Evaluating Protective Coatings for Concrete Exposed to Sulfide Generation in Wastewater Treatment Facilities

Concrete is the most widely used construction material in wastewater collection and treatment systems. Unfortunately, significant corrosion can occur on concrete when sulfide generation in wastewater is not controlled.

Sources of sulfide in wastewater include unregulated and/or uncontrolled industrial discharges, degradation of sulfur-containing organic matter, or the microbiological reduction of sulfate or other oxidized forms of sulfur. The construction of regional collection and treatment systems has increased wastewater travel time in collection systems, culminating in anaerobic wastewater and consequently increased sulfide generation. Odors from manholes or wastewater treatment facilities create significant nuisance problems. A major cause of odors is hydrogen sulfide, a gas detectable at extremely low concentrations. The gas is notorious for its toxicity and its ability to corrode a number of materials used in construction of sewer and treatment plants, including concrete. Concrete corrosion is caused by the aerobic microbial oxidation of hydrogen sulfide to sulfuric acid and the subsequent chemical reaction of the acid with the cement binder in the concrete.

The County Sanitation Districts of Los Angeles County developed a test to evaluate protective coatings applied to corroded and uncorroded concrete. An accelerated corrosion testing facility was constructed to simulate actual application conditions. The purpose of testing was to develop a list of suitable coatings and specifications for applications in new construction and rehabilitation projects.

This article describes the tests, their results, and field performance of several of the coatings tested.

Evaluation Facility

The evaluations are conducted in shallow concrete tanks constructed by inserting 2 concentric, pre-cast reinforced concrete manhole shafts into a freshly poured, wet concrete base slab. The inner tank diameter is 0.9 m (3 ft) with a depth of approximately 0.8 m (2.5 ft). The outer tank diameter is 1.2 m (4 ft) with a depth of approximately 0.9 m (3 ft).
The tanks are constructed of Type II Riverside Cement manufactured to meet or exceed the requirements for ASTM C-478, "Standard Specification for Mold for Forming Concrete Test Cylinders Vertically." The annular space between the outer and inner tank is filled with water to simulate moisture from groundwater or from an adjacent process unit. Figure 1 shows 1 test tank, while the schematic in Fig. 2 illustrates the construction of a test tank.

![Image of test tank](image-url)

**Fig. 1**
Waterblasting of test tank with corroded lower half and uncorroded upper half

*Illustrations courtesy of the Los Angeles County Sanitation Districts*

Evaluation Procedure

The lower half of each tank is allowed to corrode for 6 to 8 weeks, using 265 L (70 gal.) of a 10 percent (by weight) solution of sulfuric acid. Approximately 25 mm (1 in.) of corrosion has been observed to occur in the unprotected concrete tanks during this period. This rate of corrosion is 15 to 20 times the highest corrosion rate expected in actual service. The use of 10 percent acid is arbitrary; however, it represents a more corrosive environment than the actual service situation. The observed increased corrosion rate is accounted for by concentration and the volume of acid that is exposed to the concrete surface in the test tank. It appears that the formation of sulfuric acid on vertical and overhead surfaces in wastewater collection and treatment facilities is limited by the effects of gravity. Acid produced in excess of the quantity that can react with concrete may simply run off the vertical surfaces of the corrosion products or drip off the overhead surfaces. In the test tank, the corroding concrete is flooded by the 10 percent acid solution. Figure 1 shows the corroded lower half and uncorroded upper half of a test tank.

A coating application to the test tank is scheduled when sufficient aggregate and even some reinforcing steel have been exposed. The manufacturer is requested to apply the coating to both the corroded and uncorroded surfaces inside the test tank within an eight-hour time period. The coating manufacturer is responsible for all surface preparation prior to application of the coating. Generally, the manufacturers have chosen either abrasive blasting or high pressure water jetting for surface preparation. If too much aggregate is exposed for proper application of the coating, then the manufacturer is responsible for surface repair as well. Most surface repairs use fast curing cements or a mixture of the coating material and a sand filler.

The coating to be tested should be able to cure sufficiently so that water can be added to the test tank within 48 hours after the application. Then, a total of 96 hours after the application of the coating, sufficient concen-
trated sulfuric acid is added to the water in the test tank for a final acid concentration of 10 percent. The volume of the acid added is sufficient to expose the coated surfaces (corroded and uncorroded) to the 10 percent acid solution. This is illustrated in Fig. 2.

The test procedure has been designed to simulate the application of coatings to manholes or pipelines and the return of corrosive conditions. Coating systems that require longer application or cure times are less attractive for most rehabilitation projects but are still considered for new construction.

Holiday testing is a standard item in coating specifications, but the manufacturer is not permitted to perform any pinhole or holiday testing after the application of the coating to the test tank. Coating or application flaws are often apparent after the application and soon will be obvious during the test. A coating system that cannot be applied without pinholes or holidays on such a small scale (approximately 3.2 m²; 35 ft²) by the manufacturer is not considered a viable system.

The objective of the test is to evaluate the coating’s application properties, concrete bonding characteristics, and acid resistance for a minimum of 1 year of acid service. Unless coating failure is observed earlier, the acid solution is usually removed on a quarterly basis to allow a physical inspection of the test tank. During the inspection, photographs are taken to document any changes in the coating’s protective character or appearance. Observations are made of the coating’s bonding character, and measurements are made of the coating thickness. A cross section of the coating is inspected to evaluate pinholing, air pockets, or any gradual deterioration or reaction with the acid. The manufacturer is given the opportunity to repair any areas damaged by the inspection.

It is important to consider some of the limitations of this evaluation and testing procedure. The effects of long-term aging and exposure to moisture and any bacterial action are not evaluated. This testing procedure is believed, however, to adequately evaluate the ability of a coating system to be effectively applied and to resist extensive sulfuric acid exposure. The continuation of testing beyond the one-year acid service goal, for the successful coating systems, is done to obtain additional data on long-term performance.

Results and Discussion

From the inception of the Districts’ Testing Program in 1983, evaluations have been completed on 61 coating and liner systems. Four protective coating and/or liner systems are currently under evaluation.

The types of coatings evaluated have been coal tar, coal tar epoxies, coal tar urethane, concrete sealers, epoxy, epoxy mortars, phenolic, polyester, polyester mortars, silicone, specialty concrete, urethane, vinyl ester, and vinyl ester mortars. The liner systems evaluated include polyvinyl chloride (PVC) and polyethylene (PE). Manufacturer brochures for these coatings all recommend applications for waste-water collection and treatment facilities.

For discussion purposes, the coatings are grouped into the following categories: coal tars, concrete sealers, epoxies, liniers, phenolics, polyesters, silicones, specialty concretes, urethanes, and vinyl esters. Tabulated test results are available from the authors.

Coal Tar
One coal tar, 2 coal tar epoxies, and 1 coal tar urethane coating system were evaluated. The Sanitation Districts’ experience has been that the coatings fail in a period of just a few years when they are subjected to sulfuric acid attack.

The failure of 3 coating systems during the testing supports this observation. However, a fourth system has shown excellent results in acid testing. This system uses the application of a mixture of the coating and a sand filler to build thickness. After exposure to acid for 589 days, the system showed no signs of deterioration. It is currently specified for use as a coal tar epoxy mortar.

Concrete Sealer
Neither of the 2 sodium silicate concrete sealers tested provided any acid resistance, despite the manufacturers’ claims.

Epoxy
Nineteen tests of 18 different epoxy coating systems have been completed. The epoxy category included 6 stand-alone epoxy coating systems and 13 epoxy mortars. Only 6 systems (1 stand-alone and 5 epoxy mortars) survived the rigorous test.
The stand-alone system failed when brush-applied but was successful when spray-applied.
A minimum of 1 mm (40 mils) dry film thickness of the coating is required.

A material-filled version of the coating as an intermediate step prior to application of finish coat with the pure (or neat) epoxy. Minimum thickness of the intermediate coat is 2-3 mm (80-120 mils).

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**PLAN OF TEST TANK**

**SECTION A-A**

**CORRODING THE LOWER HALF OF THE TEST TANK**

**TESTING COATING PERFORMANCE AFTER APPLICATION TO TEST TANK**

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Liner Systems
Three liner systems have been tested. One system, applicable to new construction only, involves the use of PVC liner sections formed with the concrete section. As expected, the PVC liner demonstrated no reaction with the...
acid; however, the gasket jointing system used to interlock the lining sections was penetrated by the acid. Acid seeped behind the liner and corroded the concrete.

The other two lining systems are combinations of both a coating (mastic) and a liner. A acid-resistant, high solids, polyurethane mastic provided continuous bonding of both PE liner and PVC liner to the concrete substrate. After 598 days of testing, it was decided that the performance of the PE liner was unacceptable due to the gradual loss of bond between the mastic and the liner. The PVC liner was unaffected after 646 days of acid exposure. This system is currently specified for use for both new construction and rehabilitation projects.

Two PVC liner systems and a combination PVC liner and urethane foam undercoat are currently in testing. No problems have been observed after acid exposure times of 242, 136, and 126 days for the 2 PVC liners and the combination PVC liner/urethane foam undercoat system, respectively. The evaluations will continue for a minimum of 365 days.

Phenolic
No full scale evaluation was conducted with a phenolic coating system; however, a preliminary test of 1 system showed poor acid resistance. This system is no longer being marketed.

Polyester
One polyester mortar was unaffected by the sulfuric acid after almost 4 years of exposure and demonstrated excellent bonding to concrete. It is believed that the success of this coating hinges upon the application of a 3.2-mm (125-mil) intermediate coating thickness by mixing the polyester resin with a sand aggregate. This coating system is currently specified for use.

A second polyester resin system, also a sand-extended mortar, was successful for 378 days. During application of this coating to the test tank, an excessive quantity of solvent was spilled on the coating in the base of the test tank. Upon acid exposure, many areas in the base of the test tank blistered. These damaged areas were subsequently repaired. Test tank areas not exposed to the solvent spill, as well as the repaired areas, performed well. This coating is currently specified for use.

A third stand-alone polyester resin system was evaluated for 56 days. This system was the same coating as the polyester mortar but without the sand aggregate. The application of various thicknesses of this resin to the test tank, up to 1 mm (40 mils), without the sand aggregate, allowed penetration of acid through thin spots and pinholes.

Silicone
One silicone rubber coating that advertised both abrasive and acid resistance proved to be a rapid failure.

Specialty Concrete/Mortar
The 8 coating systems have been evaluated in 10 different tests in this category: 5 fast cure systems applicable to damp concrete; 2 more conventional, acid-resistant concrete systems typically used in the installation of acid brick; and 1 furfuryl alcohol resin-based concrete system. All of the fast cure systems showed reaction with acid. One system was more acid resistant but was difficult to apply. The acid-resistant concretes require anchoring to an underlay membrane or coating, and they can be applied by forming or blowing. They were either affected by the sulfuric acid solution or allowed the acid to penetrate through the cross section to the underlying coating.

Problems were encountered with the application of the furfuryl alcohol resin-based concrete system, which allowed acid attack to the concrete and failure of this system. Subsequent testing of this product in both spray and formed applications proved it to be acid resistant; however, the bond to the uncorroded concrete surfaces in both applications was weak. An anchoring system would be recommended.

A modified sulfur cement is currently undergoing evaluation. No problems have been observed after 126 days of acid exposure. The evaluation will continue for a minimum of 365 days.

Urethane
Sixteen evaluations were performed with 15 different urethane coatings. Problems shared by most of the urethane systems involve poor bonding characteristics to concrete and an extreme tendency to form pinholes or blow holes following application. A primer to provide a bond to concrete or an anchoring system is a necessity for urethane coating sys-
tems. The 13, two-component urethane coatings tested provided excellent resistance to sulfuric acid, and 1, together with a primer, provided a tenacious bond to the concrete substrate and a relatively pinhole-free surface. No urethane-based coatings are specified for use.

**Vinyl Ester**
One vinyl ester mortar system was exposed to acid for 548 days with no adverse effects. The long cure time required for application of the system would eliminate it for most rehabilitation projects unless “down” times of more than 1 week are possible. The system is currently specified for use.

The second system, a pure vinyl ester coating, developed pinholes and allowed acid to penetrate to the concrete.

## Summary of Laboratory Evaluations

A total of 61 evaluations have been completed, and 4 evaluations are in progress. Eleven systems have successfully completed the evaluation procedure and are either currently specified for use or will be specified for use. The highest survival rate belongs to the mortar- or filter-extended systems, regardless of whether the coating resin is a coal tar epoxy (100 percent), epoxy (39 percent), polyester (100 percent), or vinyl ester (100 percent).

The next highest survival rate belongs to the liner category (33 percent). The pure epoxy survival rate was 17 percent. None of the other coating categories survived the test.

Coating mortars exhibited a higher survival rate than the stand-alone systems. Total success was achieved by coal tar, polyester, and vinyl mortars, while stand-alone coal tar, polyester, and vinyl ester coating systems were total failures.

## Field Applications

A diverse number of concrete coating and liner systems have been installed in the Sanitation Districts' facilities. These installations are inspected regularly by the Districts' personnel. As expected, the coatings that failed the evaluation procedure also failed in the field. Unexpectedly, some of the coatings that survived the evaluation procedure failed in the field.

Table 1 summarizes 23 field applications for various concrete coating systems installed within the Sanitation Districts. The projects are organized chronologically in the table. The coating categories specified in these field application projects include 3 epoxy mortars, 4 liners, 10 polyester mortars, and 6 urethane coating systems. The information in Table 1 includes job location code, the type of structure the coating was applied to, and whether the structure was being rehabilitated or was newly constructed, the generic coating/liner system, the minimum dry film coating thickness specified, the completion date of the field application, the latest inspection date, the average pH of the condensate measured on the coating surface, and comments or observations made during the inspections.

The average pH column is an indication of the corrosiveness of the coating environment. The lower the pH, the more corrosive the environment. This is an important parameter to use in evaluating coating performance. It is of no value to report that a coating is in excellent condition if it is not in a corrosive environment.

### Field Application of Epoxy Coating Systems

There have been 3 separate applications of epoxy coatings between 1986 and 1988 (L-8, L-11, and L-17). In 2 of the projects (L-8 and L-11), the coatings have been exposed to corrosive conditions (pH ≤ 2).

In both cases, the coatings are in good condition. The same type of coating (L-17) exposed to a non-corrosive environment (pH > 5) is in good condition. The only problem noticed in this project was the occurrence of pinholes in some manholes affected by groundwater. Attempts to patch the pinholes have been marginally successful. Otherwise, the coating is in good condition.

### Field Application of Liner Systems

There have been 4 separate applications of liners between 1987 and 1991 (L-14, L-18, L-22, and L-23). In 2 cases (L-14 and L-18),
the coatings have been exposed to corrosive conditions (pH ≤ 2) and are in good condition. The 2 recent applications (L-22 and L-23) have not been inspected since their installation.

### Field Application of Polyester Mortar Coating Systems
There have been 10 separate applications of polyester mortar coatings between 1983 and 1989 (L-5, L-7, L-9, L-10, L-12, L-13, L-16, L-22, L-23). Since 1984, the coating has been exposed to corrosive conditions (pH ≤ 2). In this case, polyester mortars appear to be more protective than alternating systems.

#### Table 1: Field Applications of Concrete Coatings

<table>
<thead>
<tr>
<th>Location Code</th>
<th>Structure Type</th>
<th>Coating</th>
<th>Thickness, Mil (mm)</th>
<th>Completion Date</th>
<th>Inspection Date</th>
<th>Average pH</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1</td>
<td>3 Manholes, rehabilitation</td>
<td>Urethane</td>
<td>3.2 (85)</td>
<td>3-88</td>
<td>11-89</td>
<td>6</td>
<td>Pits and bonding failure</td>
</tr>
<tr>
<td>L-2</td>
<td>Valve structure, new</td>
<td>Urethane</td>
<td>2.2 (85)</td>
<td>4-82</td>
<td>8-81</td>
<td>5.5</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-3</td>
<td>3 Manholes, rehabilitation</td>
<td>Urethane</td>
<td>3.2 (85)</td>
<td>3-83</td>
<td>8-81</td>
<td>6.5</td>
<td>Large bubbles, poor bonding</td>
</tr>
<tr>
<td>L-4</td>
<td>8 Manholes, rehabilitation</td>
<td>Urethane</td>
<td>3.2 (85)</td>
<td>3-83</td>
<td>7-81</td>
<td>1.5</td>
<td>Coating began peeling immediately after installation</td>
</tr>
<tr>
<td>L-5</td>
<td>Primary effluent channel, rehabilitation</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>4-83</td>
<td>8-92</td>
<td>2</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-6</td>
<td>Sevier portion of chamber, rehabilitation</td>
<td>Urethane</td>
<td>3.2 (85)</td>
<td>2-84</td>
<td>8-86</td>
<td>4</td>
<td>Numerous pinholes in certain areas</td>
</tr>
<tr>
<td>L-7</td>
<td>3 Manholes and 35 ft. of 78 in. reinforced concrete pipe, new</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>4-86</td>
<td>1-91</td>
<td>5</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-8</td>
<td>1 Primary sedimentation tank and digester roof, rehabilitation</td>
<td>Epoxy</td>
<td>1.5 (30)</td>
<td>5-86</td>
<td>8-91</td>
<td>2</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-9</td>
<td>1 Manhole, new</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>7-86</td>
<td>7-91</td>
<td>2</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-10</td>
<td>2 Manholes, new</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>7-86</td>
<td>7-90</td>
<td>2</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-11</td>
<td>4 Primary sedimentation tanks and effluent channel, new</td>
<td>Epoxy</td>
<td>4 (150)</td>
<td>7-86</td>
<td>8-90</td>
<td>2</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-12</td>
<td>18 Manholes, new</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>9-86</td>
<td>7-91</td>
<td>4</td>
<td>Coating in good condition</td>
</tr>
</tbody>
</table>
19, L-20, and L-21). In 5 of the projects (L-5, L-9, L-10, L-13, and L-20), the coatings have been exposed to corrosive environments (pH ≤ 2). In 3 cases (L-5, L-9, and L-10), the coatings are in good condition. In 2 cases (L-13 and L-20), some deterioration of the coating has been observed. The same type of coating (L-12 and L-19), exposed to a mildly corrosive environment (3 < pH < 4), is in good condition. Other polyester mortars (L-7, L-16, and

<table>
<thead>
<tr>
<th>Location Code</th>
<th>Structure, Type</th>
<th>Coating</th>
<th>Thickness (Mil in)</th>
<th>Completion Date</th>
<th>Inspection Date</th>
<th>Average pH</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-13</td>
<td>4 Primary tanks, rehabilitation</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>9-86</td>
<td>9-91</td>
<td>2</td>
<td>Some deterioration of coating observed</td>
</tr>
<tr>
<td>L-14</td>
<td>Feedbag, rehabilitation</td>
<td>Polyethylene (PE) liner + mastic</td>
<td>4 (150)</td>
<td>7-87</td>
<td>9-91</td>
<td>2</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-15</td>
<td>Concrete walls of carbon filter, new</td>
<td>Urethane</td>
<td>2.2 (525)</td>
<td>1-87</td>
<td>9-91</td>
<td>7.5</td>
<td>Coating is peeling off</td>
</tr>
<tr>
<td>L-16</td>
<td>18 Manholes, new</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>7-86</td>
<td>9-90</td>
<td>6.5</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-17</td>
<td>16 Manholes, new</td>
<td>Epoxy</td>
<td>1.5 (60)</td>
<td>8-86</td>
<td>7-90</td>
<td>6.5</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-18</td>
<td>14 Primary sedimentation tanks</td>
<td>PE and polyvinyl chloride (PVC) liner + polyurethane mastic</td>
<td>4 (150)</td>
<td>12-86</td>
<td>9-91</td>
<td>2</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-19</td>
<td>15 Manholes, new</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>2-86</td>
<td>9-90</td>
<td>3</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-20</td>
<td>Primary effluent channel and sludge wetwell, rehabilitation</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>6-89</td>
<td>9-90</td>
<td>2</td>
<td>Coating disbonding</td>
</tr>
<tr>
<td>L-21</td>
<td>13 Manholes, new</td>
<td>Polyester</td>
<td>4 (150)</td>
<td>7-89</td>
<td>9-91</td>
<td>5</td>
<td>Coating in good condition</td>
</tr>
<tr>
<td>L-22</td>
<td>36 in. sewer and siphon legs, new</td>
<td>PVC liner</td>
<td>4 (150)</td>
<td>11-90</td>
<td>—</td>
<td>—</td>
<td>Recent installation</td>
</tr>
<tr>
<td>L-23</td>
<td>4 Manholes, rehabilitation</td>
<td>PVC liner</td>
<td>3.2 (125)</td>
<td>8-91</td>
<td>—</td>
<td>—</td>
<td>Recent installation</td>
</tr>
</tbody>
</table>
L-21) exposed to non-corrosive environments (pH > 5) are in good condition.

Field Application of Urethane Coating Systems
There have been 6 separate applications of urethane coatings between 1980 and 1987 (L-1, L-2, L-3, L-4, L-6, and L-15). In 1 project (L-4), the coating has been exposed to corrosive conditions (pH ≤ 2). In this case, the coating has failed. The same type of coating (L-6) has failed in a mildly corrosive environment (pH = 4) and in non-corrosive environments with pH > 5 (L-1, L-3, and L-15).

In fact, urethanes, with the exception of L-2, which is installed in a non-corrosive environment with a limited use, have failed in the field and the test environment. The major cause of failure appears to be pinholing.

Routine inspections indicate that there are no fail-safe coatings. Even coatings that survived the Districts' rigorous acid testing have failed in the field. The only system that appears to provide adequate, long-term corrosion protection for concrete in the corrosive environment is the formed-in-place PVC or PE liner. Proper welding of the seams in the joining sections of the liner is critical for the success of this type of liner system. Care must be taken during welding to insulate acid-proof welding of the joints and seams.

One such system installed in primary sedimentation tanks about 30 years ago is performing well. A recent inspection of this system indicated no failure spots. A concrete diversion structure built in the mid 1950s and protected by this type of liner was recently inspected. The inspection revealed that this liner was exposed to extremely corrosive conditions (pH < 1.0) for over 30 years. This liner has effectively protected the concrete structure. The liner has maintained its ability to be welded, flexible, and physical properties, and it is expected to continue protecting the concrete structure for 100 years.

Conclusions
The program has fulfilled its purpose of developing a list of suitable coatings and specifications for application of the coatings. Previous specifications included a polyurethane and a mastic/polyethylene liner system. Current specifications include 1 coal tar mortar, 2 epoxy coating systems, 4 epoxy mortars, 2 polyester mortars, 1 mastic PVC liner system, and 1 vinyl ester mortar system.

The results of this study indicate that mortars provide better protection for the underlying concrete than the stand-alone systems.

Sand-extended coating systems (mortars) appear to be more protective than the affiliated stand-alone coating systems. The results of this investigation indicate that about 50 percent of epoxy mortars survived the test. All coal tar mortars, polyester mortars, and vinyl ester mortars survived the test.

Author's Note: A longer version of this paper is to be presented at the National Conference and Exposition of the Steel Structures Painting Council on November 11, 1991 in Long Beach, CA and has been published in the conference Proceedings. Credit is given to all the coating manufacturers who not only agreed to submit their coatings for evaluation but also arranged for the installation of the coating system.

References