

1 **TOWARD A 100 YEAR BRIDGE COATING SYSTEM: BRIDGE TOPCOATS IN**
2 **JAPAN**

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2 **ABSTRACT**
3 Fluoropolymers have been used as topcoats for bridges in Japan for more than 30 years. Based on
4 extensive laboratory testing and long term results from the field, these materials are now required
5 as topcoats on all bridges in Japan. Properly applied, fluorinated topcoats can increase coating
6 system life to more than 60 years, with a goal of 100 years of topcoat life. These fluoropolymer
7 topcoats offer substantial reductions in life cycle costs compared to conventional coating systems.
8 This paper will discuss test results from both field and laboratory studies demonstrating the long
9 term durability of fluorinated topcoats. Surface preparation and coating application methods used
10 in Japan will be reviewed. Finally, the life cycle cost advantages of fluorinated topcoats will be
11 shown.

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15 *Keywords:* Coating, paint, bridge, maintenance, topcoat, fluoropolymer, fluorourethane,
16 weatherability, durability, life cycle cost
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1 INTRODUCTION

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3 Coatings are used on steel bridges primarily to prevent corrosion and subsequent
4 degradation of structural properties, secondarily for aesthetics. The development and widespread
5 use of zinc rich primers beginning in the 1970's have resulted in substantial improvement of
6 corrosion resistance of the typical bridge coating system. Many bridges using zinc rich primers
7 have been in service for more than 30 years without exhibiting corrosion. The struggle has been to
8 find topcoats which can match or exceed the longevity offered by zinc rich primers. Over the last
9 30 years, many longer lived types of coatings have been used with varying success including
10 polyurethanes and polysiloxanes. While these topcoats offer significant improvement over
11 materials such as alkyds and chlorinated rubber, these topcoats will begin to chalk and fade years
12 before the primers are affected, to the detriment of bridge appearance.

13 Aesthetics are becoming more important in the bridge market. As cities and communities
14 try to attract residents and businesses, they are requesting the use of attractive colors and designs
15 on infrastructure. Selecting colors like red, blue, and green, using special lighting, and improving
16 landscaping allow repurposing and upgrading of bridge structures(1). Long term gloss and color
17 retention are difficult with conventional coating systems, meaning that maintenance painting will
18 be required, sometimes after only short periods of time.

19 20 **Fluoropolymer Coatings**

21 Fluoropolymers have been used in coatings since the mid 1960's, mainly in architectural
22 applications. The best known fluoropolymer coating is polyvinylidene fluoride, or PVDF.
23 Topcoats made with PVDF offer a potential life of around 30 years while maintaining color and
24 gloss. However, PVDF coatings are suitable only for shop application via a coil coating process,
25 where temperatures above 200° C are used to form the coating. This makes them unsuitable for
26 field application, and almost impossible to use in a steel fabrication shop.

27 A new class of fluoropolymer resins known as FEVE resins offer characteristics that
28 enable them to be used where PVDF coatings cannot. FEVE resin based coatings can be thought
29 of as hybrids between conventional polyurethane coatings and pure fluoropolymer coatings. Their
30 unique polymer structure allows them to be dissolved in common solvents and to be chemically
31 reacted to form a crosslinked polymer structure like an epoxy or polyurethane. These properties
32 mean that FEVE resins can be used at room temperature, forming a hard crosslinked polymer via
33 chemical reaction and solvent evaporation. This makes maintenance painting on site and use in
34 steel fabrication shops possible, since elevated temperatures are not required to form the coating.
35 Because of the fluoropolymer portion of the polymer, FEVE based coatings offer outstanding
36 weatherability and other properties as discussed below.

37 38 **PROPERTIES OF FEVE BASED FLUOROPOLYMER COATINGS**

39 FEVE based fluoropolymer topcoats offer several advantages over conventional coatings, the most
40 important being weatherability and corrosion resistance.

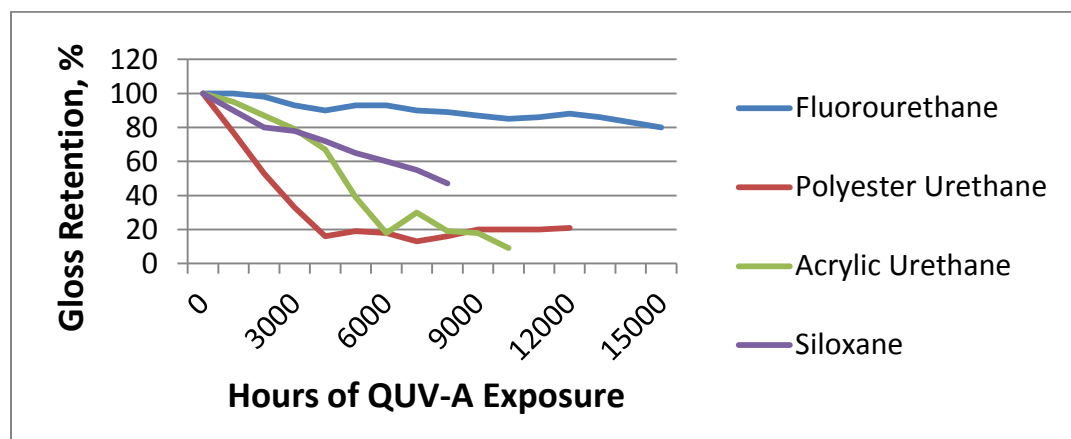
41 42 **Weatherability of FEVE Based Fluoropolymer Coatings(2)**

43 Two types of weathering tests are used for coating systems: accelerated weathering and natural
44 weathering. Both are discussed below.

45 46 *Accelerated Weathering Test Results*

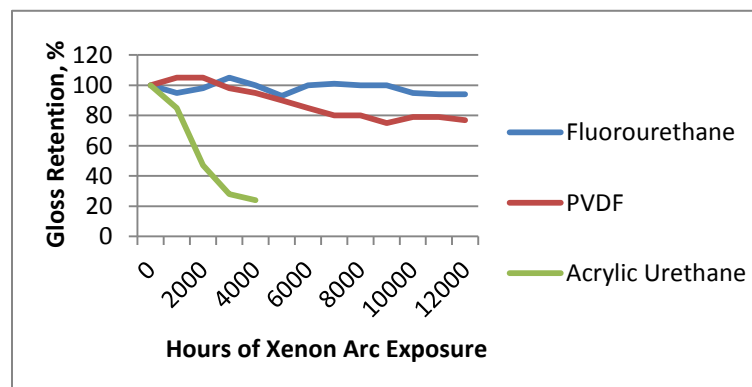
1 Accelerated testing is used to cut the time required to determine if a coating system offers long
 2 term durability. Accelerated weathering tests are difficult to correlate with natural weathering.
 3 However, they can be useful in determining the relative performance of coating systems and when
 4 results are combined from several accelerated weathering tests and natural weathering tests, a
 5 picture of the long term performance potential for coating systems can often be surmised.

6 Figure 1 below shows results from the QUV-A weatherability test, ASTM D4587,
 7 “Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings.”
 8 In this test a coating is exposed to UV light with a single wavelength at 340 nm. Results for several
 9 commonly used topcoats are shown below, and are measured by monitoring gloss retention over
 10 thousands of hours. Gloss retention is measured according to ASTM D523, “Standard Test
 11 Method for Specular Gloss,” and results below are reported for a gloss meter geometry of 60. The
 12 test method calls for a 4 hour water condensation cycle with a water temperature of 50° C.
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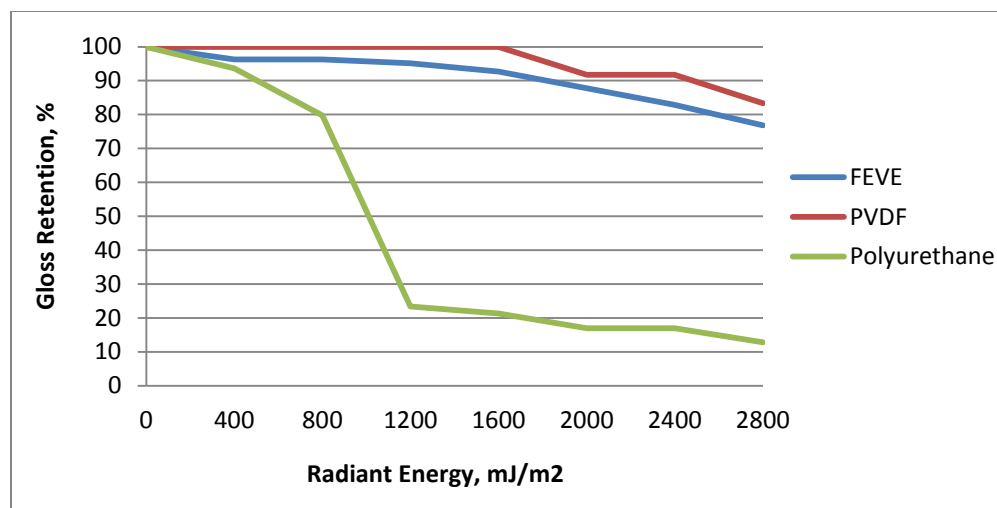
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 16 **FIGURE 1 QUV-A Weathering of FEVE Fluoropolymer Topcoat.**

17 The drawback of the QUV-A test is that it exposes the coating to only one wavelength of UV light.
 18 The UV spectrum of sunlight spans multiple wavelengths, some much more energetic than that in
 19 the QUV-A test. Exposure of coatings in the Xenon Arc test chamber in the ASTM D6695 test,
 20 “Standard Practice for Xenon-Arc Exposures of Paint and Related Coatings addresses this issue.
 21 Filters on the light source in this test allow light from wavelengths of around 300 nm to 800 nm,
 22 which more closely matches the full spectrum of light found in natural sunlight. Water is applied
 23 during the dark cycle to simulate humidity and rainfall. Figure 2 below shows comparative results.
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 36 **FIGURE 2 Xenon Arc Weathering of Fluoropolymer Topcoat.**

1 While the Xenon Arc test exposes coatings to a light spectrum that closely approximates that of
 2 natural sunlight, there are still differences. Natural sunlight is a continuous spectrum, while the
 3 Xenon Arc tends to “spike,” or let in more light of particular wavelengths. The EMMAQUA
 4 (Equatorial Mount with Mirrors for Acceleration with Water, ASTM G90) test uses mirrors to
 5 focus natural sunlight onto the surface of coated panels. As in the other accelerated weathering
 6 methods, the panels are sprayed periodically with water to simulate rainfall. Unlike most other
 7 accelerated weathering methods, EMMAQUA exposes the coated panels to all wavelengths of
 8 natural sunlight, theoretically yielding results closer to long term natural exposure. The results of
 9 the EMMAQUA test are reported in terms of the total amount of energy per unit area to which the
 10 coatings are exposed. Figure 3 below shows EMMAQUA test results for an FEVE coating, a
 11 PVDF coating, and an acrylic urethane topcoat.
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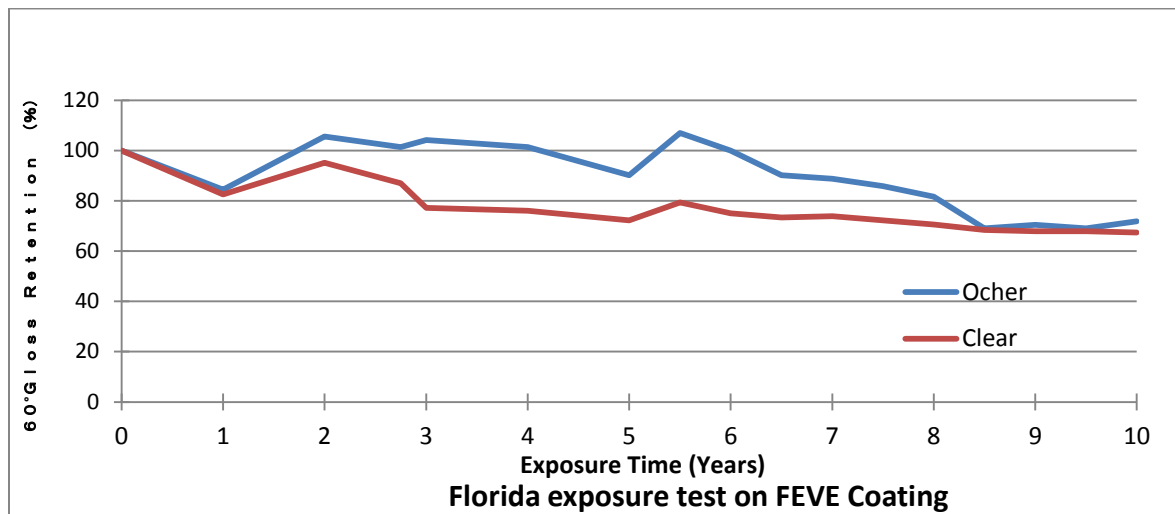


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 15 **FIGURE 3 EMMAQUA Accelerated Weathering Test of Fluoropolymer Topcoat.**
 16 EMMAQUA test results indicate that the two fluoropolymer coatings have the best gloss retention
 17 at the end of the test.
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19 *Natural Weathering Test Results*

20 Natural weathering of coatings is the preferred method to gauge coating performance. The
 21 drawback to natural weathering tests is the long amount of time required to get results. This is
 22 especially true of fluoropolymer coatings, which have expected lives of 30 years or more. Natural
 23 weathering tests are often run in areas where exposure to UV radiation and corrosion initiators in
 24 highest, in order to determine coating performance under the worst possible circumstances. South
 25 Florida in the U. S. near the ocean is a common location for natural weathering test sites. In Japan,
 26 Okinawa is a preferred location. Both Florida and Okinawa are considered humid subtropical
 27 climate zones. Since it would be impossible to obtain complete natural weathering test results for
 28 a fluoropolymer coating prior to commercialization, usually some combination of accelerated and
 29 natural weathering is performed. Exterior weathering is done using ASTM G7, “Standard Practice
 30 for Atmospheric Environmental Exposure Testing of Nonmetallic Materials.”

31 Figure 4 below shows weathering of a clear and a pigmented FEVE topcoat in South
 32 Florida.



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FIGURE 4 South Florida Weathering Test Results.

The FEVE topcoat shows good gloss retention after 10 years in South Florida.

In Japan, test sites on the island of Okinawa are used for natural weathering. Okinawa is at approximately the same latitude as Jacksonville, FL. Both regions have a humid subtropical climate. Results for an FEVE topcoat are shown below in Figure 5.

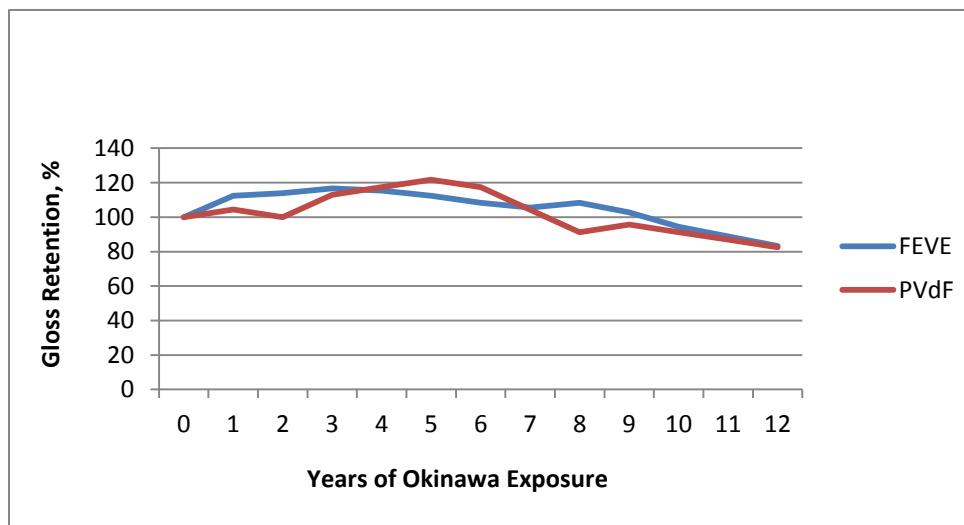


FIGURE 5 Okinawa Weathering Test Results.

Other tests have been performed on FEVE topcoats subjected to natural weathering. Several are discussed below.

Other Test Results(3)

FEVE coating systems have been tested on an offshore platform in Suruga Bay, Japan. This platform which sits 200 meters offshore is used for testing paints and coatings, plastics, and metals. An FEVE coating system consisting of a zinc rich primer, an epoxy mid coat, and an FEVE topcoat of 25 μm thickness was placed on the platform alongside a polyurethane coating system with the same topcoat thickness. The panels were left on the platform for 16 years.

1 Topcoat thickness was measured at various intervals and at the completion of the test. Results are
 2 summarized below in Table 1.

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4 **TABLE 1 Topcoat Thickness Measurement Results, 16 Years of Exposure**

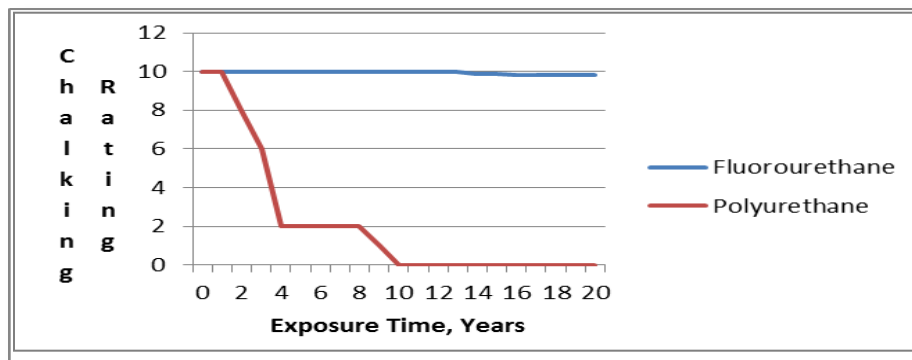
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	Acrylic Urethane Topcoat	FEVE Resin Topcoat
Initial Thickness, μm	25	25
Final Thickness, μm	0 (After 12 years)	21

6 The test results show that the urethane topcoat was completely degraded by the end of the 12th year
 7 of the test. Basically, UV radiation, salt, oxygen and other degradation initiators broke the
 8 urethane polymer into units of smaller and smaller molecular weight. Over time, the low
 9 molecular weight decomposition products were washed away by rain and wind, reducing the
 10 coating thickness. Degradation would have damaged the appearance of the urethane coating long
 11 before it disappeared. In contrast, the FEVE topcoat lost only 4 μm coating thickness over the 16
 12 year time of the test, or an average of only 0.025 $\mu\text{m}/\text{year}$. The theoretical life of the 25 μm topcoat
 13 is more than 100 years based on the average degradation rate. Gloss retention for the two coatings
 14 was not measured.

15 Also measured on the platform was the comparative rate and degree of chalking of the
 16 urethane and fluorinated topcoats. Chalking results from the accumulation of degraded coating on
 17 the surface of the coating; it will show as a white or colored powder on the coating. ASTM D4214,
 18 “Standard Test Methods for Evaluating the Degree of Chalking of Exterior Paint Films” was the
 19 method used to monitor chalking over the 20 years of the test. Coatings are rated 1-10, with 10
 20 meaning no chalking observed and 0 meaning the coating was completely chalked. Results are
 21 shown below in Figure 6.

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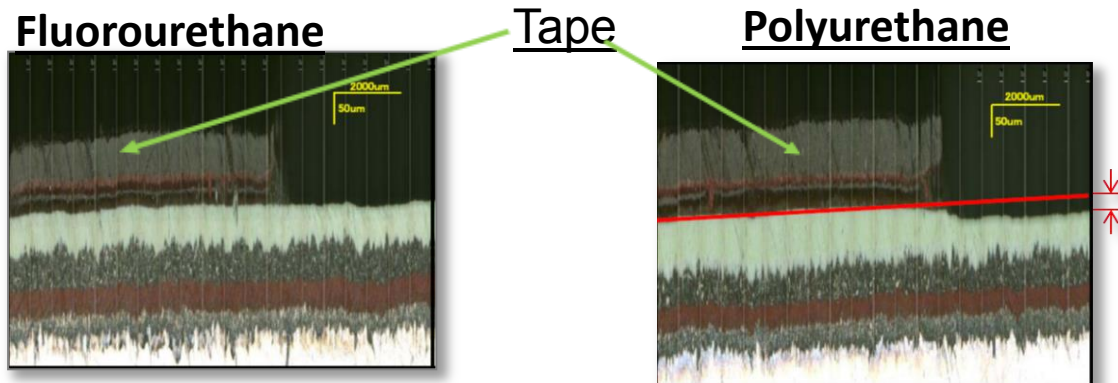
25 **FIGURE 6 Chalking Test of FEVE Coating Compared to Polyurethane**

26 Figure 6 shows that the polyurethane topcoat starts to chalk severely after only about 4 years.
 27 Although the worst chalking doesn't occur until 10 years after initiation of the test, it means the
 28 appearance of the polyurethane coating is declining from year 4.

29 In another exterior test, FEVE and polyurethane coating samples were placed on a rooftop
 30 in Hiroshima, Japan in an industrial area for 15 years. A portion of each panel was covered to
 31 prevent degradation of the coatings over time and to provide baseline measurements for
 32 comparison with the weathered coatings. Photomicrographs of cross sections from each coating
 33 sample are shown below in Figure 7.

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13 Film consumption: $0 \sim 1.1 \mu\text{m} / 15 \text{ yrs}$

14 Film consumption: $22 \sim 28 \mu\text{m} / 15 \text{ yrs}$

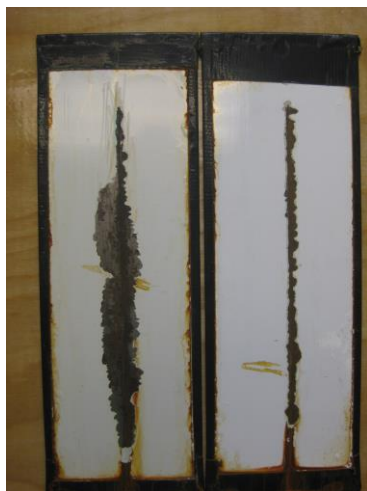
15 **FIGURE 7 Coating Degradation in an Industrial Area.**

16 The photos show that about 1/3 of the polyurethane's original thickness of $75 \mu\text{m}$ has been lost to degradation. Although coating remains, the appearance of the coating would be poor compared to its initial condition. In contrast, the FEVE fluorinated urethane topcoat has lost very little of its initial thickness of about $50 \mu\text{m}$. Losing an average of $0.07 \mu\text{m}/\text{year}$ means that the fluorinated topcoat has a theoretical life exceeding 100 years.

21 **Corrosion Resistance of Fluoropolymer Coatings**

22 As mentioned earlier the primary reason for using coatings on steel bridges is to reduce corrosion.
23 FEVE coatings have been examined in a number of tests, discussed below.

24 The ASTM B-117 Salt Fog Corrosion Test exposes scribed coated panels to a 5% salt
25 solution over a period of time, in this case 2,000 hours. Corrosion is measured by the amount of
26 rust in the scribe and under the coating adjacent to the scribe as well as by blisters formed by
27 corrosion products. ASTM D1654 describes how the scribe is made and how the results of the
28 B117 exposure test should be reported. Using Method 1 of this test, the scribe was scraped with a
29 spatula after exposure, then the amount of creepage noted. The rating is from 0 to 10 where 10
30 means zero creepage. In this case, fluorourethane, polysiloxane, and polyurethane topcoats were
31 applied over a 3 mil epoxy primer on smooth steel. Results from the fluorourethane/polyurethane
32 comparison are shown below in Figure 8, while the fluorourethane and polysiloxane comparison is
33 shown in Figure 9.



35 Left: Polyurethane, Right: Fluorourethane

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FIGURE 8 Salt Fog Corrosion Test Results, Polyurethane and Fluorourethane.

Both samples show corrosion in the scribe, but the fluorinated coating shows less creepage under the coating. The fluorourethane is rated a 6 on the D1654 scale, while the urethane is rated a 2.



Left: Polysiloxane Right: Fluorourethane

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FIGURE 9 Salt Fog Corrosion Test Results, Polysiloxane and Fluorourethane.

The fluorinated urethane is rated a 6 on the scale, while the polysiloxane is rated a 3.

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A comparison of coating systems was also performed in Electrochemical Impedance Spectroscopy (EIS). EIS allows quantitative determination of coating properties without affecting the coating, and enables detection of small changes in coating behavior in a short time period. Organic coatings initially have a high electrical resistance through the coating. As coatings age, the interconnecting porosity in the coating becomes saturated with water, chloride, oxygen and other corrosion initiators(4). The metal surface is then exposed to corrosion. In this version of the test, the coatings are first weathered in the SWOM (Sunshine Weatherometer) test, then placed in the salt fog corrosion test. The SWOM test uses a carbon arc light source, which generates a spectrum similar to sunlight but with higher intensity at 350-400 nm. The change in impedance in 100 ohms/cm² is measured for each coating system. The smaller the change in initial impedance, the better the corrosion resistance of the coating system. Figure 10 below shows the test results.

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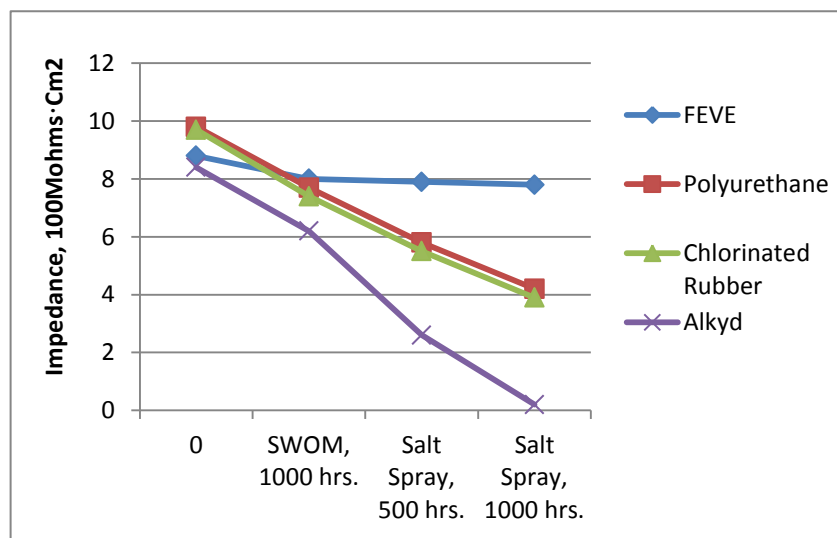


FIGURE 10 Electrochemical Impedance Spectroscopy Test Results

According to some sources, coatings with an impedance of $>10^8$ Ohms·cm² provide excellent corrosion protection, while those with $<10^6$ Ohms·cm² are said to provide poor corrosion protection(5). All of the coatings in the test start above an impedance of 10^8 . As the polyurethane, chlorinated rubber and alkyd coatings are exposed to degradation in the SWOM test and in the salt fog test, their impedance gradually drops, in the case of the alkyd, to zero. The impedance of the FEVE coating was virtually unchanged over the test cycle, indicating that the coating retained its corrosion resistance.

Earlier test results indicated that FEVE based coatings retain coating thickness over long periods of time. This property is not only important for the appearance of the coating over time but also for the corrosion resistance of the coating system. Zinc rich primers, used since the 1970's, directly protect steel by corroding preferentially when in contact with corrosion initiators like chloride ion. Epoxy or urethane mid coats provide additional coating thickness that makes damaging the coating more difficult. Topcoats also provide coating thickness. The advantage of FEVE topcoats is that they remain intact for far longer periods than conventional coatings, making it more difficult for corrosion initiators to penetrate to the steel substrate.

BRIDGE COATING SPECIFICATIONS IN JAPAN

1990 Japanese National Specification for Steel Bridge Coatings(6)

Based on years of field experience and accelerated weathering and corrosion testing on FEVE resin based coatings, the first Japanese National Specification for bridge coatings was developed in 1990. That specification is shown below in Table 2.

TABLE 2 1990 Japanese National Specification for Steel Bridge Topcoats(7)

		Environment		
		General	Slightly Severe	Severe
Coating Type		No salt or corrosives Non-industrial areas Little smog Easy to recoat	Salt used in area. Slight pollution Moderate smog Difficult to recoat	High salt levels Severe pollution Heavy smog Difficult to recoat
	General Purpose Coating	A-1, A-2	B-1	C-1, C-2
	High Durability Coating	A-3, A-4	C-3, C-4	

A-1, A-2: Long oil alkyd coatings

A-3, A-4: Silicone alkyd coatings

B-1: Chlorinated rubber coating

C-1, C-2: Polyurethane coatings

C-3: Fluoropolymer coating, fabricator applied (some components coated on site)

C-4: Fluoropolymer coating, fabricator applied

In this specification, less durable coatings were specified for use in most environments, including bridges with high levels of salt, pollution, and difficulty in recoating. The fluoropolymer topcoats were recommended for use in slightly severe and severe environments when higher

1 durability was desired.

3 **2005 Japanese National Specification for Steel Bridge Topcoats(7)**

4 Based on weathering and corrosion testing, some of which is shown earlier in this paper, in 2005,
5 the specification was revised. The new specification required the use of fluoropolymer topcoats in
6 all environments and for both new construction and field repair on steel bridges. Table 3 below
7 shows these changes.

8
9 **TABLE 3 2005 Japanese National Specification for Steel Bridge Topcoats**

	Environment	General	Slightly Severe	Severe
Application		No salt or corrosives Non-industrial areas Little smog Easy to recoat	Salt in environment Slight pollution Moderate smog Difficult to recoat	High salt levels Severe pollution Heavy smog Difficult to recoat
	New Construction, Shop Application	C-5 Coating System, Fluoropolymer Topcoat		
	Repair Coatings, Field Application	Rc-I, RC-III, Fluoropolymer Topcoat		

11
12 The changes to the 2005 specification included the requirement to use fluoropolymer topcoats in
13 all environments due to their superior weathering. Also included was a specification for field
14 application of fluoropolymer topcoats. This meant that existing bridges could now be repainted
15 using the fluoropolymer topcoats.

17 **LIFE CYCLE COST ANALYSIS OF FLUOROPOLYMER COATINGS(8)**

18 Based on labor and material costs averaged over several bridge coating projects in Japan using an
19 exchange rate of 120 Japanese yen per U. S. dollar, a life cycle cost comparison for a polyurethane,
20 and a fluorourethane coating system was performed. No discount rate was applied to the costs.
21 Results are shown below in Tables 4 and 5.

22
23 **TABLE 4 Topcoat Cost Comparison**

Topcoat Type	Topcoat Thickness, μm	Topcoat Cost, $\$/\text{m}^2$
Polyurethane	55	\$4.08
Fluorourethane	55	\$12.01

24 Based on these cost comparisons, it is roughly 3X more expensive to use the fluorinated topcoat
25 than the urethane. However, when choosing a coating system, not only the topcoat cost but the
26 applied cost of the entire coating system must be considered. Table 5
27 below shows a comparison of applied and life cycle costs for each coating system.

28
29 **TABLE 5 Applied Coating System Cost and Life Cycle Cost Comparison**

Coating System	Polyurethane	Fluorourethane	
Total Repainting Cost, $\$/\text{m}^2$	85.65	93.87	
Estimated Coating Life, Years	18	30	60

Total Applied Coating System Cost, \$/m ² /year	4.76	3.13	1.56
Cost Index	48	32	16

1 Each topcoat is part of a coating system including a primer, mid coat, and topcoat.
 2 The cost of the primer and midcoat are the same regardless of the topcoat used. The cost of labor,
 3 staging, fuel, and time is also about the same regardless of the coating system chosen. The real
 4 difference between the coating systems is the cost of the topcoat. When these additional costs are
 5 taken into account, total repainting costs for each system are not that different. The fluorinated
 6 urethane is only about 10% more expensive than the urethane. The true cost of the coating system
 7 is given by the metric of \$/m²/year. When the time factor is added, the advantage of the fluorinated
 8 coating becomes apparent. The fluorinated coating system is 33-67% less expensive than the
 9 urethane system, which is the most commonly used system in the U.S. In the U.S. the cost of the
 10 fluorinated paint is higher than in Japan. Even if the cost of the fluoropolymer topcoat doubles to
 11 \$24.01/m², the life cycle cost advantage remains.

13 CONCLUSIONS

14 Based on years of field experience and accelerated testing, the Japanese highway authorities have
 15 made the use of fluoropolymer topcoats mandatory on steel bridges. The use of these topcoats
 16 offers substantial life cycle cost advantages over conventional topcoats, and can substantially
 17 reduce the need and cost for maintenance painting. This means over the life of the structure, far
 18 fewer maintenance cycles will be required, not only reducing direct costs but the cost of increased
 19 traffic and delays caused by maintenance. There is a great deal of evidence that FEVE based
 20 coatings offer good gloss and color retention for up to 60 years, and some experimental evidence
 21 they can offer protection for 100 years. In any case, these fluoropolymer topcoats provide the best
 22 match between coating system life and asset life available today.

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