of the FEVE polymer. They provide many of the properties that make it possible to use these fluoropolymer resins in coatings. These properties include solubility in solvents, gloss, hardness, flexibility, and adhesion. In addition, the vinyl ether groups can be modified to provide crosslinking sites, in this case, hydroxyl groups. These resins can be cured with standard isocyanates to form fluorourethanes, fluorinated analogs to polyurethanes. This unique structure makes possible the production of coatings that can be cured at room temperature, sprayed through standard paint application equipment, with the same curing and application characteristics as polyurethane coatings.

WEATHERABILITY OF FEVE COATINGS

In both accelerated and natural weathering tests, FEVE fluorourethane coatings show exceptional weatherability. In some cases, data comparing the weathering of fluorourethanes with other coatings is available.

QUV-A TEST - In this test, ASTM D 4587, coated metal panels are exposed to UV light of wavelength 340 nm. Gloss retention is measured over a period of time, usually about 5,000 hours. Figure 2 below shows comparative results for four types of coatings: a fluorourethane, a polyester urethane, an acrylic urethane, and an epoxy polysiloxane. The fluorourethane has about 80% gloss retention after 15,000 hours of exposure, while the other urethane coatings are extensively degraded. Even the siloxane, considered an extremely weatherable coating, falls far short of the results obtained with the fluorourethane.

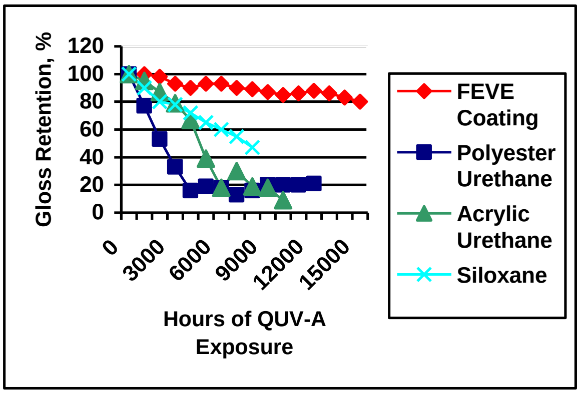

Figure 2-QUV-A Weathering Test Results

EMMAQUA TEST - EMMAQUA (Equatorial Mount with Mirrors for Acceleration with Water), ASTM G 90, uses mirrors to focus natural sunlight onto coated coupons, exposing the coating to all of the wavelengths of sunlight. The panels are periodically sprayed with deionized water to simulate rain. Test results are expressed in units of energy exposure per unit area rather than in time as is common in other exposure tests. Figure 3 below shows results from comparative EMMAQUA testing of PVDF, another fluoropolymer resin, and an acrylic urethane (AU). Both the FEVE fluoropolymer and the PVDF outperform the acrylic urethane. PVDF coatings are typically shop applied, and require high temperatures to form a coating. They would not be considered useful for structures like bridges.

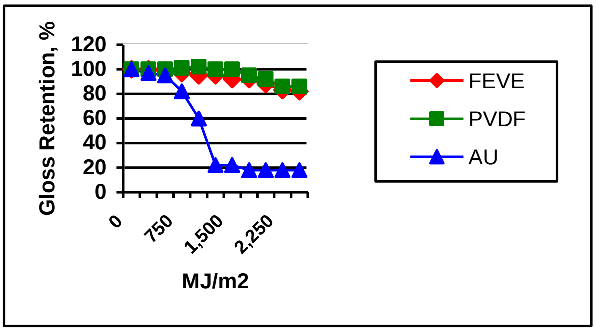

Figure 3-EMMAQUA Test Results

It is believed that each 1,000 MJ/m^2 of radiation exposure is equivalent to 10 years of actual exposure. Both the FEVE and PVDF fluoropolymers show excellent performance even after the equivalent of 25 years of exposure.

SOUTH FLORIDA WEATHERING - While accelerated weathering tests may give an indication of the long term performance of a coating, actual outdoor exposure is the best method for assessing coating viability. Because of the harsh conditions found there, testing for coatings is often conducted in south Florida. In this environment, coatings are exposed to high UV levels, salt air, and heavy rainfall. Figure 4 below shows results of 10 years of south Florida exposure for a clear and a pigmented fluorourethane coating. Gloss retention of 70% for both FEVE coatings is excellent.

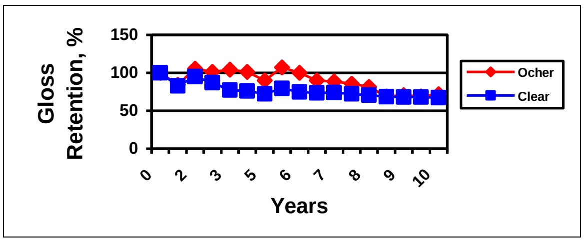

Figure 4-South Florida Weathering Results

All of the weathering tests run on FEVE resin based coatings confirm their extreme weatherability. In addition, comparison with other topcoat types indicates that fluorourethanes offer superior durability.

CORROSION PREVENTION WITH FEVE COATINGS

Three coat systems are typically used for coating bridges: a zinc rich primer, a middle coat, usually epoxy, and a durable, weatherable topcoat. Zinc rich primers, which corrode preferentially to steel under the right conditions, are the main guard against corrosion on steel bridges. The topcoat protects the middle coat from degradation by sunlight and chemicals, while the middle coat protects the zinc rich primer from damage. In addition, the top and middle coat reduce the movement of corrosion initiators, such as chloride from road salt, oxygen, and water, These contaminants will start corrosion of the zinc rich primer if they reach it. As the zinc rich primer is consumed, corrosion of the steel can begin. It is therefore critical that the topcoat and middle coat remain intact for as long as possible to prevent corrosion.

EIS TEST - One measure of the corrosion resistance of a coating system is Electrochemical Impedance Spectroscopy (EIS). In this test, an alternating current is sent between a 3% salt water solution and a metal panel. The panel is coated, with that surface exposed to the salt solution. The change in impedance at a constant frequency of 1 kHz is measured. The smaller the change in impedance, the better is the corrosion protection offered by the coating system. The change in impedance is related to the movement of corrosion initiators, in this case chloride, through the coating system to the metal. For this test, the four coating systems were first exposed to 1,000 hours of accelerated weathering, and to 500 and 1,000 hours of the ASTM B 117 salt fog test, an accelerated test for corrosion. Impedance was measured at each step of the test. In this case, each topcoat was part of a three coat system consisting of a zinc rich primer, an epoxy middle coat, and the topcoat. Results of the test are shown below in Figure 5.

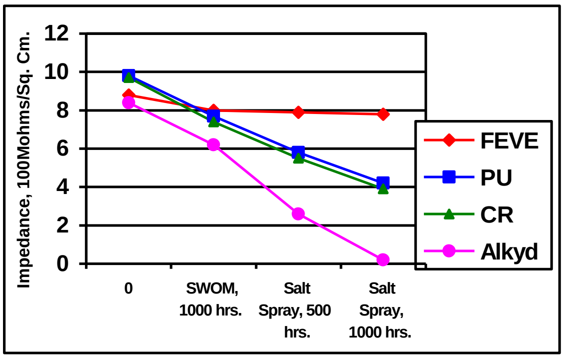

Figure 5-EIS Test Results

The test results compare the various coating systems after the accelerated tests discussed above. They should give an indication of the relative performance of the topcoats over time, since the other components of the coating systems are the same. Results show that the fluorourethane has an expected life double that of the polyurethane and chlorinated rubber topcoats. The alkyd topcoat was destroyed after the second exposure in the salt fog test.

GAS PERMEABILITY TEST - FEVE coatings are also able to reduce the impact of other corrosion initiators like oxygen and carbon dioxide. They continue to do so even after weathering for extended periods. Table 1 below shows results from a test designed to measure coating permeability to gases. In this test, oxygen permeability of 25 µm (1 mil) polyurethane and fluorourethane coatings was measured before and after exposure in a Sunshine Weatherometer, another accelerated weathering instrument.

Table 1-Gas Permeability Test Results

Gas Type	Coating Type	SWM Exposure Time, hrs.	Permeability, ml $(s\ cm\ Hg)^{-1}$
O_2	PU	0	2.6×10^{-10}
		5,000	Film destroyed
	FU	0	4.5×10^{-11}
		5,000	4.2×10^{-11}
CO_2	PU	0	-
		5,000	-
	FU	0	1.5×10^{-11}
		5,000	1.2×10^{-11}

The results in Table 1 show that the gas permeability of the fluorourethane coating is unchanged after exposure in the SWM. The polyurethane coating was destroyed after only 2,000 hours of exposure in this instrument. This test confirms the lower permeability of FEVE coatings to corrosion initiators.

FEVE coatings primarily contribute to corrosion resistance by impeding the transmission of corrosion initiators. In the next section, it will be shown that they continue to do so even after years of weathering, because they lose little film thickness over time

LONG-TERM EXPOSURE TESTS OF FLUOROURETHANE COATINGS

FEVE based coatings have undergone extensive testing by several agencies of the Japanese government. In this section, two of these long term tests will be discussed.

SURUGA BAY TEST PLATFORM - The Japanese Ministry of Land, Infrastructure, and Transport operates a test platform in Suruga Bay, south of Tokyo. The platform sits 250 m offshore in the bay, the deepest in Japan. Coated coupons can be left on the platform for many years, yielding real time weathering results for coating systems. In this case, a zinc rich primer (75 µm)/epoxy (150 µm)/fluorourethane topcoat 75 µm system was prepared. Panels were left on the platform for 16 years, and were examined periodically to monitor changes in coating thickness. Results were compared to those obtained for polyurethanes by the Honshu-Shikoku Authority. Test results are summarized below in Table 2.

Table 2-Suruga Bay Platform Test Results

Topcoat Type	Initial Thickness, µm	Final Thickness, µm
Polyurethane	25	0 (13 years)
Fluorourethane	25	21

The polyurethane topcoat lost an average of 2.1 µm per year after the first year, until it was completely eliminated by Year 13. At that point, the epoxy middle coat was exposed. Since the epoxy is not light stable, it will degrade rather rapidly, substantially increasing the chances of damage to the zinc rich primer. In contrast, the FEVE coating began losing thickness in Year 8. It lost only about 16% of the total coating thickness over the 16 year period, an average of only about 0.38 µm per year. At this rate of change, the estimated life of the FEVE topcoat is about 60 years. Because the FEVE coating retains most of its thickness over time, it continues to act as a barrier to corrosion initiators.

ROOFTOP TEST - Coupons with fluorourethane (D), polyurethane (C), chlorinated rubber (B), and alkyd (A) topcoats were placed on the roof of a government ministry in Japan for 22 years. Gloss and chalking of each topcoat were noted. Photos of each coating after the test are shown below in Figure 6. The FEVE topcoat is the only one with enough gloss remaining to reflect the sun. In addition, the fluorourethane is the only coating not exhibiting severe chalking after exposure.

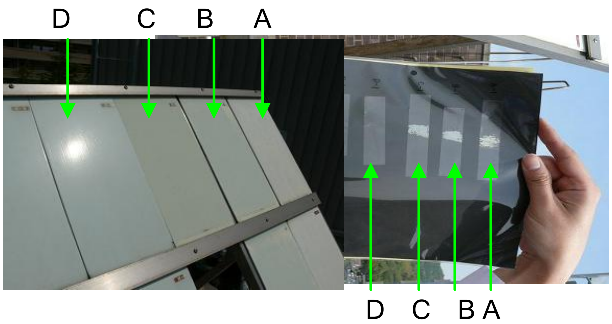

Figure 6-Gloss Retention and Chalking of Topcoats After 22 Years

Table 3 below gives gloss retention data for each of the coatings shown in Figure 6.

Table 3-Gloss Retention After 22 Years

Coating System	Alkyd (A)	CR (B)	PU (C)	FU (D)
Initial Gloss	75	77	83	73
Final Gloss, 22 Years	4	2	2	22
Gloss Retention, %	5.3%	2.6%	2.4%	30.1%

The fluorourethane outperforms all of the other coatings, with the best gloss retention and no chalking, even after 22 years. However, the gloss retention of the FEVE coating is lower than expected at about 30%. An investigation is underway to try to determine the cause of this unexpected loss of gloss.

LONG-TERM EXPOSURE OF FEVE COATINGS ON BRIDGES

FEVE resins were developed in Japan in the early 1980's. Beginning several years after that, as part of a test program with the Japanese Ministry of Land, Infrastructure, and Transport, a series of 27 bridges were painted using FEVE fluorourethane topcoats. In most cases, half of the bridge was topcoated with a fluorourethane, while the other half was topcoated with a material in widespread use in Japan at that time. The bridges were left to weather until a coating needed to be replaced to ensure the structural integrity of the bridge. In at least two cases, discussed below, enough information was collected to give a reasonable estimate of the relative life cycle costs of each coating system.

DAIICHI MUKAIYAMA BRIDGE - Hiroshima, Japan

This bridge was painted with an alkyd topcoat in 1986, and with a fluorourethane topcoat in 1987. The bridge is in a mountainous area, and substantial amounts of road salt are used in the winter to keep the road ice-free. Each topcoat was applied over multiple coats, and included a corrosion resistant primer coat.

By 1989, the alkyd topcoat had already begun to fade. After 6 years, chalking of the alkyd topcoat was severe, and corrosion around bolts had started. In addition, some peeling of the coating was noticed. In year 16, the peeling of the alkyd off some flat surfaces was complete, and severe rusting was observed. The portion of the bridge topcoated with the alkyd was repainted in 2005 using a polyurethane topcoat. Photos of the alkyd topcoat are shown below in Figure 7.

Figure 7-Alkyd Topcoat After 16 Years

In contrast, the fluorourethane topcoat showed good color and gloss retention over the entire period. The photos shown below in Figure 8 were taken in 2007, twenty years after application of the fluorourethane coating, which still retains its initial color and gloss.

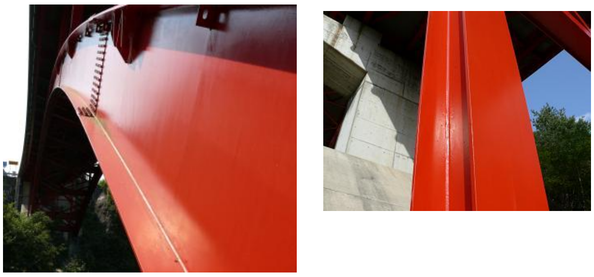

Figure 8-Fluorourethane Topcoat After 20 Years

Applied coating costs for the Daiichi Mukaiyama Bridge were monitored over the life of each coating, and are summarized below in Table 4.

Table 4-Applied Coating Costs for Daiichi Mukaiyama Bridge

Coating	Applied Cost, $/m^2	Years Service	Life Cycle Cost, $/m^2/yr.
Alkyd	$29.50	18	$1.64
Polyurethane	$88.50	2	-
Total	$118.00	20	$5.90
Fluorourethane	$94.00	20	$4.70

The total applied cost of the fluorourethane coating is about 20% lower than that of the alkyd and polyurethane. This is true even though the initial applied cost of the fluorourethane is over three times that of the alkyd. If the polyurethane and fluorourethane topcoats each have an additional life estimated at about 20 years, the FEVE coating has a life cycle cost of $2.35/m^2/year, while the alkyd/polyurethane system a cost of $2.95/m^2/year. The FEVE coating is therefore still about 20% more cost effective. In addition, costs such as bridge downtime and diverting traffic are not accounted for, but would further increase the cost of the alkyd/urethane coating. By allowing the alkyd coating system to weather so long prior to replacement also increased the risk of corrosion, since the alkyd coating had severe problems beginning early in its life. Based on comparative weathering data of fluorourethanes versus polyurethanes, it is likely that the urethane will change appearance during the 20 year expected life, adversely impacting the appearance of the bridge long before corrosion protection is compromised.

TOKIWA BRIDGE – Hiroshima, Japan

The Tokiwa Bridge was coated in 1986, half with a fluorourethane topcoat, and half with a chlorinated rubber topcoat. The costs associated with coating the bridge, along with the performance of the coating over time were closely monitored. Photos documenting the condition of the FEVE coating used on the Tokiwa Bridge over a 21 year period are shown below in Figure 9.

Oct. 1988

Apr. 1993

July 2007

Figure 9-Tokiwa Bridge Over 21 Years

After 21 years, the color and gloss of the fluorourethane topcoat have changed very little. Table 5 below shows the exact changes below.

Table 5-Tokiwa Bridge Topcoat-Change in Color and Gloss

	Gloss Retention	Color Change, ΔE
Washed Coating	100%	2.3
Unwashed Coating	92%	3.5

Application costs for the Tokiwa Bridge were monitored closely over the life of the coatings. These costs are summarized below in Table 6.

Table 6-Life Cycle Cost Comparison for the Tokiwa Bridge

Coating	Applied Cost, $/m^2	Initial Cost Ratio	Coating Life, Years	Life Cycle Cost, $/m^2/yr.
Chlorinated Rubber	$53.09	1.00	8	$6.64
Fluoro-urethane	$78.14	1.47	>21	$3.72
Life Cycle Cost Ratio		1.47		0.56

Table 6 shows that the initial applied cost of the FEVE coating is about 1.5 times that of the chlorinated rubber. However, the chlorinated rubber coating required replacement after only 8 years, while the fluorourethane is still in use after 21 years. This means that the actual cost of the FEVE coating is only about half that of the chlorinated rubber. And, since the fluorinated coating is still in service, the life cycle cost will continue to decrease. The cost of replacing the chlorinated rubber coating has also not been taken into account in this analysis.

There are other advantages in using long life FEVE topcoats. FEVE solid resins can be dissolved in environmentally friendly solvents which do not contribute to the formation of ozone. Total emission of solvents over the expected life span of a bridge can be greatly reduced due to the longevity of fluorourethanes. CO_2 emissions associated with the manufacture of solvents and paints, with equipment used during application, and with slowing and blocking of traffic during repainting operations can be eliminated.

Aesthetic considerations also point toward the use of fluorourethanes. The appearance of bridges can now be maintained for extended periods of time. Spot repair of the bridge coating can be done using the original paint without being noticeable. It can allow for the use of unconventional colors, increasing design options. The ability to more closely match the life of the coating system to expected life of the bridge is perhaps the greatest advantage of using fluorourethanes. FEVE resins allow both preservation of the appearance of the bridge, and the preservation of the structure over the life of the coating system.

LONG SPAN BRIDGES WITH FEVE TOPCOATS

A large number of long span bridges in the Far East especially have been topcoated with FEVE topcoats. Probably the best known is the Akashi Straits Bridge, linking the islands of Honshu and Awaji in Japan. It is the world's longest suspension bridge, with the longest span in excess of 2,000 meters. The entire bridge was topcoated with a fluorourethane, even the cables, from 1991-1998. The bridge is pictured below in Figure 10.

Figure 10-Akashi Straits Bridge

Other examples of long span bridges include the Swan Bridge in Hokkaido, Japan, the Yeong Jong Grand Bridge in Inchon, South Korea, and the Yong Jiang Bridge in China. Almost all of the bridges built or repainted after 2005 in Japan also use FEVE topcoats.

STATUS OF BRIDGE TOPCOATS IN JAPAN

As of 2005, fluoropolymer topcoats are required to be used on all bridges in Japan, both for new construction and for maintenance on existing bridges. Details for the required coating systems are shown below in Table 7.

Table 7-Coating Systems for Bridges in Japan

A. New Construction

Coat	Type of Coating	Thickness, µm
Primer	Zinc Rich Primer	75
Middle	Epoxy	120

Coat		
1st Topcoat	Fluorourethane	30
2nd Topcoat	Fluorourethane	25

B. Maintenance Painting

Coat	Type of Coating	Thickness, µm
Surface Cleaning	White/Near White Metal Blast	-
Primer	Zinc Rich Primer	75
Middle Coat	High Viscosity Epoxy	60
Middle Coat	High Viscosity Epoxy	60
1st Topcoat	Fluorourethane	30
2nd Topcoat	Fluorourethane	25

The Japanese Paint Manufacturers Association, the Japanese Society for Steel Construction, and the Japanese Bridge Association estimate that the life expectancy of fluoropolymer coatings is 50-60 years.

FEVE COATINGS IN THE U. S.

Fluorourethane coatings are beginning to find application on bridges in the U. S. Their use in this market has likely been slowed by the development and wider use of coatings with improved weatherability, such as polysiloxanes. There has also been a move in the U. S. to using fewer than three coats for time and labor savings. Fluorourethanes have traditionally been used in three coat systems, and work will need to be done to prove their efficacy in two coat systems.

A series of bridges in Nashville, Tenn. have been partially or fully topcoated with fluorourethanes. These include the Shelby Street Bridge, a pedestrian bridge connecting downtown to LP Field, the Tennessee Titans' stadium, the Woodland Street Bridge, and the Victory Memorial Bridge. The best known of these is the Gateway Bridge, which won an NSBA award in 2005. The red portion of the bridge is topcoated with a fluorourethane. The bridge is pictured below in Figure 11.

Figure 11-Gateway Bridge, Nashville, TN

CONCLUSIONS

FEVE resins can be used to ensure that the life of coating systems can be designed to almost match that of bridges. By minimizing the necessity for repainting, direct costs like labor and the cost of paint can be substantially reduced. Life cycle costs of fluorourethane topcoats are therefore much lower than those of competitive coatings. In addition, environmental problems associated with the use of solvents and with CO_2 emissions can be reduced. FEVE topcoats have been proven effective by more than 25 years of use in the field. Based on this experience, fluoropolymers are now required for use on all bridges in Japan.

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