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IMPROVED FIELD RELIABILITY OF HIGH PERFORMANCE COATINGS

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Appendix A - Best Current Technology

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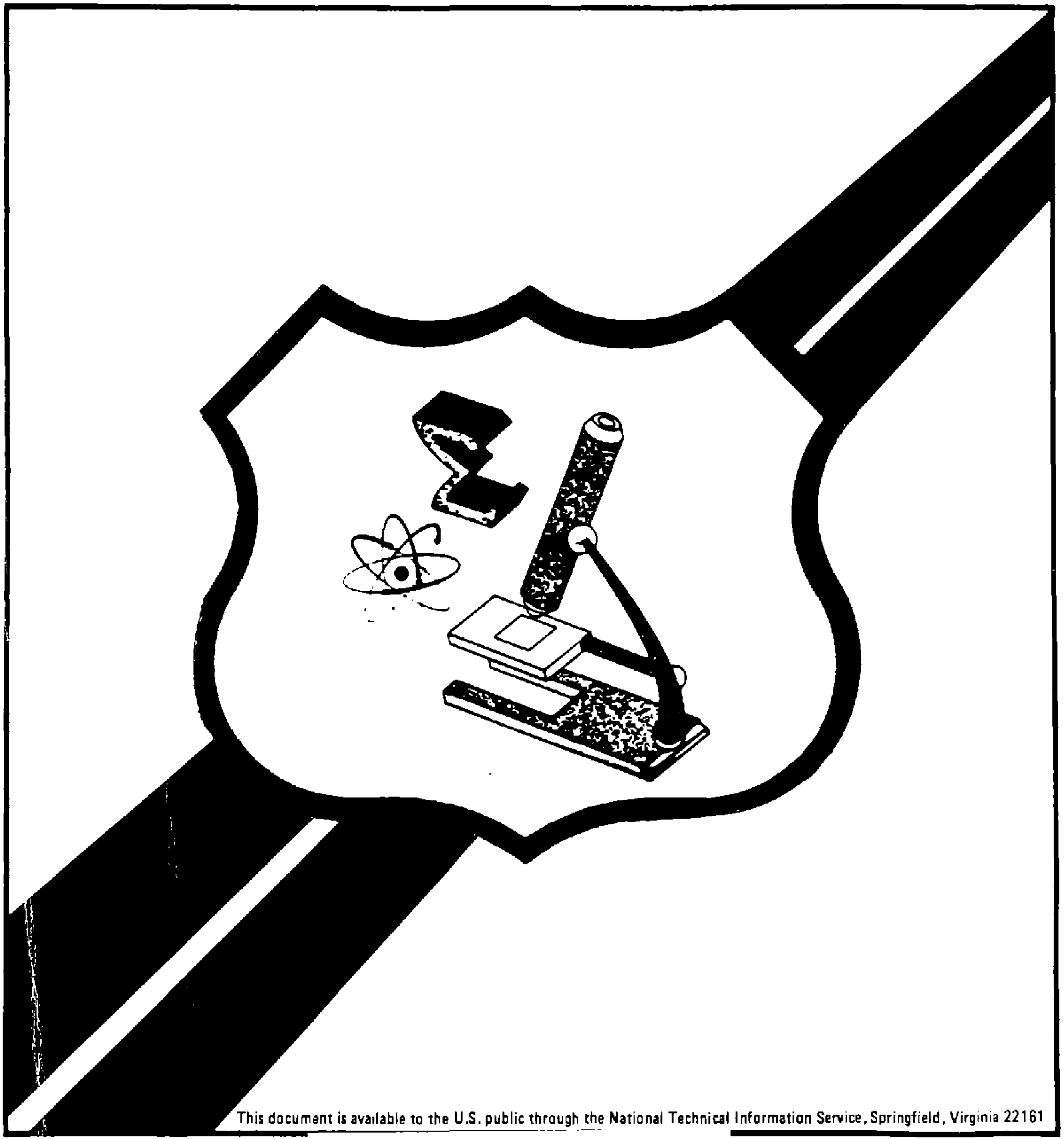

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C. J. Ray, L. E. Henton, and F. A. Rideout

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Engineering Experiment Station
Atlanta, Georgia 30332

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16. Abstract

The best method for qualifying high performance coatings incorporates field testing and laboratory testing to determine performance characteristics.

Recommended practices for cleaning structural steel and applying paints apply to high performance coatings. However, inspection is critical, as both surface cleanliness and film thickness are the exacting parameters that determine the performance of the coating system.

Current contracting standards did not contribute to the lack of reliability of high performance coating systems.

This report is Appendix A of the main report, FHWA/RD-82/118, "Improved Field Reliability of High Performance Coating Systems - Phase I: Identification of the Technology," which is available only from National Technical Information Service.

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APPENDIX A

Best Current Technology

1.0 Introduction

This document represents an assessment of the best technology currently applied in the use of high performance coatings in protecting structural steel. It is based on the findings of the four major tasks of this research study. These were:

1. Review Field and Laboratory Tests. The objective was to review tests, procedures, and criteria used to evaluate, characterize, and qualify protective coatings for use on structural steel.

2. Review Application Procedures. The objective was to review current practice in the application of high performance coatings under both shop and field conditions. Site visits at shops and bridges were included as sources of information.

3. Review Contracting Practices. The objective was a review of the contents and provisions of contracts for the cleaning and painting of structural steel.

4. Investigate Causes of Failure. The objective was to identify causes and their relative frequency in contributing to the failure of high performance coatings. This was to be done by analyzing cases of failure on bridges and similar structures.

In the original scope of the research study, high performance coatings were defined as coatings whose corrosion protective qualities are expected to be superior to coatings commonly classed as lead based paints using oil or oleoresinous binders. High performance coatings include zinc rich primers, vinyls, epoxies, urethanes, acrylics and other coatings based on resins of high molecular weight, synthetic polymers.

Waterborne coatings were also considered within the scope of high performance coatings. This was done based on expectations that they will find increasing use in corrosion protection of structural steel. This increased use is based on factors other than performance comparison with lead based paints. Examples are environmental restrictions on solvent emissions, health and safety considerations, and marketing.

Zinc rich primers with vinyl topcoats were the predominant high performance coatings system found in specifications for protecting bridges. The technology discussed below reflects this. Other types of coatings (e.g. urethanes, waterborne) are being evaluated for protecting bridge steel but at this time these are prototype systems. Laboratory test results and field trial results from these will form the base on which specifications (property and application) will be written.

The elements of the technology associated with high performance coatings are:

1. Qualification of Coatings.
2. Procurement Specifications.
3. Quality Control and Quality Assurance.
4. Coating Contract Provisions
5. Qualifying Contractors, Painters, and Inspectors.
6. Overcoating Zinc Rich Primers.
7. Defining and Correcting Field Failures.

Each of these is discussed below

In the order shown above.

2.0 Qualification of Coatings

This section concentrates on the tests, procedures, and criteria used to qualify a coating system for use on structural steel. It represents what can be done to maximize the probability that a coating selected will yield a service life sufficient to justify its use.

2.1 General Considerations

There are three major elements to be included in a qualifying scheme designed to select protective coating systems. These are

1. Field trials and exposures required before a paint system is placed on a qualified products list (QPL).
2. Coating systems qualified as single, complete units. Coating system here is defined as the quality of surface preparation, primer, intermediate (if included), topcoat, and film thickness for each coating layer.
3. Specifications based on performance qualifications in preference to ones based on compositions.

2.1.1 Field Trials and Exposures

Ideally, results obtained from a set of laboratory qualifying tests on a coating system would be used to predict the coating's field performance in terms of service life. In practice, this is not the case. The consensus in the paint industry is that performance properties observed through laboratory exposure tests such as salt fog and accelerated weathering do not predict nor correlate with field exposures or in-service use.

The relationship between laboratory testing and in-service performance has recently been studied under FHWA sponsorship and reported (Campbell, 1981). The conclusions of that study indicate that service life prediction is not within the scope of the laboratory tests used and that correlation of laboratory data with outdoor exposure data was poor.

The need to incorporate outdoor exposure and field trials then is a direct consequence of the general lack of correlation between laboratory test exposures and "real world" exposures.

Two specifications were found which included outdoor exposure performance criteria as part of product qualification. One is the specification for inorganic zinc rich primer based coating systems used by Florida Department of Transportation (Standard Specifications for Road and Bridge Construction, 1977, Section 971-15 "Self-Curing Inorganic Zinc Coating"). The other is a specification used by NASA at the Kennedy Space Center for protection of carbon steel against atmospheric corrosion (KSC-SPEC-C-0002, "Protective Coatings, Single-Component Inorganic Zinc, Inhibitive Polyamide Epoxy, and Aliphatic Polyurethane").

The qualification procedure used by Florida DOT most closely approximates actual field use since candidate coating are applied to a girder on a bridge in a coastal environment and not test panel as is the case with the NASA procedure.

The field qualification under Flori DOT requires that the coating limit rust develop on the girder to less than one per cent of a coated area after three years of exposure. This applied individually to the girder sections painted with primer alone, primer plus topcoat, and the complete three coat system (prim intermediate, and topcoat). No blisteri cracking, peeling or loss of adhesion is allowed to develop in any of the coating combinations after the three year exposure.

The NASA qualification requires a five year exposure of the primer alone and the complete paint system on KTA test panels. The exposure site is a marine environment. The acceptance criteria are rust development no less than a rating of 9 (ASTM D 610), blister development no less than a rating of 9F (ASTM D 714), and an over all corrosive environment resistance rating of at least 9 (ASTM D 1654).

The application process and conditions during film formation of a coating can be listed as sources contributing to the poor correlation of laboratory data with in-service performance. In the course of product development and qualification, coatings are applied in a laboratory environment in which ambient conditions are stable in respect to the variations in temperature, humidity, and wind encountered in field work. The use of field trials, then, helps one to get some information about a paint system's "real world" behavior, especially application characteristics.

It should be recognized that the information obtained in a field trial is not complete. The trials are small scale paint jobs and, therefore, do not cover the time span of a bridge painting job. This shorter time period reduces the range of temperature, humidity, and wind conditions in which the paints are applied and during which the films are formed.

In a qualification process, preference is to be given to field trials over outdoor exposure of test panels. The reason for this is that test panel painting is done in a laboratory environment so that the effect of field conditions on the application process itself and film formation are not included in the evaluation. The exposure times for either method are the same, generally, so neither has an advantage in that regard.

The National Association of Corrosion Engineers (NACE), through one of its technical practices committees, has recently published a guide to conducting atmospheric exposure tests on painted panels (NACE, 1981). The document is NACE Standard RP-02-81 Method for Conducting Coating (Paint) Panel Evaluation Testing in Atmospheric Exposures.

The scope and procedures for field trials can be defined by each State to reflect their bridge maintenance needs. The key elements in Florida's procedure are:

1. The State supplies or identifies the bridge.

2. The State specifies the surface preparation, anchor pattern, coating thicknesses, scheduling of application, and layout of the coating system on the bridge member (e.g. one-third primer and topcoat only).

3. The State specifies the acceptance criteria for both application properties and protection properties.

4. The coating manufacturer provides the material and painter.

The scope of such testing can include testing on bridges in different environments. The Florida procedure uses bridges in a marine environment.

2.1.2 <u>Complete Coating System Qualifications</u>

There are two aspects to qualifying a paint product for use on structural steel. One is that the product alone is not qualified but the paint coupled with the degree of surface preparation, anchor pattern, and dry film thickness for each layer is the thing qualified. The other aspect is a corollary to the first. Different paints (i.e., primers, intermediates, and topcoats) from different qualified systems are not used together unless qualified in that combination. For example, the topcoat from qualified system A is not to be used with the primer from qualified system B.

The performance of paint films on steel is dependent on their composition, film thickness, the cleanliness of the surface, the anchor pattern of the surface, and the nature of the exposure environment. This relationship is at least axiomatic. It is consistent with general experience in the paint industry and has been confirmed, in part, in research studies (see, for example, Keane, 1969; Keane 1976; and NACE, 1977). Recent FHWA sponsored research has also identified these factors as ones affecting protective coating performance (Frondistou-Yannas, 1980).

Although these factors are recognized, their effect on the performance of a paint is not known quantitatively. Hence, the paint, film thickness, surface preparation, and anchor pattern must be considered as an integral unit.

The prohibition against combining paints from different qualified systems reflects the empirical nature of coating technology. In practice this means that paints from different manufacturers are not used together unless qualified as such. This is seen as a practical means of insuring intercoat compatibility and adhesion, both of which are necessary qualities in a protective coating system.

2.1.3 Performance Specifications

There are two general categories of protective coating specifications: performance specifications and composition specifications. The review of specifications done in the course of this study indicated that paint specifications, in general, have elements of both types. Both types of specifications are written to insure a performance level from products.

The specifications are written by end users so their emphasis in preparing specifications necessarily is performance. They are not coatings chemists so formulations given in specifications are rudimentary. Often they are "starting"formulations developed by raw material suppliers. A formulation listed then is one instance of a composition that gives acceptable performance. Such formulations are developed on the basis of performance observed in laboratory tests. Since the degree of correlation between laboratory data and field performance is weak, the value of a specification that incorporates formulations correspondingly is lessened.

In principle, end users need to define product specifications in terms of performance characteristics. For protective coating systems for structura steel these characteristics are rust inhibition and durability of the coating itself in terms of resistance to cracking, flaking, peeling, color change, etc. Performance specifications which rely on laboratory tests to measure thes qualities for specific paints are also then, limited by the uncertainty introduced through the low degree of correlation between laboratory and outdoor results. This, fundamentally, is the reason field trials after laboratory screening tests have been included in the best technology.

Some degree of compositional specifications still play a role in specifications in which performance criteria predominate. These, however, are general statements limiting the scope of materials to be considered to certain generic types and concentration ranges. Concern about exact compositions is not pertinent to qualification of coatings; it is premature. It is more important to monitor compositional uniformity in qualified products as part of a quality assurance program.

2.2 Zinc Rich Primer Systems

This section deals with protective coating systems in which a zinc rich coating is the primer and various other types of paint films are intermediate coatings or topcoats. Hot dip galvanize coatings are not within the scope of this discussion; they were not within the scope of the research study.

2.2.1 Composition Considerations

Functionally, the zinc dust in a zinc rich primer coating is the active ingredient. It must be present in high enough concentration that particle-to-particle contacts and particle-to-steel contacts form an interconnected network so that, under electrolytic conditions, the steel is galvanically coupled with the zinc coating. The binder in zinc rich coatings is present to hold this network together and to bond it to the steel.

Compositional considerations then for zinc rich primer systems are the dust, binders, their respective concentrations, intermediate coats, and topcoats.

2.2.1.1 Zinc Dust Qualities

Qualities of zinc dust that affect coating performance are zinc purity level, the nature of impurities, and the zinc particle size distribution. These factors have been discussed in the technical literature (Elm; Garland, 1978; NACE, 1976).

The review of specifications indicates that the quality of zinc dust is defined by reference to ASTM D 520 Zinc Dust (Metallic Zinc Powder). This specification includes purity levels for metallic zinc, zinc compounds, and non-zinc impurities as well as particle size criteria based on sieve analysis.

Two types of zinc dust are defined in this specifications. Type I is the most commonly cited in zinc rich specifications. The two types are contrasted in Table A-1.

A companion specification, ASTM D 521, gives procedures that can be used to chemically analyze zinc dust.

2.2.1.2 Zinc Rich Binders

Several different types of binders are used in zinc rich coatings. The broadest classification is organic and inorganic binders.

The organic binders are generally synthetic polymers or prepolymers such as epoxy-polyamides, vinyls, chlorinated rubber, urethanes, and phenoxy. The resins are the ones usually associated with high performance coatings in general.

From a compositional standpoint, it is more important to exclude the use of certain organic binders. These binders are those that contain fatty acid esters which are susceptible to hydrolysis. The corrosion products of zinc, such as

Table A-1. Comparison of Type I and Type II Zinc Dust Based on ASTM D 520-51

	Type I	Type II
Total zinc, calculated as Zn, min, percent	97.5	98.0
Metallic zinc, min, percent	94.0	94.0
Materials other than metallic zinc and ZnO, max, percent	1.5	--
Calcium, calculated as CaO, max, percent	0.7	0.7
Lead, calculated as Pb, max, percent	--	0.01
Iron, calculated as Fe, max, percent	--	0.02
Cadmium, calculated as Cd, max, percent	--	0.01
Chlorine, calculated as Cl, max, percent	--	0.01
Sulfur, calculated as SO_2, max, percent	--	0.01
Moisture and other volatile matter, max, percent	0.1	0.10
Oily or fatty matter, or both, max, percent	--	0.05
Zinc oxide (ZnO), max, percent	6.0	remainder
Coarse particles, max, percent		
Total residue retained on a No. 100 (150-µm) sieve	none	0.1
Total residue retained on a No. 200 (75-µm) sieve	--	0.8
Total residue retained on a No. 325 (45-µm) sieve	4.0	3.0

ZnO, $ZnCO_3$, and $Zn(OH)_2$, are basic. Under moist conditions, the shift in pH to alkaline conditions catalyzes the hydrolysis (Tator, 1976). Hence, binders that are not to be allowed are oils, oleoresinous materials, epoxy esters, alkyds, and oil modified urethanes.

Inorganic zinc rich coatings use binders derived from silicates although phosphates and titanates can be found listed in specifications. The silicates are the only ones to be considered here.

The inorganic zinc rich types can be grouped into two categories: water reducible and solvent reducible. The water reducible ones generically include alkali metal silicates and quaternary ammonium silicates. The solvent reducible ones are alkyl silicates, i.e. esters of silicic acid, $Si(OH)_4$. The most common alkyl silicates are condensation products of ethyl orthosilicate, $Si(OC_2H_5)_4$. The review of State specifications indicated that alkyl silicate based zinc rich primers are the most used.

Comparison of organic and inorganic zinc rich coatings has been made in the general technical literature and in experimental studies. These are useful as guidelines.

Table A-2 contains a qualitative comparison of organic and inorganic zinc rich coatings for several attributes that are factors in the field use of the coatings. The rating of the two primer classes is a condensation of comparisons found in the literature (e.g. Buras, 1974; Garland, 1978; Manta, 1974; Tator, 1974).

Based on comparative generalization, organic zinc rich coatings are the preferred type since they can be used over lower quality surfaces (i.e., more tolerant of surface preparation variation) are more tolerant to thick film application (e.g., mudcracking does not occur), and can be topcoated with fewer defects (e.g. bubbling of the topcoat, intercoat adhesion).

The relative ranking of organic, and inorganic zinc rich coatings in terms of length of service is generally in favor of the inorganic type. However, the magnitude of the difference is not known.

It is concluded that organic zinc rich coatings, as a class, are more reliable than inorganic zinc rich because of their ascribed greater tolerance to field application processes. The amount of variability or the number of exceptions to this is expected to be high since the data from which these generalizations are based is difficult to identify and scrutinize.

Some specific comparisons between organic zinc-rich and inorganic zinc rich have been made and discussed in the technical literature.

The selection of an organic zinc rich paint (phenoxy resin base) in preference to a two package, inorganic zinc rich paint as a specification in California was made on the basis of the following (Anon., 1973):

1. The phenoxy zinc rich was simpler since it had application characteristics similar to lead-based paints.

2. The two package, inorganic zinc rich required control of mixing ratios at the job site that was judged difficult to do correctly consistently.

3. The adhesion of the phenoxy zinc rich to other paints and itself is spot repair was better than the inorganic.

Table A-2. Qualitative Comparison of Organic and Inorganic Zinc Rich Primers

Attribute	Organic	Inorganic
Protective Performance Life Time	0[a]	0
Surface Prep. (min.)	Commercial	Near White
Topcoating	+	-
Repair	+	-
Film Build	+ (more tolerant of thicker film)	- (Min. & Max. critical; mudcracking)
Applicator Skill	+	-

[a] "0" denotes comparable performance, "+" denotes superior performance, and "-" denotes inferior performance.

4. The inorganic zinc rich films mudcracked if the film thickness was greater than 5-6 mils; the phenoxy zinc rich did not demonstrate mudcracking even in films at 30 mils.

These reasons were generated through field experience. They do not address the question of relative service life but indicate, at least on an intuitive level, that the phenoxy zinc rich was more reliable than the inorganic one.

The reported experience in Florida is the opposite to the one reported for California (Ramsey, 1974). Phenoxy zinc rich were found to fail within eighteen months; Florida specifications, then, allows only inorganic, self-cure zinc rich primer systems.

Test panel exposures were run by NASA to evaluate the suitability of commercially available zinc rich coatings to protect steel structures in the marine environment at the Kennedy Space Center (Paton, 1973; Morrison, 1978). After five years of exposure, it was concluded that untopcoated, inorganic zinc rich coatings outperformed their organic counterparts in terms of rust development (ASTM D 610 scale). For example, for all inorganics (solvent and water reducible), twenty-seven of thirty films had a rust grade (ASTM D 610) eight or greater. The remaining three had a rating of four or less. In contrast, the organic zinc rich paints (single and multipackage combined) had five cases out of twenty-nine rated at eight or better; the balance were rated at less than three. Figure A-1 summarizes the data for the untopcoated primer films.

Topcoated zinc rich primers were included in this NASA study. Only three primers were used with forty-seven topcoats. The primers were an inorganic solvent and water reducible types, and an organic type. Figure A-2 presents some of the exposure data.

Nine of the forty-seven systems with the organic zinc rich primer were rated eight or better in terms of rust development after three years of exposure (five year exposure data for these systems was not reported). The distribution of rust ratings for this group of primers is wide (see Figure A-2), covering the full spectrum of results.

The systems with the inorganic, solvent reducible zinc rich primer (alkyl silicate type) demonstrated superior performance characteristics than those which used the inorganic, water reducible zinc rich primer (Figure A-2). The variability in performance was also the least for the inorganic, solvent reducible primer systems among all three sets of topcoated panels.

Evidence of primer-topcoat interaction is in the data from the NASA study. The organic zinc rich primer exposed untopcoated for three years had a rust rating of four. Thirty organic primer-topcoat combinations were rated ten after five years of exposure. In some cases (see Figure A-2), topcoating these primers resulted in poorer performance. These observations support the recommendations that protective coatings be qualified as a complete system and that primer-intermediate-topcoat combination be from the same manufacturer.

The direct extrapolation of results and conclusions from this NASA study to field performance is not

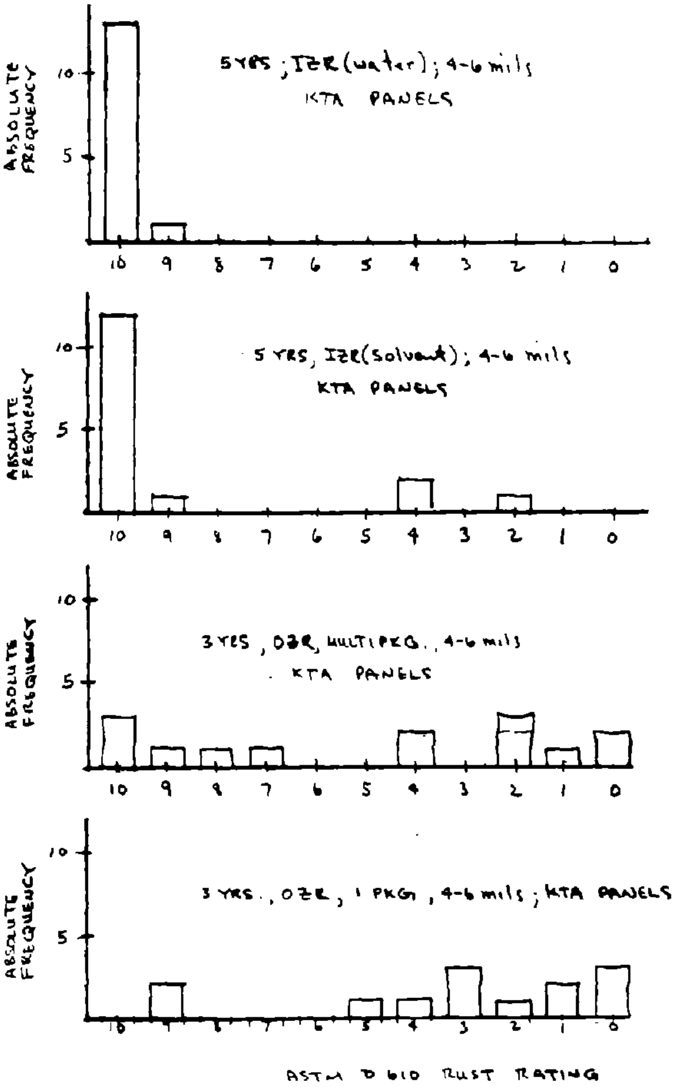

Figure A-1. Histograms for Untopcoated Primer Exposure Data.

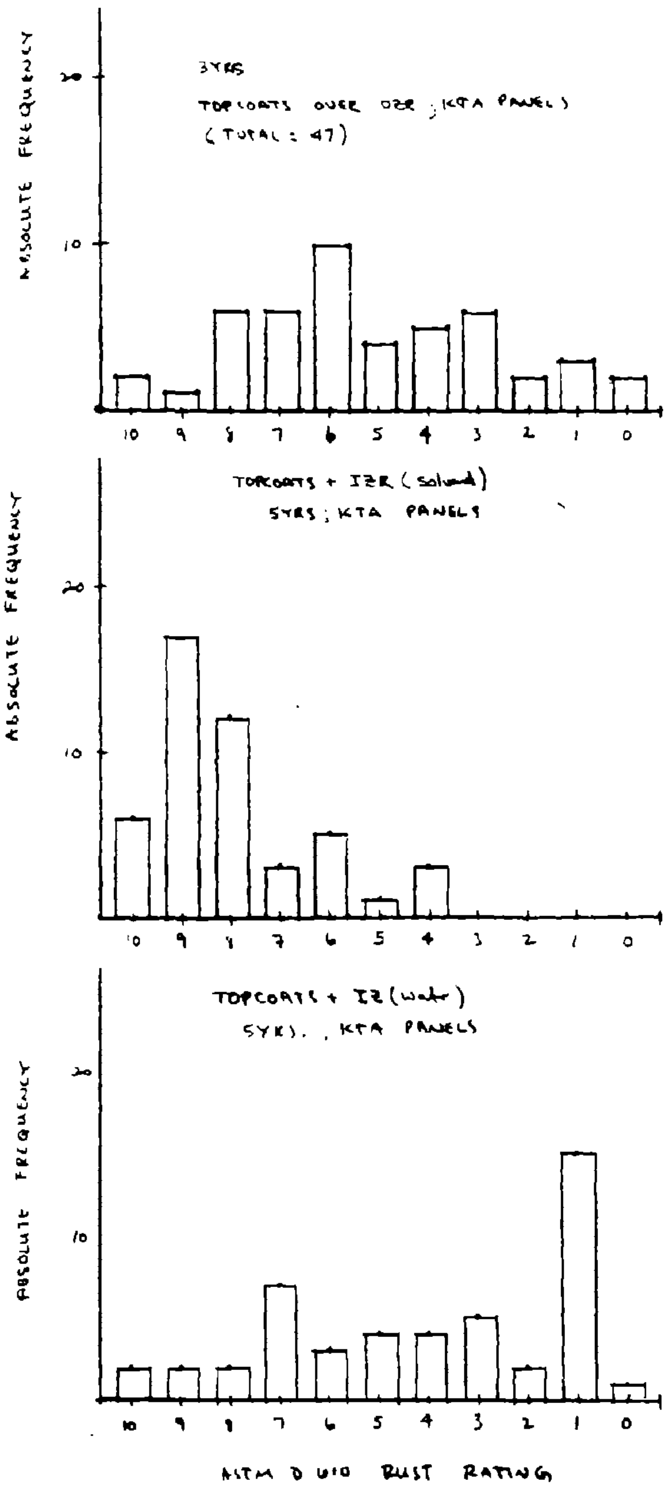

Figure A-2. Histograms for Topcoated Primer Exposure Data recommended. The films were applied in a laboratory environment and conditioned there. Field factors such as variable temperature and wind, therefore, were not included. Only one type of environment was used in the study: marine. The distribution in performance within the generic groups of coatings weakens conclusions about characteristics of these groups and indicates that each coating is to be viewed as unique.

An experimental study of zinc rich primers was also conducted by the U. S. Army in its Chemical and Coating Laboratory, Aberdeen Proving Ground (Thompson, 1970). Commercial as well as experimental zinc rich primers were evaluated in a series of laboratory tests (20% salt spray and aerated water immersion) and outdoor exposures (temperate and tropical sites). The conclusions based primarily on exposure at the tropical site (forty-one months maximum) were

1. Organic zinc rich primers had better adhesion to solvent cleaned steel than inorganic zinc rich primers.
2. Optimum corrosion protection requires a white metal surface condition.
3. The corrosion protection of organic zinc rich primers was usually upgraded when topcoated.
4. The corrosion protection of inorganic zinc rich primers was better when they were not topcoated.
5. Variance in performance among the groups of primers (organic and inorganic zinc rich) does not allow one to a priori select a binder; selection should be done on a case by case basis.

The Steel Structures Painting Council has reported on a study designed to determine what problems occur in topcoating zinc rich primers and develop recommendations for topcoating (Keane, 1981). The following conclusions and observations are relevant in terms of characteristics of different types of zinc rich primer. They were made on the basis of five year exposure at three different exposure sites (two industrial and one marine) and the experience in painting the panels.

1. The three water reducible, inorganic zinc rich primers were difficult to spray apply to a film of uniform thickness due to settling of the zinc dust even with continuous agitation; films greater than three mils thick had poor adhesion.
2. The porosity of the films from the water reducible zinc rich primers was greater than that in other types of films; topcoats were "soaked up."
3. No application problems were observed with the organic zinc rich primers or the inorganic, solvent reducible primers.
4. As a group, the water reducible inorganic primers demonstrated better corrosion protective properties than the solvent reducible, inorganic primers; this order is reversed when the primers are topcoated.
5. Differences in performance between untopcoated and topcoated primers indicate that neither is a predictor of the other (again, each coating or coating system must be treated as unique).

A comparison of the performance characteristics of topcoated organic and inorganic (both solvent and water reducible types) zinc rich primers can be made based on SSPC data. A cross-tabulation table of five year exposure summary data is in Table A-3 (Table A-3

Table A-3. Crosstabulation Table for Generic Primer Type and Corrosion Protection Performance.

Primer Type	Good	Fair	Poor	Total
Inorganic (water reducible)	68	21	9	98
Inorganic (solvent reducible)	95	18	4	117
Organic	16	4	0	20
Total	179	43	13	235

---

[1] Good = 10 (ASTM D 610); Fair = 8 or 9; Poor = 7 or less.

was derived from Table 20, p. 35 of the SSPC report). The table entries are the number of panels. Panels from all three exposure sites are included, i.e., no segregation on the basis of exposure site is made. A similar table of data for untopcoated primers was not presented.

Application of the chi-square test statistic to the distribution shown in Table A-3 indicates that the distribution is not sufficiently different from a random assignment of performance gradings to conclude that differences observed are assignable to the broad generic types of primers. The statistical criterion applied in reaching this conclusion was a level of statistical significance equal to 0.05. The chi-square value found was 7.54; the critical value of chi-square was 15.5. This conclusion may change as additional exposure data are collected.

Again, the variability of performance within commonly used generic classification schemes does not allow one to assign "Characteristic" properties.

2.2.1.3 Solvents

The selection and use of solvents is the realm of the coating developer and manufacturer. Laboratory evaluations and field trials will provide the feedback on the suitability of solvent blends used in the basic formulation and thinning operations.

Restrictions on solvent types and quantities due to health and environment protection regulations are proper types of specification requirements. Formulation of a compliant product remains the manufacturer's responsibility in achieving qualification.

2.2.1.4 Additives

Additives play a critical role in developing a commercially viable product. The level and type of additives is, realistically, best determined by paint chemists and coatings manufacturers. This reflects the preference for performance qualification.

Properties associated with additives in zinc rich coatings are color, viscosity control, dispersion aides. for the zinc dust, and moisture scavengers. The concentration of additives is, generally, less than five per cent by weight of the film forming portion of a paint.

2.2.1.5 Mixed Paint Composition

The key to the performance characteristics of zinc rich coatings is electrical contact between the zinc dust particles and the steel. The galvanic nature of the corrosion protection it gives to iron and steel then is activated when a water or aqueous electrolytic environment couples the zinc rich paint and steel electrochemically. The barrier properties of zinc rich coatings also contribute to the corrosion protection but that is not the basis for their use. Zinc rich coatings by definition, are used to provide sacrificial, cathodic protection.

Minimum concentration of zinc dust in the dry film is a necessary qualification property for zinc rich coatings. The minimum value is different for inorganic and organic types of primers. This reflects the difference in density between the binders. For example, for ethyl silicate derived binders, the matrix is expected to be essentially silicon dioxide, SiO_2. The density for it is in the range of 2.2-2.7 g/cc (Handbook of Chemistry and Physics, Forty-fourth Edition). The density of organic polymers is less than this, e.g. vinyl resins are in the range of 1.33-1.39 g/cc and phenoxy resins have a density of approximately 1.18 g/cc. For equal volume loadings of zinc dust, a greater amount of zinc on a weight basis is needed in the organic types.

The survey of specifications on zinc primers identified eighty per cent zinc dust on the basis of dry film weight as the minimum level in organic primers. Seventy-five per cent was the minimum found specified for inorganic type primers.

Information from NACE indicates that the zinc dust content for organic primers is in the range of eighty to ninety-five per cent (dry film basis) while the range is sixty to eighty-eight per cent for inorganic types. Both types have zinc loadings in the range of forty-five to eighty per cent on a volume basis (NACE Publication 63173 Organic and Inorganic Zinc-Filled Coatings for Atmospheric Service).

Steel Structures Painting Council zinc rich primer specification SSPC 20x80P requires a minimum zinc dust concentration of seventy-four and seventy per cent based on total solids for inorganic and organic types, respectively (Berger, 1981).

A best practice in qualifying zinc rich primers and coating systems is a minimum requirement on the concentration of zinc dust. The minimum value found in SSPC's zinc rich specification (SSPC 20x80p) are recommended as the best technology to date. These values are seventy-four per cent for inorganic types and seventy-seven percent for organic types.

The physical basis for a minimum zinc concentration is the packing of the zinc dust particles to achieve electrical continuity throughout the film. A maximum concentration is defined or limited by the maintenance of film forming properties. Adhesion and cohesion of the film is expected to degrade as the zinc dust concentration approaches one-hundred per cent of the film weight. Testing of coatings in the course of product development and qualification is expected to be sufficient in identifying this maximum on a product to product basis.

A few cases were identified in the review of specifications in which an upper limit to zinc dust concentration was included (e.g., Union Carbide Corporation's CUPE 102 Zinc Rich Primer System).

The minimum requirements on zinc dust concentration in effect, eliminate formulations that use conductive extenders to maintain electrical continuity in the film while reducing the zinc dust concentration. The di-iron phosphide extender of empirical formula Fe_2P is an example; its role and performance in zinc rich formulations has been discussed in the literature (Fawcett, 1980; Metil, 1977, 1978, and 1979). Replacement of forty percent (weight basis) of the zinc dust is reported.

Comparisons of extended zinc rich coatings with traditional zinc rich coatings based on laboratory test results are favorable. However, no corresponding service performance data was located in the course of this research study. Because of this, zinc rich primers that use conductive extenders have been intentionally excluded from the best technology category.

2.2.2 Intermediate Coats and Topcoats

The practice in painting steel structures and especially in the case of highway bridges is to overcoat the zinc rich primer. This is done for two reasons. One is aesthetics. The other is the protection of the zinc rich primer itself from corrosive environments.

The corrosion rate of zinc is dependent on the pH of the environment (see, for example, Munger, 1977). Outside the pH range of 6 to 12 corrosion rate is very sensitive to change in the pH (see Figure B-3). Specific atmospheric pollutants can also affect the corrosion rate (see Figure B-4). The prevalence of acid rain, then, coupled with the sensitivity of zinc corrosion to acidic environments supports the overcoating of zinc rich as part of the best technology.

A wide variety of intermediates and topcoats are used over zinc rich primers. The most common are vinyl resin based coatings and ones based on epoxy-polyamide materials. Consistent with the general guideline of a systems view of protective coatings, the best technology is the qualification of primer, intermediate, and topcoat as a unit. A corollary to this is the use of paints only from the same manufacturer in a given coating system.

Coatings that are in direct contact with a zinc rich primer should be resistant to basic hydrolysis. This is the same prohibition placed on binders for use in zinc rich coating formulations. Again, this is due to the basic nature of the natural corrosion products of zinc, e.g. basic zinc carbonate. This concern excludes resins containing fatty acid ester groups from the best technology.

The susceptibility of oil containing and modified resins to hydrolysis and subsequent degradation in a coating's protective qualities is mirrored in guidelines on the compatibility of different paint type combinations. These guidelines are:

1. NACE Publication 6H180 Topcoating of Zinc Rich Primers for Atmospheric Exposure.

2. U. S. Navy, Civil Engineering Laboratory Techdata Sheet 77-19 Incompatibility of Paints.

3. Structural Painting, Louisiana Department of Transportation and Development.

A condensed summary of these guidelines as applied to overcoating zinc rich primers is given in Table A-4.

Review of Table A-4 (and its parent tables) indicates that there is not universal agreement on what coatings are compatible with zinc rich primers. Provisions for the use of tie coats or intermediate coats reflect the variance in performance that can be expected within the coarse generic classes used in presenting such guidelines. The exclusion of resin types likely to be hydrolytically unstable is a point of agreement, however.

2.2.3 Property and Performance Consider

2.2.3.1 Physical Properties

Zinc rich specifications were surveyed for physical attributes and corresponding values required of dry film in the qualification procedure. The anticipated attributes were hardness, flexibility, impact resistance, adhesion, color, and abrasion resistance

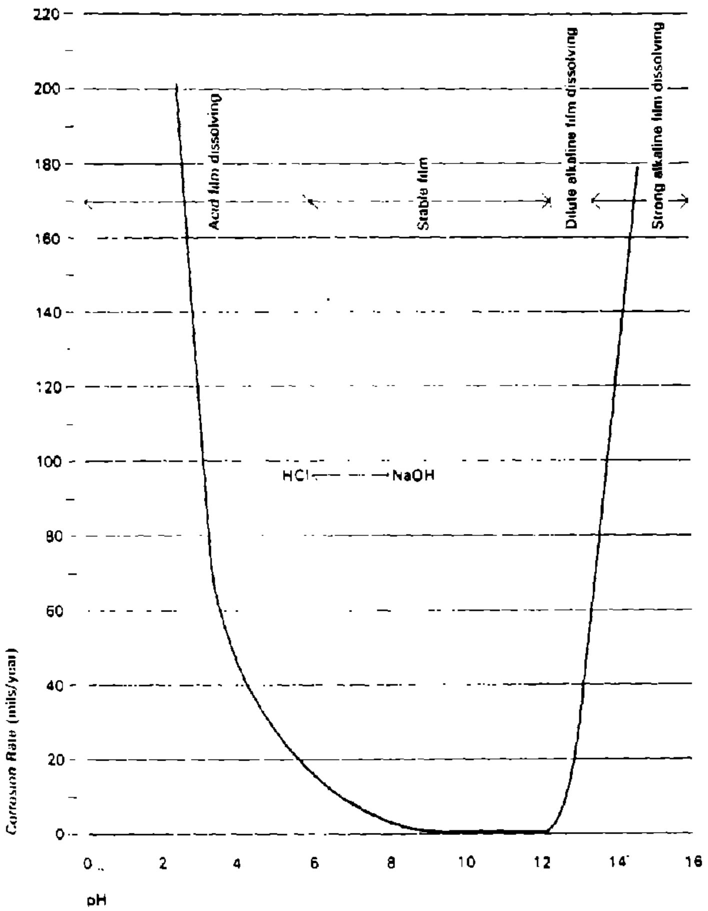

Figure A-3. Effect of pH on the Corrosion of Zinc (Slunder, 1971).

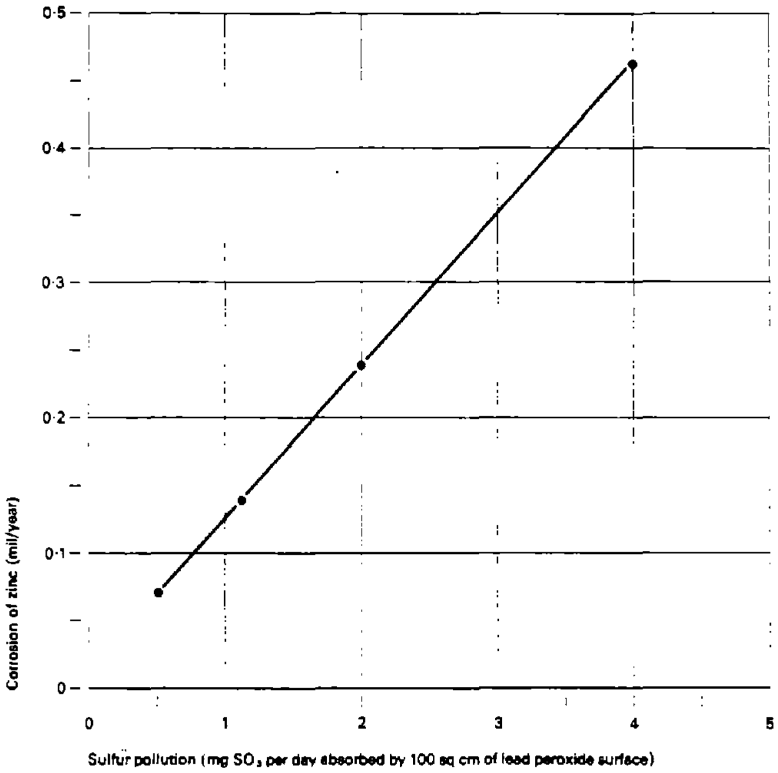

Figure A-4. Corrosion Rate of Zinc Sheet In Sulfur Contaminated Atmospheres (Slunder, 1971).

Table A-4. Summary Guidelines for Overcoating Zinc Rich Primers.

Intermediate or Topcoat	NACE		NAVY		LA DOTD	
	Organic	Inorganic	Organic	Inorganic	Organic	Inorganic
Acrylic, solution	1,2	NR	--	--	R	R
Acrylic, latex	R	3	NR	R	R	R
Alkyd	3	3	NR	NR	NR	NR
Bitumen	--	--	--	--	R	R
Chlorinated Rubber	4	4	R	NR	R	R
Epoxy Ester	3	3	--	--	5	5
Epoxy Polyamide	6	R	R	R	R	R
Polyesters	--	--	R	R	R	R
Polyurethane (oil free)	4	4	7	7	R	R
Vinyl	4	4	R	R	R	R

R: recommended or acceptable applied directly to zinc rich primer.
NR: not recommended or acceptable when directly applied to zinc rich primer.
1: acceptable if crosslinked primer
2: tie coat may be required if primer is lacquer dry type; formulation specific.
3: tie coat required.
4: tie coat may be required; formulation specific.
5: marginal.
6: not recommended over lacquer dry type primers; otherwise recommended.
7: polyol of the polyether or acrylic type is acceptable; polyester polyol not acceptable.

were used to specify desired physical properties. These attributes were listed in only a few specifications; no specification used all of them. They were applied to the primer film only. A summary of these findings is given in Table A-5.

The paucity of physical property requirements in specifications is taken as an indication that they are not necessary in selecting coatings. The imprecision in the methods used to measure these properties also reduces the value of defining limits. Hence, it is concluded that prequalification and qualification requirements for these properties are not necessary.

2.2.3.2 Performance Properties

The main performance property of zinc rich coatings is retardation of steel corrosion. Exposure of coated steel panels to a five per cent salt spray per ASTM B117 is the most common method used to evaluate this property. Other methods found were immersion tests in water or salt solutions. High humidity exposures were not cited in the specifications sampled.

The exposure times in salt fog differed for organic and inorganic zinc rich paints. For organic types, the range found was five hundred to fifteen hundred hours; for inorganic types, the range was three hundred to four thousand hours.

Acceptance or performance criteria for organic and inorganic zinc rich primers also were similar. No blistering, under film corrosion beyond scribe lines limited to one-sixteenth of an inch, no rust development, or loss of adhesion were the acceptance criteria found. These apply only to the primer, performance of a complete coating system was not included in the specifications.

The longer a coating retards rust development of a steel panel exposed to the salt fog atmosphere, the better are its corrosion resistance properties by definition. Additionally, if good corrosion resistance is observed in the highly corrosive salt fog, one, at least intuitively, expects equivalent or better resistance to less aggressive environments such as atmospheric exposure. However, the performance observed in the salt fog test is not a strong indicator of field performance (Campbell, 1981).

There are several reasons for the lack of correlation of salt fog exposure with field performance. These have been discussed recently in the literature (Campbell, 1981; Appleman 1982; Hare, 1982) as well as in previous sections of this appendix. In summary, these reasons are:

1. The salt spray test environment is not representative of atmospheric exposure; it does not include weathering factors such as ultraviolet light, ozone, and pollutants (e.g. SO_2).

2. The mechanism of failure in the salt fog may not correspond to that observed in the field due to the elevated temperature of the test, specific chemical reactions between coating components and the chloride ion (e.g. zinc chloride formed instead of zinc carbonate), and the high conductivity of the salt solution which can enhance the level of cathodic protection artificially.

3. A lack of reproducibility between test cabinets and for the same test cabinet at different times. The source of this variability is due, at least in part to variations in operation of the cabinets (temperature control, uniformity of salt spray dispersal,

Table A-5. Physical Property Requirements of Zinc Rich Primers.

Attribute	Method	Criterion
Hardness	Pencil (ASTM D3363)	B or greater (organic zinc rich) 4H or greater (inorganic zinc rich)
Flexibility	Conical Mandrel	"No loosening of film above point of longest continuous crack." (organic zinc rich) 10% elongation or greater (inorganic zinc rich)
Adhesion	Knife Test (Federal Test Method 141.6304)	"...Film shall adhere and not flake or crack from the metal."
Color	visual	"sufficient" contrast from blast cleaned metal appearance.
Abrasion Resistance	Taber Abraser	no greater than 0.2g loss per 1000 cycles.

Table A-6. Immersion Tests for Corrosion Resistance of Zinc Rich Primers

Corrosive Medium	Test Duration	Performance Criteria
Tap water	30 days	no rusting, blistering or softening of the coating; applied to organic and inorganic primers
Salt Solution (5%)	30 days	no rusting, blistering or softening of the coating; applied to organic and inorganic.
Bullet Hole Immersion salt solution (3.1%)	variable	minimum of 100 hrs. without rust for organic primers; minimum of 650 hrs. without rust for inorganic primers.

atomization, pressure, solution flow rate, frequency of interruptions to the test, and spacing between panels).

4. Differences between laboratory studies and in-service applications in terms of the type of steel, surface preparation, anchor pattern, and conditions during film formation.

The length of time in the salt fog and the corresponding extent of coating degradation and rust production have no significance themselves. They are used to compare coatings; they are used as measures to order or rank coatings. This ordering on the basis of relative performance is expected to be maintained in outdoor exposures (Lin, 1980). Quantitative measures of the degree of rank correlation were not found however in the course of this study or in the FHWA sponsored "Short-Term Evaluation Procedures for Coatings on Structural Steel" that concentrated on such questions. (Campbell, 1981, p.7).

The best technology applied to salt fog testing is to include a control coating in each test series and evaluate the performance of candidate coatings in respect to the performance of the control coating. This control coating needs to be one whose field performance is known. The control coating should be similar in composition to the test coatings so that performance and degradative mechanisms in the salt fog environment will also be similar. Hence, more than one control coating may be necessary. This procedure may not insure field performance correlation but it is expected to improve it.

The stable operation of the salt fog cabinet within specification guidelines, proper placement of panels, conditioning of films, etc. are a necessary part of this best technology.

Other tests used to assess the corrosion resistance properties of zinc rich primers were immersion in tap water for thirty days, immersion in salt water, and a bullet hole immersion test. This latter test is intended to measure the ability of a zinc rich coating to cathodically protect bare steel against a corrosive environment. (Hare, 1982). It is included in the SSPC specification for zinc rich primers (SSPC 20x80P). A brief summary of these immersion tests is given in Table A-6.

These tests suffer from the same shortcomings of the salt fog test in their correlation with field performance for similar reasons. If used, they are best applied with the inclusion of a control coating.

Only a few other performance tests were found in the specification survey. Accelerated weathering (ASTM G23 for one thousand hours with no rust development or loss of adhesion was one; resistance to high temperatures for inorganic zinc rich primers was another (Florida DOT 971-15.2.3.1; 600°F for three hours; no loss of adhesion, no softening, no flaking, or cracking).

Most of the specifications reviewed concentrated on the zinc rich primer alone. Tests of topcoated primers dealt with the adhesion of the topcoat to the primer. In most cases, the adhesion under normal laboratory environment was the sole criterion. Maintenance of adhesion in corrosive environments was not frequently encountered as an explicit qualification criterion although it implicitly is so.

On the basis of the survey and in light of information available about laboratory tests used in paint development and qualification, the best technology in performance testing is:

1. Use laboratory performance tests only as screening devices to identify paints for outdoor exposure evaluation and field trials.

2. Use a control coating in laboratory performance tests and judge the performance of candidate coatings in relation to the performance of the control coating (the control coating must be similar in composition to the candidate and it must have its own field performance history).

3. Performance testing of primer alone is not sufficient if they are to be used with a topcoat; the primer-topcoat interaction can enhance or degrade the performance level expected based on primer performance alone (Morrison, 1978; section 2.2.1.2, p. A-9).

4. Standardized operating procedure and sample preparation techniques must be followed to minimize variability in test results.

5. Use outdoor exposure testing and field trials in the qualification procedure; do not qualify coatings on the basis of laboratory tests alone. The length of exposure and acceptance criteria can be set by each State or user. For information purposes, NASA requires a five year outdoor exposure of test panels and Florida DOT requires a three year exposure on a bridge girder (see section 2.1.1).

6. Include salt fog exposure (ASTM B 117) in laboratory performance testing since it is the most common and guidelines in interpreting results are available (Campbell, 1981; Appleman, 1982; Hare, 1982). Other performance tests should be included that expose the coating to different types of degradative stresses to provide some information on the sensitivity of a coating's performance to different environments. Suggested tests are high humidit (ASTM D 1735), accelerated weathering (e.g. ASTM G-53), and cyclic exposures (ASTM D 2933), and adhesion using the Instron tensil testor. The need for control coatings in these remains.

2.2.4 Vinyl Topcoats and Zinc Rich Prime

Vinyl topcoats are commonly used as topcoats over zinc rich primer systems. Because of this, the following guidelines are given.[1]

2.2.4.1 Vinyl Resin Type

The vinyl resins used in topcoats are synthetic polymers made chiefly from vinyl chloride monomers and vinyl acetate. A typical proportion is eighty-six parts by weight of vinyl chloride to fourteen parts by weight vinyl acetate. The two major modifications to the basic polymers are the introduction of acid groups (e.g. maleic acid) or hydroxyl groups (hydrolysis of of acetate group) into the polymer. The acid modified versions are recommended for adhesion to steel and other metal surfaces; the hydroxy functional polymers are recommended for adhesion to non-vinyl coatings. Both types work with zinc rich primers but the acid-modified resins are preferred.

2.2.4.2 Pigmentation

The vinyl resins are not stable to ultraviolet (UV) light exposure (sunlight). Pigments and UV stabilizers are included in vinyl paint formulations to protect the resin from sunlight induced degradation.

Titanium dioxide (rutile) pigment acts as a UV screen besides contri-

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[1] Information supplied by Frank Rideout, Frank A. Rideout Company, 642 Bouldercrest Drive, Marietta, Georgia 30064.

buting to hiding and color. In order to be effective as a stabilizer, its minimum concentration must be sixty-five parts (by weight) per one hundred parts or resin. The upper limit is about twice the minimum; this limit is roughly defined by degradation in physical properties of the coating. Other pigments that provide UV stabilization in vinyl paints are aluminum flake, carbon black, and antimony oxide. These are effective at lower concentrations than the titanium dioxide.

Since vinyl resins are not in themselves stable to sunlight and rely on other coating components to retard or prevent their photochemical degradation, screening tests such as accelerated weathering and outdoor, panel exposures should be included in qualification schemes.

Some pigments react with vinyl resins to degrade the polymer or gel the liquid paint. Examples of these are natural iron oxides, Prussian blue, chrome greens, and gold and bronze metallic pigments. Basic pigments and fillers can gel formulations that contain acid modified vinyl resins. Materials to be excluded because of this are red lead, chrome yellow, chrome orange, zinc dust, zinc oxide, strontium containing pigments, and calcium carbonate. These points are more appropriate to a coating's manufacturer and his efforts in product development.

2.3 Non-Zinc Rich Primer Systems

Few cases of high performance coatings other than ones based on zinc rich primers are found in the survey of specifications and in the course of the research study. High performance systems other than zinc rich ones are used, of course. For the most part and in contrast to zinc rich systems, the high performance quality is mainly due to the nature of the polymer in the coating. Hence, high performance coatings encompass acrylics, vinyls, epoxies, urethanes, and chlorinated rubber.

Pigmentation in the primers of high performance coatings is broad in scope. Corrosion inhibitive pigments have been red lead, zinc chromate, and other chromates, molybdates, zinc phosphate, basic lead silicochromate, calcium borosilicates, barium metaborate, and zinc phosphooxide. Several of these pigments are under study by the Steel Structures Painting Council in the PACE project as replacements for lead based and chromate based inhibitive pigments (Keane, 1979).

Because there are pigment-binder interaction and, in general, a range in performance for any generic class of coating, it was not possible in this study to exclude certain materials or require inclusion of certain materials in a set of qualification guidelines. This can be done on an arbitrary basis, of course. Some materials can be restricted based on regulations intended to protect the environment and to provide for worker health and safety. Primary examples of this on the regulation imports on the use of lead based and chromate containing pigments.

The best technology applied to non zinc rich primer systems is essentially the same as the best technology applied to zinc rich in terms of performance qualification. This is:

1. Performance testing (e.g. corrosion resistance and weathering resistance) must be done with a control coating included.
2. Performance results should be interpreted with reference to the performance results for the control both

in the test themselves and in actual service.

3. Outdoor exposures and field trials should form a part of the qualification process; qualification on the basis of laboratory testing alone is not the best practice.

4. Coating systems (primers, intermediates, topcoats) need to be tested as an integral unit; the individual coatings can be tested separately but, due to interactions between the coatings, performance of the combined system cannot be predicted from the individual performances.

5. Specific tests, durations, and acceptance criteria can be established by the user. Interpretation of results can still be made in reference to a control coating. The control coating must be similar in composition to the candidate coatings. Suggested tests are salt fog exposure (ASTM B 117), high humidity exposures (e.g. ASTM D 1735), accelerated weathering (ASTM G-53), and cyclic exposure (ASTM D 2933). The length of exposure, properties tested, typical times to failure, and failure modes in these and other tests have been reviewed in the FHWA sponsored study "Short Term Evaluation Procedures for Coatings on Structural Steel," (Campbell, 1981).

2.4 Waterborne Maintenance Coatings

Waterborne maintenance coatings for steel was included in this study because it is likely that their use will increase and because their tolerance to variances in surface preparation and application procedures is lower than oleoresinous systems. Hence, improvements in the technology for high performance coatings may be applicable to waterborne coatings.

Waterborne is a broad term that covers different types of "waterborne" coatings and different polymer types. It is used interchangeably with "water based "and" water reducible." The different types of waterborne coatings are latex (also often called emulsion but this is not correct), alkali soluble, and emulsions. The types of polymers used in waterborne coatings include acrylics, vinyls, polyurethanes, alkyds, polyvinylacetates, styrene-acrylic polymers, and epoxies. The alkali metal silicates are waterborne coatings but they are not considered in this section.

The state of development of waterborne maintenance coatings (and other low solvent concentration coatings technologies) has been assessed recently in another FHWA sponsored project, "Evaluation of Low-Solvent Maintenance Coatings for Highway Structural Steel," (Bruno, 1981).

Highlights of this assessment are:

1. At least two years are required before low-solvent coatings can be proven for use in mildest environments.

2. Most waterborne coatings are less tolerant of oily, dirty or chalky surfaces and therefore, proper surface preparation is more critical.

3. Acrylic and styrene-acrylic latex polymers have received the most development and promotion of the waterborne technologies for protecting structural steel.

4. Successful application of latex maintenance paints in the field up to three years in "mild" environments) is attributed in part to non-typical field supervision, surface preparation quality, and favorable application and curing conditions.

In terms of field reliability, these findings are interpreted to mean waterborne coatings on steel bridges must be treated as experimental. Field trials then are essential before qualification for use on full sized structures.

The California Department of Transportation, through its Office of Transporation Laboratory, is developing waterborne maintenance coatings. The development effort and results of laboratory tests have been presented (Warness, 1979). Field trials of some of the paints developed are in progress in coastal areas which are considered more severe than the locations where initial trials were made.

Florida Department of Transportation is also involved in field evaluation of waterborne coatings. The procedure is the same one used for the field qualification of zinc rich coatings (section 971-15.2.3.3 Standard Specifications for Road and Bridge Construction-1977). The paints are applied to a bridge girder and their performance is monitored. At this stage, there are no laboratory qualifying tests; paints that perform acceptably in the field trials are to be used to define laboratory performance standards.

2.4.1 Waterborne Specifications and Guidelines

Only a few specifications and guidelines on waterborne maintenance coating systems were located. These were:

1. Military Specification MIL-P-28577A(RD) Primer, Latex, Corrosion Resistant, for metal surfaces.
2. Military Specification MIL-P-28578 Paint, Water Reducible, Semi-Gloss, Exterior and Interior.
3. NACE Publication 6H176 Acrylic Latex Coatings for Resistance to Atmospheric Corrosion to Metal Surfaces (Materials Performance, vol. 15, no. 4, 13-16 (1976).
4. "Water-Based Coatings for Protection of Steel Structures", Report No. FHWA/CA/TL-79/24.

Waterborne coating technology is described in Waterborne Coatings: Emulsion and Water-Soluble Paints, (Charles R. Marteres, Van Nostrand Reinhold Company, New York, 1981, 316pp.). It provides an overview to the technology and includes discussions on raw materials, formulation, typical properties, and the physicochemical nature of the different types of waterborne coatings. Maintenance paints is the subject of one chapter.

The value of the military specifications in establishing the best technology resides in their lists of performance tests and acceptance criteria (Table A-7). The qualitative composition requirements for materials are vague so they do little to limit the scope of materials. Because of this, the quantitative requirements on pigment concentration, solids, and weight per gallon are not meaningful.

The specifications in the California DOT paint development work are formulations so the materials and their proportions are fixed. The performance characteristics from these formulations can serve as benchmarks for performance acceptance criteria. For example, the best primer has reported salt fog resistance ratings of no blisters, no surface rust, 1/16 inch with scribe undercutting, and 9 underfilm corrosion rating (ASTM D 610) after 3,000 hours of exposure. These ratings have no significance themselves, their value lies in the fact that they

Table A-7. Some Performance Tests and Acceptance Criteria from Latex Coatings Military Specification.

		Performance Level	
Test Characteristic	Test	Primer	Primer + Topcoat
Fungus Resistance	ASTM D3273	rating $\geq$6	
Flexibility	1/4 inch mandrel bend	no cracking, chipping, or flaking	
Adhesion	tape adhesion + score line	maximum 1/16 removal beyond score line	
Humidity Resistance	condensing moisture (ASTM D2247) 250 hours	NA	no rust bleed blisters $\leq$ 6MD, rust creep $\leq$ 1/8 inch
Salt spray resistance	salt fog (ASTM B117) 250 hours	NA	blisters $\leq$ 6MD, rust creep $\leq$ 1/8 inch.

were the best from among different formulations.

Several of the paints developed and screened through salt spray exposure (primers and primers plus topcoats) are being exposed outdoors on test panels and on bridges. The results of these trials can be used to determine the relative merits of the coatings and explore correlations with laboratory screening.

The PACE project run by the Steel Structures Painting Council includes an experimental study (salt fog exposure and natural exposure at three different sites) of waterborne coatings. The design of the waterborne coating evaluation includes alkyd and oil type maintenance paints as controls. Phase II of PACE is in progress under HPR pooled funding from twenty-five states. The waterborne coating exposures started in Phase I are being continued; more waterborne coatings such as epoxy based systems have been added to the study. The results of this work, when completed, can provide information about the expected level of performance for waterborne coatings as a general class and according to different subgroups (e.g. latex, and epoxy emulsions).

2.4.2 Special Performance Tests

Waterborne maintenance coatings have the same functional purpose as other maintenance coatings, namely the retardation of steel corrosion. Hence, the performance tests used in qualification procedures are similar. For example, salt fog exposure is used for solvent borne and waterborne coatings.

The presence of water in waterborne coatings and the mechanism of film formation in latex polymer based systems adds other tests to the battery of performance evaluations. Some of these are carry-overs from latex paint product development while others have been developed in response to observations in field trials. These tests are minimum film forming temperature (MFT), flash rusting, early rust, wet adhesion, freeze-thaw stability, and mechanical stability.

2.4.2.1 Minimum Film Forming Temperature

The MFT is a test appropriate to latex polymer systems in contrast to other types of waterborne coatings. As the name implies, it is the temperature below which a latex polymer or paint will not form a film. Instead, a loose, powdery deposit remains after the water evaporates.

Latex polymers are aqueous dispersions of colloidally sized spheres of polymer. In the first stages of film formation, water evaporates and the polymer spheres are compacted together but retain their individual integrity (i.e. there is little or no mixing or migration of polymer segments between polymer spheres). Continued evaporation of water and the development of capillary forces generate stresses that lead to deformation of the polymers spheres and their gradual fusion. The total film forming process can take days to months to complete.

The degree of coalescence of latex polymers is dependant on the viscoelastic properties of the polymer which, in turn, are dependant on the nature of the polymer, level and type of plasticizes and coalescing solvents, and temperature.

For a given latex paint (the unit with which the user is concerned), there is a temperature below which the mechanical film forming stresses are insufficient to deform the polymer spheres (the viscoelastic properties of polymers increase in rigidity as the temperature decreases). Hence, one needs to know what that limit is as one piece of information to be used in defining the range of climatic or substrate conditions in which painting can be done.

A method of determining MFT has been standardized in ASTM 02354. Minimum Film Formation Temperature (MFT) of Emulsion Vehicles. The method is applied to the polymers only. For latex house paints and maintenance paints, MFT values are around fifty degrees Fahrenheit (50°F).

2.4.2.2 Flash Rusting

Flash rusting is "the corrosion of a ferrous substrate that occurs during the drying process of an aqueous coating." (New England Society for Coatings Technology, 1982). Rust spots or stains appear soon after the coating is applied. It occurs most often under conditions of high humidity and low temperatures, conditions which slow down the rate of water loss and film forming processes.

The effect of this rust on the durability of a coating is not known. NACE Publication 6H176 on acrylic latex maintenance paints treats flash rusting as a cosmetic problem; it suggests overcoating with an additional primer layer. At a minimum, it is a barrier to market acceptance of waterborne coatings. Efforts have been directed at eliminating the phenomenon through product development and formulation (e.g. Campbell, 1978; Sullivan, 1981).

A number of compounds have been evaluated as additives for inhibition of flash rust (New England Society for Coatings Technology, 1982). Their subsequent effect on salt fog resistance and water immersion resistance relative to the additive free, parent paint was included in the evaluations. This study demonstrated that flash rusting can be controlled but, symptomatic o paint formulation, other performance measures may be degraded. Hence, there is no panacea; flash rust inhibitors must be evaluated on an individual basis.

The presence of rust in or under a primer film is undesirable. Best practice then requires waterborne coatings to be evaluated for their flash rust resistance. No standardized method is available but methods have been reported. A brief description of different flash rust tests is given in Table A-8. High relative humidity is a common feature. Based on the combination of low temperature (50°F) and high relative humidity (∿ 75%), the test procedure of Rohm and Haas is the most severe. No assessment of the relative merits of the tests in eliminating flash rusting under a variety of field conditions can be made with the information and data collected.

2.4.2.3 Early Rusting

Early rusting is closely related to flash rusting. It is observed with latex maintenance paints. It has been defined as "rust discoloration of a latex maintenance paint film which may occur within several days after the coating has dried to the tack-free stage." (Campbell, 1978).

The conditions under which early rusting has been observed are:

1. Thin paint film (less than 3 mils).
2. Cool substrate temperature (around 50°F).
3. High humidity and condensation. It can manifest itself even through a

Table A-8. Flash Rust Resistance Tests.

Source	Test Conditions	Acceptance Criteria
MIL-P-28577A(YD)	3 mils WFT; air dry 48 hrs at 73°F and 80% RH	no rust bleed through no underfilm corrosion
New England Society for Coatings Technology, 1982	5 mils WFT; air dry 1 hr. at 76°F and 95% RH; 2 hr. 75°F and 45% RH	rated by ASTM D610
Martens, Waterborne Coatings, p. 213	80°F and 90% RH	inspect for rust and underfilm corrosion
Rohm and Haas Seminar on Latex Maintenance Paints, New Orleans, January, 1982	Blast cleaned, hot rolled steel; 1.2-1.6 mil DFT; air dry 2.5-3 hrs at 50°F and 70-80% RH. A control coating is to be included in the test	pass-less than 5% rust spotting

topcoat.

These fall within the range of field conditions one can encounter in painting bridges so evaluation of waterborne coatings for early rust resistance is part of qualification.

Latex maintenance paints suffer this early rust phenomenon because of their film formation mechanism. The conditions in which early rust occur slow the rate of film formation and coalescence of the polymer particles. The partially fused polymer phase is porous and allows for the transport of water and ion salts through the coating. The continued, gradual coalescence eliminates the pores eventually.

Two procedures have been described that can induce early rusting in latex paints (Grourke, 1977). They have been used to develop formulations that eliminate early rusting. These methods are contrasted with field conditions in Table A-9. This work also demonstrated that primer-topcoat combinations must be evaluated together since topcoats can induce early rust in an otherwise early rust resistant primer.

2.4.2.4 Wet Adhesion

Wet adhesion is a term used to describe the ability of a latex paint film to maintain its "integrity" under severe exposure to water and film dislodging forces..." (Kambanis, 1981).

Test procedures used to evaluate wet adhesion are summarized in Table A-10. Wood panels are the substrate used in several; this reflects the house paint background to the phenomenon. A wet adhesion test using a steel substrate is part of MIL-P-28577A(YD) qualification. A test or qualification for wet adhesion may be most appropriate for latex paints to be used over old alkyd coatings. For latex paints over latex primers on new paints (e.g. zinc rich), exposure testing in salt spray or high humidity can be expected to provide information on wet adhesion.

2.4.2.5 Freeze-Thaw Stability

Waterborne coatings are subject to freezing but at temperatures below 32°F (normal components and additives depress the freezing points). Although water soluble (alkali soluble) paints generall are stable to freezing and thawing, late paints and emulsion are not (Monteus, 1981, pp. 46-47). Latex paints can become coagulated and emulsions separate into two distinct phases.

Qualification tests subject the paint to several freeze-thaw cycles. Acceptance is based on viscosity, stability and the absence of grit in cast films. Table A-11 contains information on some freeze-thaw stability tests.

2.4.2.6 Mechanical stability

Latex polymers are aqueous colloidal dispersions of polymer. They are intrinsically unstable so latex paints are routinely evaluated for mechanical stability. This is done in anticipation of mechanical stresses placed on these paints in operations suc as mixing, pumping, and spraying.

The mechanical stability test in MIL-P-28577A (YD) involves the continuou rotation for one week of a can partially filled with paint (one quart can, three-fourths filled). Stability is judged by comparing the tested paint with untested paint for viscosity change (within ten per cent) and presence of coagulation.

2.4.2.7 Immersion Testing

The service environment of coating on bridges is atmospheric exposure. The justification for the use of immersion type tests in evaluating properties is, then, not obvious. Latex paints are not

Table A-9. Early Rust Test Methods (Grourke, 1977)

	Laboratory Method A	Field Procedure		Laboratory Method B
(1)	Rusted hot rolled steel panels (rusted in rural atmosphere for 1 year), are commercially blasted.	Rusted, hot rolled steel, commercially blasted by contractor.	(1)	Hot rolled steel panels rusted in rural atmosphere for one year are white-metal blasted
(2)	Panels, not paints are equilibrated for 4 hrs at 50°F (10°C)/77% RH. Paints are maintained at about 72°F (22°C), except when being applied to panels.	50°F(10°C) is the lower limit of temperature recommended for application of latex paint.	(2)	Panels are equilibrated for 4 hr at 50°F(10°C) /77% RH.
(3)	First coat of primer is spray or brush applied at 1.5 dry mils in the afternoon of the first day (50°F(10°C)/77% RH).	Contractor applies first primer coat in the afternoon, after blasting.	(3)	One coat of paint is spray or brush applied at 1.5 dry mils in the morning of the first day.
(4)	Second coat of primer is spray or brush applied at 1.5 dry mils in the morning of the second day followed by 1.5 mils of latex topcoat in the afternoon of the 2nd day (50°F (10°C)/77% RH)	Contractor applies second primer coat, followed by latex topcoat, both the second day.	(4)	One coat of latex topcoat is brush or spray applied at 1.5 dry mils in the afternoon of the first day.
(5)	After 16 hrs equilibration at 50°F(10°C) /77% RH the panels are placed in the modified Cleveland Condensing Humidity Test cabinet and subjected to high moisture conditions for 24 hr.	Paint film is subjected to high moisture conditions for an extended period soon after application.	(5)	After 16 hr equilibration at 50°F (10°C)/77% RH the panels are placed in modified Cleveland Condensing Humidity Test cabinet and subjected to high moisture conditions for 24 hr.

Table A-10. Wet Adhesion Tests.[1]

Test	Panel Preparation	Wet Condition	Adhesion Test
TTP-001511	Alkyd Enamel TT-489-C on ground glass, dried 3 days, baked 2 hrs @ 200°C. Test paint dried for 48 hr.		Underwater scrubbing for 3500 cycles; film scribed
TTP-001511 Modified	As above; Embed cheese cloth in the latex film Dry for 24 hr.	Immerse in water for one hour.	Pull cheese cloth It passes if latex-alkyd interphase intact.
Wet Adhesion Abrasion Test-Interior Semi-Gloss	Alkyd Enamel TT-489-C on Leneta chart-dried 6 days-Test paint dried for 7 days.	Scrub with an abrasive soap solution to failure or 1500 cycles.	
Exterior Wet Adhesion Test	Alkyd Enamel TT-489-C on cedar siding-exterior exposure for 3 months. Two coats of test paint with 24 hr drying after each coat.	Wet panels and place them in polyethylene bag and in a freezer (-40°C) for 16 hr.	After thawing, rub film 10 times with thumb. Recycle until failure.
Moisture Blister Resistance for Exterior Paints ASTM-2366-68	Two coats of test latex paints on cedar siding with seven days drying after each coat.	Expose panels in blister cabinet.	Measure portion of panel showing blisters.
Canadian Government Test 1GP-138	Alkyd enamel 1GP-189M on white pine panels. Dry for 7 days. Test latex to dry for 2 hr.	Expose in water spray chamber with six nozzles delivering 34.2 L./hr for 1 hr.	Check blistering. Scrub for 3500 cycles.
Exterior Exposure Rural Ontario 79.5°West 44.6°North	1 coat 1GP-35 oil primer on white pine panels. Dry for 7 days. 2 coats of latex.	Exposed for six years on exterior fence. Facing south at 45° angle.	Examine for adhesion failure (peeling off, film checking).
MIL-P-28577A (YD), Section 3.4.10	TT-E-506 Enamel; later primer dried 48 hr. at 73°F and 50% RH	Paint film scrubbed while under water; 500 brush cycles at 37 cycles per minute. (Fed. Test Method Std. 141B, Method 6141)	No adhesion failure between primer and alkyd.

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[1] Note: All tests except MIL-P-78577A(YD), Section 3.4.10 taken from S.M. Kambanis and G. Chip, "Polymer and Paint Properties Affecting Wet Adhesion," J. Coatings Technol., vol. 53, no. 682, 57-64 (1981).

Table A-11 Freeze-Thaw Stability Tests.

Source	Condition	Acceptance Criteria
Martens, <u>Waterbourne Coatings</u>, p. 47	15°F for 16 hrs; 77°F for 8 hrs.	5 cycles; no excessive viscosity change
MIL-P-28577A(YD)	15°F for 16 hrs; 77°F for 8 hrs.	viscosity change less than 5 Krebs units; film on gloss panel appears the same as film from untested paint (gloss, color, grit, etc.)
ASTM D2243	15°F for 168 hrs;	evaluate 6 hrs. and 48 hrs. after removal from 15 F; measure viscosity and examine paint for gels, settling, flocculation, etc; compare film with one from control sample.

recommended for immersion service (NACE, Publication 6H176 Acrylic Latex Coatings for Resistance to Atmospheric Corrosion to Metal Surfaces). However, immersion tests do form an integral part of protective coatings testing in general so it is likely that such tests will be incorporated in qualification schemes.

Immersion testing of latex paint films in aqueous electrolyte solutions requires special precautions (Hare, 1975). It was observed that steel panels coated on both sides with a latex paint system had poorer corrosion resistance than panels coated on one side only. The test environment was a salt solution. Investigation of the phenomenon resulted in an explanation termed a "galvanic surface effect.": the uncoated panel surface or face becomes anodic in respect to the coated surface and cathodically protects the painted face.

The phenomenon did not occur if the latex painted panel was backed with coatings such as vinyls, epoxies, or phenolics.

In terms of qualification testing, this observation translates into a procedure for immersion testing in electrolyte solutions that require both sides of test panels to be painted with the test paint or the backside to be painted with a barrier type coating like a vinyl or epoxy. The electrochemical coupling of panel surfaces when immersed in the solutions also demands one panel only to be exposed in a test container.

3.0 Procurement Specifications

The particular paint used on a bridge painting job is typically the contractor's option. His choice, however, must be a system that has been qualified and approved by the State. State approval of paints on a batch-to-batch basis is a condition of product qualification, an element of quality assurance, and a requirement to be satisfied before application.

Designation of the product name or other unique product identification is sufficient for procurement since qualification requires that the same composition approved be supplied in subsequent batches. Changes in composition are treated as new products which must then be qualified.

Methods and criteria used to assure qualified product uniformity are elements of quality control and quality assurance. They are discussed in the next section.

4.0 Quality Control and Quality Assurance

The scope of this section on quality control and quality assurance includes the monitoring of materials for conformance to specifications and procedures used in the field to monitor paint application.

The definitions of quality control (QC) and quality assurance (QA) have been adopted as given by ASTM Subcommittee D01.43 on Coatings for Power Generation Facilities (Manual of Coating Work for Light-Water Nuclear Power Plant Primary Containment and Other Safety-Related Facilities, 1979, p. 179):

1. Quality Control - administration and engineering procedures employed to attain the desired level of quality assurance.
2. Quality Assurance - the verification of the conformance of materials and methods of application to the governing specifications, in order to achieve a desired result.

4.1 Materials QC and QA

This section deals with QC and QA intended to insure that the paint materials qualified and approved are the same used on a job.

4.1.1 Materials QC

There is one major QC element involved and that is the requirement of sampling and testing from each batch of paint. Included within the QC function is a determination of the number of samples per batch and a judgment of conformance based on the data collected, its analysis, and allowed tolerances.

The number of samples to be taken from a batch of paint was not included overtly in the various specifications reviewed. It was not a point emphasized in personal contacts since field procedures on actual jobs were the focus. Hence, it is not known how widely or how vigilantly statistically based sampling plans and data analysis were used. Statistical quality control methods applied to sampling and data analysis are the best technology and, therefore, should be used.

An application of statistically based sampling techniques to acceptance testing of paints has been reported (Law, 1977, 1978). It was the only reference found dealing with statistical quality control applied to paints. A detailed treatment of statistical quality control applied to concrete materials and application was also located (DiCocco, 1973). This latter report is invaluable to quality control and assurance in field painting since it demonstrates that such techniques are applicable to field environments and operations.

The need for statistically based sampling schemes and data interpretation rests in the fact that measurements are subject to variations and that no paint is exactly the same from batch to batch. Statistical methods help one to determine if the variations seen from batch-to-batch or between samples from the same batch are within "normal" limits or reflect a batch that is (likely) outside specification bounds.

One sample per batch is considered insufficient to judge conformance because a batch of paint is divided into several containers for shipment and use. For bridge paints, five gallon pails are typical so a batch of paint may be divided into several hundred containers. If a measured property deviates from a specified value, one cannot determine (with one sample) if the deviation is due to the batch of paint, variations between containers, or experimental error.

The sampling plan for paint batches split into containers discussed by Law and Anarica was:

Total Containers Per Batch	Number of Containers to be Sampled
1 - 15	3
16 - 25	4
26 - 90	6
91 - 150	8

They concluded, after analyzing historical, paint property data and applying acceptance sampling methodology, that eight samples for a lot of eight or more containers were sufficient to judge the homogeneity of the lot and its conformance to specifications (Law, 1977, p. 17). The properties used as measures of product homogeneity were viscosity, density, and fineness of grind.

The statistically based acceptance sampling scheme for high performance coatings was not within the scope or plans of this study. However, the methodology has been identified and its applicability to highway and bridge maintenance demonstrated by reference. Flexibility exists in the principles and methods of statistical quality control so that individual states can set their own criteria and interpretations.

4.1.2 Materials QA

The properties measured to establish conformance to a specification or to establish that a batch of paint is the same composition or the approved material are listed in Table A-12. Table A-12 is not at exhaustive list but represents a combination of tests frequently found. A review of the analysis of paints and paint film has been recently made (Lear, 1981a,b) in which methods of separation of components and their subsequent analysis are given.

Most specifications reviewed used physical property measurements such as solids concentration or weight per gallon or indicators of composition conformance. Infrared analysis of the binder was often included but analysis of other components (pigments, solvents) was not widely included in the acceptance routine.

The best technology in monitoring composition uniformity of approved products on a batch-to-batch basis is:

1. Do not use laboratory tests of environment performance as indicators of material conformance.

2. Sequence the analysis of paints to first establish conformance to physical properties such as solids, weight per gallon, and viscosity and then the more laborious and costly chemical analysis of composition if the physical properties are within specification limits.

3. Use a sampling scheme that takes samples from different containers so that an estimate of the uniformity of a lot of paint can be made in addition to conformance to specification properties.

4. The analysis of the paint should be done by the owner of the structure to be painted (a State DOT) or an independent laboratory.

4.1.2.1 Laboratory Performance Tests.

The variability of results obtained from laboratory performance tests like salt fog exposure precludes their use in a quality assurance program. Variances in performance cannot be attributed to the materials since many other factors can affect the performance. Examples are stability of test cabinet conditions and variability in test panels, surface preparation, and application. Experimental designs to separate the effects of these factors are not employed in routine testing so meaningful conclusions cannot be drawn from the data collected.

4.1.2.2 Analysis Sequence.

A "common sense" approach to checking conformance to a specification is to do the easier tests first. If the results of these indicate compliance, then more experience and involved analyses can be performed. This method is used by New York State DOT; the initial screening tests are viscosity, weight per gallon, and fineness of grind.

Chemical analysis of composition is done if these properties are acceptable. The procedure recommended for paints scheduled for use in containment areas of light-water nuclear power plants also uses a sequence analysis plant. (Manual of Coating Work..., Chapter 9, pp. 132-140). The tests are weight gallon, viscosity, solids by weight, fineness of grind, flash point, pot life, gloss, sag, and dry times of

Table A-12. Properties Measured to Test for Materials Conformance with Specifications

Property		Method
Solids Content		
Per Cent Solids by Weight	e.g.	ASTM D 2832 Determining Nonvolatile Content of paint and Paint Materials
Per Cent Solids by Volume		ASTM D 2697 Volume Nonvolatile Matter in Clear and Pigmented Coatings
Per Cent Pigment		Federal Test Methods Std. 141A, Method 4022 Pigment Content (Supercentrifuge)
Per Cent Vehicle		
Infrared Curve for Binder	e.g.	ASTM D 2621 Infrared Identification of Vehicle Solids from Solvent Type Paints
Chemical Analysis of Pigment	e.g.	ASTM D 521 Chemical Analysis of Zinc Dust (Metallic Zinc Powder)
Analysis of Solvents		Gas Chromatography
Viscosity	e.g.	ASTM D 1200 Test for Viscosity of Paints, Varnishes, and Lacquers by Ford Viscosity Corp.
Flash Point	e.g.	ASTM D 93 Test for Flash Point by Pensky-Martens, Closed Tester
Dry Times (dry to touch, dry hard, dry through)	e.g.	ASTM D 1640 Tests for Drying, Curing, or Film Formation of Organic Coatings at Room Temperature
Fineness of Grind	e.g.	ASTM D 1210 Test for Fineness of Dispersion of Pigment - Vehicle System

dry to touch, dry hand, and dry through. Subsequent tests of a chemical analysis nature are infrared spectra of the vehicle, solvent analysis by gas chromatography, and chemical analysis of zinc dust. Other tests are vehicle solids by weight, pigment solids by weight, and hiding power of the dry paint films.

Chemical analysis is required in the New York DOT procedure but it is optional in the procedure suggested for the nuclear power plant applications. Best practice would require chemical analysis routinely.

A minimum set of physical property measurements that are at least supportive indicators of composition stability are density (weight per gallon) and a solids concentration determination. Both of these involve simple laboratory procedures (weighing samples) that are precise and do not require data interpretation.

The density is an important property to measure since it depends on the composition of the whole paint and the density of individual components.

Solids determination can be done by weight or volume. Of the two, solids by weight is the easier. Determination of the volume solids requires data for the density of the wet paint and the solids by weight.

The flash point can be used as a coarse indicator of solvent composition stability batch-to-batch. Properties like dry times, although in principle depedent on composition, are subject to variation due to sample preparation and film conditioning. They are less precise than solids and density determination so they are supportive of composition integrity but only supplemental to solids and density measurements.

Physical properties that are indicators of product processing more than composition are viscosity, fineness of grind, and color or hiding. These too are elements of the minimum set of property measurements for material quality assurance.

Color, which is a function of the materials used, their concentration, an degree of dispersion, can be evaluated by visual comparison against a retention color chip. Instrumental measurement of color (tristmulus values, chromaticaly coordinates) is also possible.

Viscosity is also a property that is dependent on composition and the degree of dispersion of suspended material. Since paint viscosity is, in general, non-Newtonian (i.e., it depends on shear rate), and dependent on temperature, the method, and conditions used to determine viscosity must be standardized.

There is no single and reliable method to interconvert viscosity values obtained at different temperatures and with different types of viscometers. This also supports the need for dardized methods and procedures of viscosity determination.

Fineness of grind (ASTM D1210) is a coarse measure of pigment dispersion. The value obtained is dependent on a subjective judgment of an end point and consequently, it is not a precise measurement. Because of this, toleranc limits will be large.

4.1.2.3 Chemical Analysis

The chemical analysis of paint is directed at three major classification of components: the solid vehicle or binder, pigments, and solvents. Infrared analysis of the vehicle was widely referenced in the specifications reviewed. The analysis of the pigment portion was listed as a required test on a batch basis in only a few specifications. Analysis of the solvent portion was included in the recommendations for coatings in nuclear power plants and then only if the paint was suspect on the basis of deviations in physical properties or some other unspecified reasons.

Infrared absorption spectra of the film forming portion of a coating (vehicle solids) gives qualitative and quantitative information about the composition. For material quality assurance, a reference spectra of the qualified vehicle solids is needed. Acceptance criteria then include no new absorption peaks, no missing absorption peaks, and the same relative intensities among the absorption peaks. This latter criterion is quantitative while the former two are qualitative.

The need for "expert" interpretation of the infrared spectra is minimized since the spectra from paint batches are compared with a reference spectra.

One element of interpretation that remains in analyzing the IR spectra (as well as any of the test results used to establish conformance with a specification) is the assignment of deviations of relative intensities from the reference spectra to experimental error or to departures in composition. The magnitude of deviations that can be reasonably assigned to experimental error requires input based, in part, on experience and a knowledge of sources of error inherent in the method.

Qualitative and quantitative methods and applications of IR spectroscopy appropriate to paints have been presented by the Chicago Society for Paint Technology in Infrared Spectroscopy: Its Use in the Coatings Industry (Federation of Societies for Coatings Technology, Philadelphia, 1980, 896 pp.). The information therein can be applied to establishing error limits.

Standardized and reproducible film preparation procedures, film conditioning, and operation of the infrared spectrophotometer are required to minimize their effects on the recorded spectra. For such routine analysis, there is no need to interpret the spectra in terms of the chemical groups and structures associated with the absoprtion bands.

The analysis of zine dust in zinc rich systems is described in ASTM D521. This method and other qualitative and quantitative chemical analysis schemes are time consuming and somewhat archaic because of the development of instrumental methods of analysis.

Instrumental methods of pigment analysis are emission spectroscopy, atomic absorption spectroscopy, x-ray fluorescence, and x-ray diffraction (Lear, 1981 a, p. 55). These methods will give information about the element makeup of a mixture of pigments so qualitative analysis is their immediate output. Quantitative data about pigment composition can be obtained if reference blends of pigments are used. These methods are then applicable to QA for the pigment portion of a qualified paint since spectra from suceeding batches can be compared against a standard. The procedure used to isolate the pigment mixture and analyze it, of course, must be standardized.

Solvent analysis is also an element of recommended materials QA (it was, however, not explicitly required in the specifications reviewed). The method used is gas chromatography (GC). High pressure liquid chromatography (HPLC) can also be used to analyze the solvent portion of a paint.

Two procedures in GC analysis are covered by ASTM methods. In one, the solvents are first isolated by distillation to give a neat solution (ASTM E 260). In the other, the solvents are not separated from the paint but a paint sample in toto is used (ASTM D 3271). In either case, the application to materials QA is comparison with the qualified solvent blend. There is not a need to identify the individual solvents since the chromatograms are interpreted the same way as infrared spectra for vehicles: no new peaks, no missing peaks, and peak heights in the same relative ratios as the chromatagram for qualified product. This reduces the need for "expert" interpretation.

Batch-to-batch homogenity of thinners used with qualified paints was not explicitly included in the materials QA schemes reviewed. Best practice would, however, require that they be.

4.1.2.4 Waterborne Coatings.

The analysis of latex polymer based waterborne coatings is more difficult than solvent borne systems because a latex paint uses more ingredients and several of these are at low concentrations. (e.g., surfactants, thixotopic agents, and antifoam agents). Table A-13 contains a latex primer formulation taken from California DOT's work as an example (Warness, 1979, p. B-5. Substitution of a different antifoam for the one listed in Table A-13 (NXZ for Noper NDW) resulted in a film that blistered after 600 hours of salt fog exposure, whereas the paint using Noper NDW did not blister. This was taken to indicate that the waterborne paints are sensitive to minor changes in composition; hence, the need for composition confirmation. Another aspect of latex polymer systems that may need monitoring is polymer particle size distribution. Polymer size effect properties such as viscosity, and film formation, properties that impact the application and protective qualities of a latex paint.

Particle size distribution or singl value estimates of particle size can be obtained by light scattering methods, microscopic analysis, and Coulter Counter analysis,* for example.

The analysis methods discussed abov (IR, GC, x-ray) are applicable to water borne coatings but the need for additional techniques in waterborne systems such as the latex ones may arise. An in-depth study of the analytical techniques specifically needed for waterborne coatings was not within the scope of this work. In addition, the use of waterborne coatings in bridge maintenance is not yet widespread so the need and justification for special materials QA is not pressing. The point of this section is that special techniques of analysis may be needed because of the characteristics of waterborne coatings relative to solvent borne ones.

4.1.3 Determination of Materials Conformance

The above (sections 4.1.1 and 4.1.2 presented the elements of quality control and quality assurance. The work involved, apart from the QC aspects of establishing the number of samples and interpretation of results in terms of specification tolerances, is laboratory oriented. The range of sophistication in the QA methods is wide: simple, direct paint property determination to quantitative, instrumental chemical

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*Coulter Counter, Coulter Electronics, Inc., Hialeah, Florida 33010.

Table A-13. Latex Primer Formulation (Warness, 1979, p. B-5)

Component	Parts by Weight	Parts by Volume	Role
Mix at low speed:			
water	135.0	16.21	
Tamol 731	17.0	1.93	dispersing aid
Triton CF-10	3.0	0.34	surfactant
Nopco NDW	2.0	0.27	antifoam
ethylene glycol	28.0	3.02	
Dowicil 75	0.6	0.05	
R&R 551	2.0	0.24	dispersing aid
Grind under high shear, 15-20 minutes:			
Red Oxide R-4098	90.0	2.10	
Zinc yellow Y5390	15.0	0.52	
Mica 325	33.0	1.41	
Snoflake	200.0	8.87	
HEC CP-4400	1.25-1.35	0.11	thixotrope
Zinc Phosphate 317	30.0	1.14	
Mix in under low speed (let down):			
Nopco NDW	1.0	0.13	antifoam
Arolan X820-W49	504.0	57.27	latex polymer
Ammonia	7.0	0.93	
Butyl Carbitol	6.0	0.76	coalescing aid
Butyl Carbitol Acetate	6.0	0.74	coalescing aid
Aroplay 1271	25.6	3.07	
Tritan CF-10	1.4	0.16	surfactant
	1107.8	99.27	

analysis. The latter requires expensive equipment, trained operators, and, in general, experienced interpretation of results. The recourse of referencing analytical results for a batch of paint to the results obtained with the qualifying composition minimizes the need for interpretation, but does not eliminate it.

Each State DOT or other government unit involved with bridge maintenace and procurement of paints cannot afford the cost of equipment purchase, maintenance, and operation. Several specifications accept a certification of composition integrity from the manufacturer in lieu of batch analysis, reflecting this. This however, cannot be recommended as "best practice" since such a certification is dependent of the quality control and assurance program of each manufacturer (his QC and QA criteria are not likely to be known or to be made known for proprietary reasons).

If a State cannot do the QA on the paints itself, the work should be done by an independent laboratory. It can provide the chemical and instrumental analysis along with interpretation. The State can decide on the acceptability of a batch of paint with this information.

4.2 Application Quality Control and Quality Assurance

Quality control and quality assurance for the application of paints in the shop and in the field have two major divisions: surface preparation and paint application. Surface preparation is discussed first.

4.2.1 Surface Preparation QC and QA

The QC for surface preparation is simple: prepared surfaces must be approved by the inspector or the project engineer before paint is applied. This practice defines completion of surface preparation on some segment of a bridge or piece of steel e.g. section of beam between two stiffeners) as a hold point: painting may not start until approval is obtained. Since the dependence of a paint's performance on the quality and level of surface preparation is axiomatic in corrosion protective coatings technology, this is an essential element in QC.

The minimum degree of surface cleanliness for zinc rich coating systems is near white as defined in SSPC-SP10:

> "A Near-White Blast Cleaned Surface Finish is defined as one from which all oil, grease, dirt, mill scale, rust, corrosion products, oxides, paint or other foreign matter have been completely removed from the surface except for very light shadows, very slight streaks, or slight discolorations caused by rust stain, mill scale oxides, or slight, tight residues of paint or coating that might remain. At least 95 percent of each square inch of surface area shall be free of all visible residues, and the remainder shall be limited to the light discoloration mentioned above."

The near-white surface condition defined as NACE No. 2 is equivalent to SSPC-SP10. There is support in the technical literature for commercial quality blast cleaning (SSPC-SP6) as the minimum degree of surface cleanliness for zinc rich coatings (see, for example, Siebert, 1974; Tator, 1974; Montague, 1974).

Data were not available to investigate the relative merits of near-white surface cleanliness and commercial surface cleanliness. The selection of near-white as the best technology is a fail-safe position reflecting the narrower range of surface conditions within the scope of the near-white definition than within the commercial blast definition. This, in part, is illustrated in Figure A-5.

In practice, there will be a distribution of "percent area" clean metal so blast cleaning graded near-white will have some areas less than 95 percent clean metal. Correspondingly, commercial blast jobs will have areas less than 67 percent clean metal. Hypothetical distributions are shown in Figure A-5. The extent of the deviations depend on factors such as (1) the adequacy of visual comparison standards in reflecting the intent of the surface cleanliness definition and (2) the interpretation of the definitions and visual standards used by the project engineer and inspector on a job-to-job and day-to-day basis.

The deviations or distribution of surface cleanliness over a section of a bridge and the whole bridge reflect "normal" practice in achieving a specification goal. The wider range of surface cleanliness expected for commercial quality than near-white is interpreted to mean a wider range in performance over commercial quality blast cleaned surfaces than near white. This is contrary to improvement in reliability. Hence, the choice of near-white.

The surface texture imparted to metal when abrasviely blast cleaned is another element of surface preparation and quality. The profile or anchor pattern value commonly found is in the range of one to two mils (.001-.002 inch), (.00254-.0508 mm). This is a nominal range since the value depends on the method used and the amount of surface area sampled. However, this range can be accepted as best practice.

Quality assurance for surface cleanliness is visual comparison of the prepared steel against a photographic standard or sample metal coupon.

The photographic standards from SSPC, SSPC-Vis 1, were used as the reference standards in almost all the specifications and literature reviewed. NACE uses metal coupons encased in plastic to demonstrate the different qualities of sandblasted steel (NACE standard TM-01-70).

These standards are best considered examples of the different degrees of blast cleaned surface quality. Precautions listed by both SSPC and NACE to be considered in applying these standards to inspections are listed by both SSPC and NACE:

1. Different steels can give different appearances.
2. The nature of the surface before surface cleaning can change the final appearance e.g. mill scale, rust, corrosion pits, and paint).
3. Profile can change appearance.
4. Differences in illumination of the standards and the actual work can affect appearance.

The actual adjustments to be made in applying these standards to the inspection task are left to the judgment and interpretation of the project engineer and inspector.

Best practice in inspecting surface cleaning for conformance to specifications is twofold. First, judgment of surface cleanliness is to be made in re-

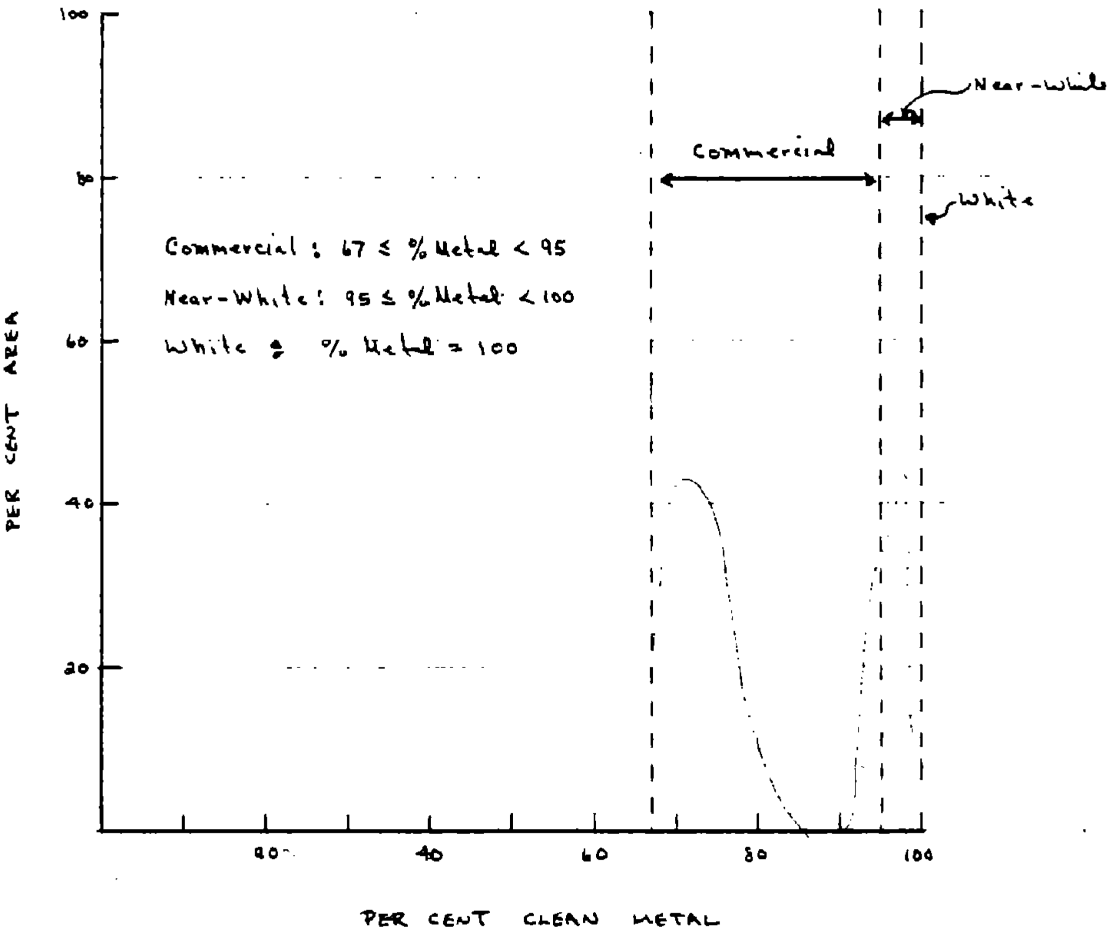

Figure A-5. Graphical Illustration of Abrasive Blast Grades of Surface Cleanliness.

ference to the definition of the degree of cleaning; visual standards are aids making the judgment. Second, visual standards should be prepared for each job using the actual structure or steel to be used. This will not eliminate all the adjustments that have to be made in applying visual standards to the inspection task but the standards will be more representative and, thereby, minimize arbitrariness in the adjustments. Photographs of sample prepared areas can be taken to serve as inspection standards. Support for this position can be found in a case history report offered by Tator (Tator, 1978). Disagreement between the contractor and inspectors on the quality of surface preparation was traced to the limitations of blanket visual standards (e.g. SSPC-Visl) applied to a specific job. The conflict was resolved by preparation of a sample area of the structure according to the written description of the degree of surface cleaning. This area then became the inspection standard for the job.

Best practice demands that the visual standards selected for a job actually be used at the time of inspection. Although this is an obvious point, observations made during shop and field site visits in the course of this study indicated that this was not done. Reliance was placed on memory of what the surface was to look like. The standards were looked upon as a device to resolve differences in interpretation between the inspector and contractor. However, disagreement is most likely to occur when the contractor feels more cleaning than required is being asked by the inspector. This protects the contractor from over cleaning; it does not protect the owner from under cleaning.

Additional reinforcement for the use of visual standards at the time of inspection is found in a study reported by Harris (Harris, 1969):

> "The effectiveness of using limit samples (a limit sample is one which demonstrates a rejection limit for some quality feature) was illustrated in a study of the inspection of glass panels for the fronts of television picture tubes. Inspectors had been accepting or rejecting these panels in terms of their mental image of acceptable versus unacceptable panels. After establishing an inspection procedure which employed the use of limit samples, inspection accuracy increased 76 percent. In this procedure several limit samples were employed by an inspector, one for each type of defect."

Although photographic standards or decision aids are not strictly limit samples, they can represent the defects that distinguish acceptable quality from unacceptable quality. Metal coupons used by NACE to supplement the written description of the different degrees of blast cleaning are limit samples.

With the vigilant use of reference standards, either photographic or limit samples, one can expect better quality surface preparation. In effect, the width of the distribution of percent clean metal (Figure A-5) will be reduced.

There are several methods available to measure the surface profile. Three methods are visual comparison against a set of reference samples (e.g. Keane-Tator Surface Profile Comparator), a depth micrometer, and replica tape coupled with a micrometer (Tator, 1981).

No attempt was made to establish the "best" method of profile measurement. A comparison has been made by SSPC (Keane, 1976). Methods of measuring profile in the field studied were depth micrometers, replica tape, magnetic gages (fixed probe type), and the Keane-Tator optical comparator. Using an optical microscope as the referee method of measuring profile heights, it was found:

1. Replica tape with peak heights measured with a micrometer agreed the best with optical microscope measured peak heights.

2. Depth micrometers required the addition of a correction factor to readings to agree with peak heights obtained with the optical microscope.

3. Magnetic gages (fixed probe type) require calibration to give results that agree with the peak height values from the optical microscope; calibration is needed with each type of abrasive used.

4. The optical comparator is a subjective method; no quantitative comparison with the optical microscope was reported.

Overall, it was concluded that the methods were sufficiently accurate to identify large departures from recommended profiles that are associated (based on laboratory tests) with performance degradation.

Best practice for field and shop blast cleaning is to actually make determinations of profile. This inspection task is abused and ignored, however, based on the limited site visits made. Information or guidelines to be used in establishing the number of measurements of profile and manipulation of the data obtained was not found. The profile wanted or given in a specification must be qualified by the method of measurement to be used since different values for the same surface are obtained with different methods.

There are two other inspection elements associated with surface cleaning. Both reflect a concern about oil and grease contamination of the surface. Sources of this contamination are oil and grease from the pressurized air supply and contamination of the abrasive through recycling. Both of these are part of a general body of information referred to as "good painting practice" collected in guidelines like SSPC's Steel Structures Painting Manual, Volume 1 Good Painting Practice (Chapter Four and Five, Industrial Maintenance Paintin (P.E. Weaver, National Association of Corrosion Engineers, 1973), and ASTM D 3276 Guide for Paint Inspectors. Thes concerns apply to paints in general and are covered in the guidelines cited; the are not discussed here. Because high performance coatings and waterborne coatings are commonly characterized as having a lower tolerance to deviations from "good practice" then oil and oleoresinous type coatings (a premise of this research study), adherence to these practices is essential for reliability.

4.2.2 Application Quality Control and Quality Assurance

The quality control and quality assurance aspects of paint application are organized here into three groups. One is associated with climatic conditions and substrate conditions. These are external to the painting process. The second group is a collection of things dealing with the handling and application processes themselves. The last group are end result features, i.e., measures of the quality of the paint film applied.

Quality control for any of these is essentially the broad requirement for project engineer or inspector approval of whatever is done at the job site. This administrative function is tracked through documentation such as project diaries, work logs, and daily inspector reports.

The set of functions and tasks that comprise quality assurance are well established and presented in various guidelines for inspectors. Again, these are reflections of "good painting" practices translated into inspection tasks. These tasks are also the procedures the paint applicators need to follow; the inspection function is to confirm that they are followed.

The elements of "good painting" practice can be found in:

1. ASTM D 3276 Standard Recommended Guide for Paint Inspectors.

2. "Durability of Coatings Applied to Steel Structures", Report No. FHWA-WV-80/005, pp. 57-90 (May, 1980).

3. Steel Structures Painting Manual, Vol. 1, Good Painting Practice, Chapter Four "Practical Aspects, Use, and Application of Paints," and Chapter Five, "Inspection", Volume 2, Systems and Specifications, Section IV, Paint Application Specifications." (1979 printing).

4. Industrial Maintenance Painting (4th Edition, National Association of Corrosion Engineers, 1973), Chapter 10, "Application" and Chapter 11,"Inspection".

5. Structural Painting, A.L. Dunn, ed. (Louisiana Department of Highways, October 1976, 206 pp.)

Reference to these guidelines and others (by extrapolation) as housing elements sufficient to define a QA program for high performance coatings at firsthand might appear superficial. But review of the guidelines shows them to be broad in scope and generalized enough to cover all types of paints. For example, the need to mix a paint prior to use to homogenize it and dispose any settled pigment is applicable to a red lead and oil primer as well as a zinc-rich primer. The consequences of not mixing the paints "properly" may be different but these do not change "good practice" dictums.

4.2.2.1 QA for Climatic and Substrate Conditions

Water and substrate conditions that can affect paint application and film formation are summarized in the variables of air temperature, humidity, steel temperature, surface moisture, and wind velocity. The range of values that generally are cited as acceptable for field application of paints are given in Table A-14. For waterborne coatings, especially latex paints, the minimum ambient temperature is better approximated at 50°F.

Specific conditions for a particular paint are usually covered by "...according to the manufacturer's recommendations." Coatings applied under these ranges of conditions are, in principle at least, to have equivalent protective properties and durability.

Some deleterious effects anticipated in operating outside the range of "acceptable" climatic and substrate conditions are:

1. Solvent retention (low temperatures)

2. Extended drying time or reduced extent of core (low temperatures)

3. Bubbling, blistering, skinning, rapid solvent loss with impariment of film formation (high temperatures and wind speeds).

4. Reduced adhesion (high temperatures, presence of moisture surfaces, dust from blast cleaning and overspray)

5. Runs, sags (high temperatures, low temperatures).

Table A-14. Range of Climatic and Substrate Conditions Considered Acceptable for Painting.

Condition	Range
Ambient Temperature	$40 - 95^{\circ}F$
Relative Humidity	$\leq 85\%$
Wind Speed	< 15MPH
Substrate Condition	
Temperature	5 Fahrenheit degrees above dew point with temperature increasing; less than $120^{\circ}F$
Moisture	No condensation, not wet
Cleanliness	Free from dust from blast cleaning, force of overspray, dry spray; no rust

A few of these defects are easily detected (e.g. runs, sags, blisters) and sufficient in themselves for rejection. Others (e.g. degree of cure, solvent retention, reduced adhesion) are not as easily detected or obvious; their subsequent effect on coating durability is not known in a quantitative sense. To illustrate this, consider the case shown in Figure A-6.

Figure A-6 represents an adhesive strength "number line" divided into two segments labelled pass and fail. This is a generalization of tape adhesion type tests in which degrees of film removal are ignored. The two paints "A" and "B" on the line represent the adhesive strength values for the same coating but applied under different conditions (e.g. presence of moisture on the surface). A tape adhesion test (hypothetical) does not differential the adhesion of the two coatings. Intuitively, however, one expects the durability of coating "A" to be less than "B" because weathering and corrosion processes are expected to degrade adhesion and "A" is closer to this failure paint when put into service.

Measurement of the air temperature, humidity, metal temperature, metal surface dryness, and wind speed must be done at the job site periodically during painting. One cannot rely on weather data reported for a general region (especially when conditions are near the limits of the acceptable range) since variations in local climatic conditions occur.

Determination of the metal temperature, dew point, and freedom of the metal from condensation are, perhaps, more important than the determination of ambient conditions (they are, however, not independent) since these will be subject the most to local variations and lag behind changes in ambient conditions.

Instruments used to measure climatic and substrate conditions are reviewed in the guidelines listed above as well as in:

1. D.M. Berger, "The Role of Today's Coatings Inspector," American Painting Contractor, Industrial Maintenance Painting Section, June, 1977, pp. 2-4, 6-8, 10-11.

2. Tator, K.B., and Trumber, K.A., "Coating Inspection Instruments: Types, Uses, and Calibration," Modern Paint and Coatings, vol. 76, no. 11, S4-58 (1981).

3. Tator, K.B and Trumber, K.A. "Inspection Tools," American Painting Contractor, Industrial Maintenance Section, Ocotber 1981, pp. 2-5, 8, 10, 12-14, 16-25.

The above concentrates are conditions at the time of paint application. Climatic conditions during the film forming and curing period can, of course, affect the coating and its durability (e.g. early rusting). This general problem, in practice, is left to the judgment and discretion of the project engineer and inspector and is dependent on experience and input from the coating's manufacturer. Temperature below freezing, rain, or condensation within the first sixteen to twenty-four hours after paint application are suspect conditons. They should trigger a more thorough inspection procedure than that employed routinely.

Film properties such as hardness and adhesion can be used to monitor the progress of film formation; their departure from expected behavior can be used to help decide if weather conditions

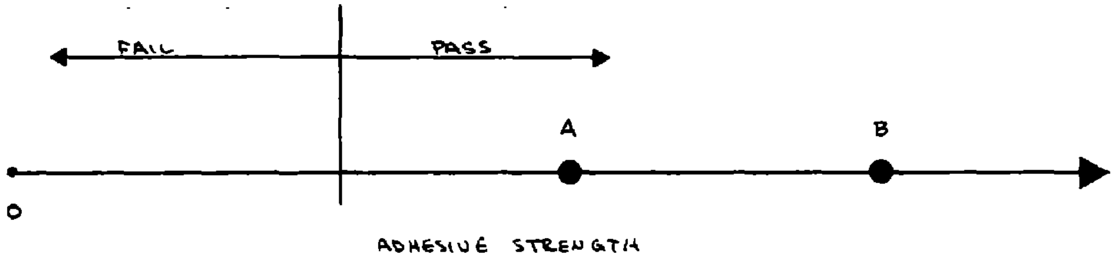

Figure A-6. Adhesive Strength Number Line.

have detrimentally impacted the coating.

4.2.2.2 Quality Assurance for Paint Handling and Application

QA for the handling and application of paints is organized, for this discussion, into three categories: mixing, equipment operation and paint deposition, and scheduling.

Best recommended practice is inspection of the mixing and thinning of paints to confirm that the correct materials are used and in the correct proportion. This constitutes a QA check in integrity. It is particularly important in multipackage paint systems like epoxy-polyamide zinc rich primers, for example. The packaging of multicomponent paints should be such that whole containers for each component are used to get the ratio of components needed.

The high proportion of zinc dust in zinc rich paints requires close attention to proper mixing ratios. Excess zinc dust levels can be expected to manifest themselves through poor film forming properties (adhesion and cohesion), and, therefore, may be detected in the inspection of the applied film. Deficient zinc dust levels are not expected to be reflected in initially poor film qualities, however. Performance is expected to degrade but the time frames to detect this are too long to be useful.

End points that an inspector can use to help confirm that mixing and thinning of paints have been done properly are homogeneous color and appearance, lack of sediment in containers, viscosity, and examination of material retained in straining paint during transfer to pressure ports. Again, these all are elements of good painting practice applicable to paints in general.

The amount of thinning of a paint is difficult a priori to quantify or to limit since it is one method that a painter has at his disposal to get a paint to work under a variety of field conditions. Manufacturers offer recommendations but these are not absolute bounds since the manufacturers expect and rely on adjustments made by the painter. This does not remove thinning operations from the list of inspection items, however. Documentation of the amount and type of thinner and resultant viscosity is to be maintained.

General guidelines list inspection of paint application equipment (oil and water traps, pot and gun pressures, hose length and diameter, compressor capacity, etc.) as within the scope of QA in paint application. The need and propriety of check performed on oil and water traps is contamination, the consequences of which may not be detectable in the visual examination of applied films. Concern about hose length and diameters includes settling and segregation of components which can yield deposited films of a different composition than mixed.

Operating pressures for spray equipment have a range of values one can label "typical." These are based on coating manufacturer's recommendations, equipment manufacturer's recommendations, or experience. The value of inspection or having a predetermined range of values is vague since pressure and flow rate adjustments, like thinning, are best considered the realm of the painter. End point criteria reflecting the quality of the deposited film (color uniformity, freedom from defects like runs, sags, or pinholes, leveling, gloss uniformity, etc.) are best used to judge the application process.

One application process that stands out for zinc rich coatings is the need for continuous agitation of the paint while in the pressure pot. The high density of zinc promotes faster settling of the dust relative to the settling rate of other particulate paint components, in general. Continuous agitation counteracts this. The consequences of not maintaining agitation are similar to composition deviations discussed above: films of poor adhesion and cohesion with excessive zinc concentrations and degradation of galvanic protection in vehicle enriched films. Tator and Ginsberg have also discussed this point (Tator, 1976, p.10; Ginsberg, 1981, p. 138).

Application of paints within an acceptable time "window" falls within the domain of QA. Here, the schedules reflect the elapsed time between surface preparation and coating application and elapsed time between application of different coats.

Abrasively blast cleaned surfaces are to be painted before rust can develop or before the surface becomes contaminated. For the near-white surface condition, the maximum allowed time is twenty-four hours before recleaning is required. Preferred timing, however, is within eight hours. Inspection of the cleaned metal for rust and surface contaminants (e.g., blast cleaning dust, salts from ocean water spray) is still required within the allowed time period.

Time windows for successive paint applications, either the same paint or a different one, reflect the "dry to recoat" concept. Minimum time values reflect concern about film formation interference between the layers due to prolonged solvent retention, stress development, and running and sagging, for example. Maximum times reflect, at least partly, the potential for surface contamination or, in the case of cross-linking systems, decreased intercoat adhesion. As was the case with surface preparation, inspection at the time of application is still required to establish that a "dry-to-recoat" condition has been achieved or surface cleanliness has been maintained. Recoating schedules suggested by the paint manufacturers are used to roughly gage successive paint applications.

Techniques found that are used to assess the cure or drying of paint films were coin hardness, pencil hardness, and adhesion (tape, knife). The merits and reliability of these methods is not known, however. Their use is part of field practice and lore.

One other scheduling task in paint application is the monitoring of pot life of reactive systems like epoxy - polyamides and some zinc rich coatings. There are two aspects to pot life. One is the increase in viscosity with time that limits the sprayability. This is the most practical and obvious field criterion defining pot life. Coating manufacturers list pot life value for their materials but the values are not absolute since they are dependent on temperature and the quantity of mixed material.

Thinning of mixed paints to counteract viscosity increases is the other aspect to pot life. The acceptability of such a practice is dependent initially on the paint manufacturer's recommendations. Its impact on the performance of the paint is largely unexplored, especially in qualification tests.

Air and airless spray are the methods used to apply high performance coatings. Application by brush is allowed but only in cases where the surface is inaccessible to spray application. This is especially true for zinc rich coatings. Neither air spray nor airless spray could be selected as a preferred application method based on the findings of this research study.

There is some discussion in the technical literature about air bubbles formed and trapped in coatings when applied by spray techniques. For example, Bayliss and Bray concluded that "modern" synthetic polymer based coatings (e.g. polyurethane, chlorinated rubber) dry too quickly to allow air entrained in a film to escape. This is independent of air or airless spray application (Bayliss, 1981). McKelvie identified the deposition of a full coating layer thickness in one application by airless spray as a factor in air entrapment (McKelvie, 1981). It is not clear if this is controllable by the operator (e.g., deposit thinner films, addition of thinner or limited by inherent deposition characteristics of airless spray. Beitleman suggests that wet film thickness per application with airless spray be defined by the onset of air entrapment (Beitleman, 1977). It should be noted that the air bubbles of concern are those not normally detectable by visual examination of a coating. Bubbles visible at the surface are sufficient evidence for rejection or acceptance of a paint job. Air bubbles within the coating layer, in effect, reduce the amount of protective material and are sites for collection of water and other corrosive materials. The extent to which such defects occur in actual practice and their effect on durability and service life of coatings relative to ones that are void free is not known.

An examination of the morphology of paint films deposited by air spray and airless spray at different initial wet film thicknesses and at different times between coats and formed under different temperatures, humidities, and simulated wind speed conditions is planned in a phase II proposal. The relationship between the different film morphologies (if any) and corrosion resistance properties will be investigated by salt fog and condensing humidity exposures in this proposed work.

4.2.2.3 Quality Assurance for Applied Films

The measures of quality for a paint film are film thickness, film thickness uniformity, color and gloss uniformity, adhesion, and the extent to which it is free of defects like runs, sags, and pinholes.

Color and gloss uniformity as well as the presence of film defects are subject to visual examination. The acceptance criteria found in specifications for film defects were not specific or defined; the criterion was "not excessive." Hence, the frequency and spatial extent of defects that are allowed is subjective and arbitrary. Although it is conceded that the application of a defect free film under field conditions is not possible, the limit on what is acceptable and the consequences of the defects on service life are not known. Acceptance is left to the judgement and experience of the project engineer and inspector.

A film defect of concern in zinc

rich paints is the deposition of dry spray and subsequent (potentially) application of other paints over it. The phenomenon, of course, can occur with other types of paints. It is attributed to the drying of the atomized paint before it is deposited or drying to such an extent that flow and leveling into a film are impaired. Some dry spray is due to overspray. Best practice requires removal of dry spray and overspray (e.g. by sanding with aluminum screening) before other paints are applied. Problems or failures associated with painting over dry spray are adhesion degradation and reduction in galvanic protection since the zinc dust becomes encapsulated in vehicle, isolating the zinc dust.

Pinholes in paint films are sites of early corrosive attack and coating failure. For non-conductive coatings (i.e., other than zinc rich coatings), electrical holiday detectors are available that can be used to locate pinholes. However, for bridge coatings, such devices are not used. Instead, visual examination for pinholes prevails. This probably reflects common practice for coatings used in atmospheric exposure; holiday detection is required (usually) to establish a pinhole free state for coatings to be used in immersion service.

The need to have zinc rich coating films free of pinholes is a difficult question to answer since the mechanism by which they protect steel in corrosive environments is different than that of other types of paint films. The problem is compounded by the porous nature of zinc rich coatings. The pores, depending on the magnification used to examine films, may be interpreted as pinholes.

An argument, by way of example, is made for not requiring zinc rich coatings to be pinhole free ("... no excessive pinholing...") even for pinholes detectable without magnification (Mallon, 1980). The argument is based on the galvanic action of the zinc rich coating, "throwing power" (the ability of the zinc coating to galvanically protect steel at a distance), and the generation of zinc corrosion products that fill in pores and, presumably, pinholes. However, one case of pin-point rusting in an organic zinc rich film was found in the course of analyzing field failures for this study.* The pinholes were detectable at 10X magnification, the primer was not topcoated during the time that the rust developed. Based on the corrosion protective mechanism given above, this rusting should not have occured.

Because there are so many factors, vagories and unknowns in field application of coatings and subsequent service life, it cannot be considered best technology to allow pinholes that are visible to the unaided eye in zinc rich coatings.

Adhesion of coatings to steel and to each other is also a measure of the quality of a painting job. The methods used to check adhesion vary from cutting and prying at the coating with a pocket knife to tensile pull test units that give quantitative estimates of adhesive strength (e.g. Elcometer adhesion tester). Tape adhesion tests are common in this application. Acceptance criteria are referenced to the level of adhesion expected based on laboratory testing and qualification as well as

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*Project No. 23-01-08, Fulton Street Red River Bridge, Alexandria, LA experience. The test gives basically a pass or fail result. The number of spots to be tested for adhesion and interpretation of results is not explicitly defined.

Application of adhesion tests are complicated by the fact that adhesion can improve with time before reaching a value representative of a fully "dry" or "cured" coating. This time can vary from overnight to a month, reflecting the effect of ambient conditions and substrate conditions as the rate of film formation.

Dry film thickness of individual coating layers and the total coating system are quantitative measures of paint application quality. The acceptance criteria are that the thickness fall within the sepcification thickness ranges.

Wet film thickness is not considered a necessary part of a QA program, at least from the owner's standpoint, because the protection is in the dry film thickness. Wet film thickness has more meaning to the painter since it can provide an early feedback on the likely dry film thickness if the volume solids are known. It forms a part of the painter's QA program. However, the loss of solvent between the gun and steel, the loss of solvent in the time elapsed between paint deposition and wet film thickness measurement, and thinning combine to make wet film thickness data too imprecise to use in the owner's QA.

The importance of achieving specified film thickness rests in the general experience that performance (salt fog resistance, natural exposure resistance, service life) increases as film thickness increases as long as no sags, mudcracking or other gross defects are encountered. For oleoresinous paints, there is evidence that this dependence is linear with a twenty month increase in service life expected for each mil increase in paint thickness (Keane, 1969). Assuming that a linear dependence is valid for high performance coatings, one would expect a longer service life for high performance coatings than oleoresinous ones at equivalent thicknesses and a greater increase in service life per unit film thickness increase. This is illustrated in Figure A-7. In terms of reliability then, i.e., achieving the performance level expected, control of film thickness is more critical for high performance coatings than oleoresinous coatings.

The language in the specifications reviewed required that no part of the structure have a film thickness less than the minimum specified value. The interpretation and implementation of this generally was that the average film thickness from a set of measurements be within the specified range. In addition, an absolute minimum for any one measurement is invoked to guard against low film thickness deviation that might be masked in the average thickness by high side deviations.

Most specifications emphasize achievement of a minimum film thickness. Deviations beyong the maximum specification thickness (if given) are not explicitly part of acceptance criteria. An exception here is the guidelines developed by ASTM Subcommittee D01.43 on Coatings for Power Generation Facilities; Table A-15 reproduces its guidelines on minimum and maximum film thicknesses). However, thick films, especially those applied in one application, can be expected to affect properties. Prolonged drying and solvent retention are obvious effects but long term effects on adhesion, internal stress, and service life in general are not known. Hence, upper limits on film

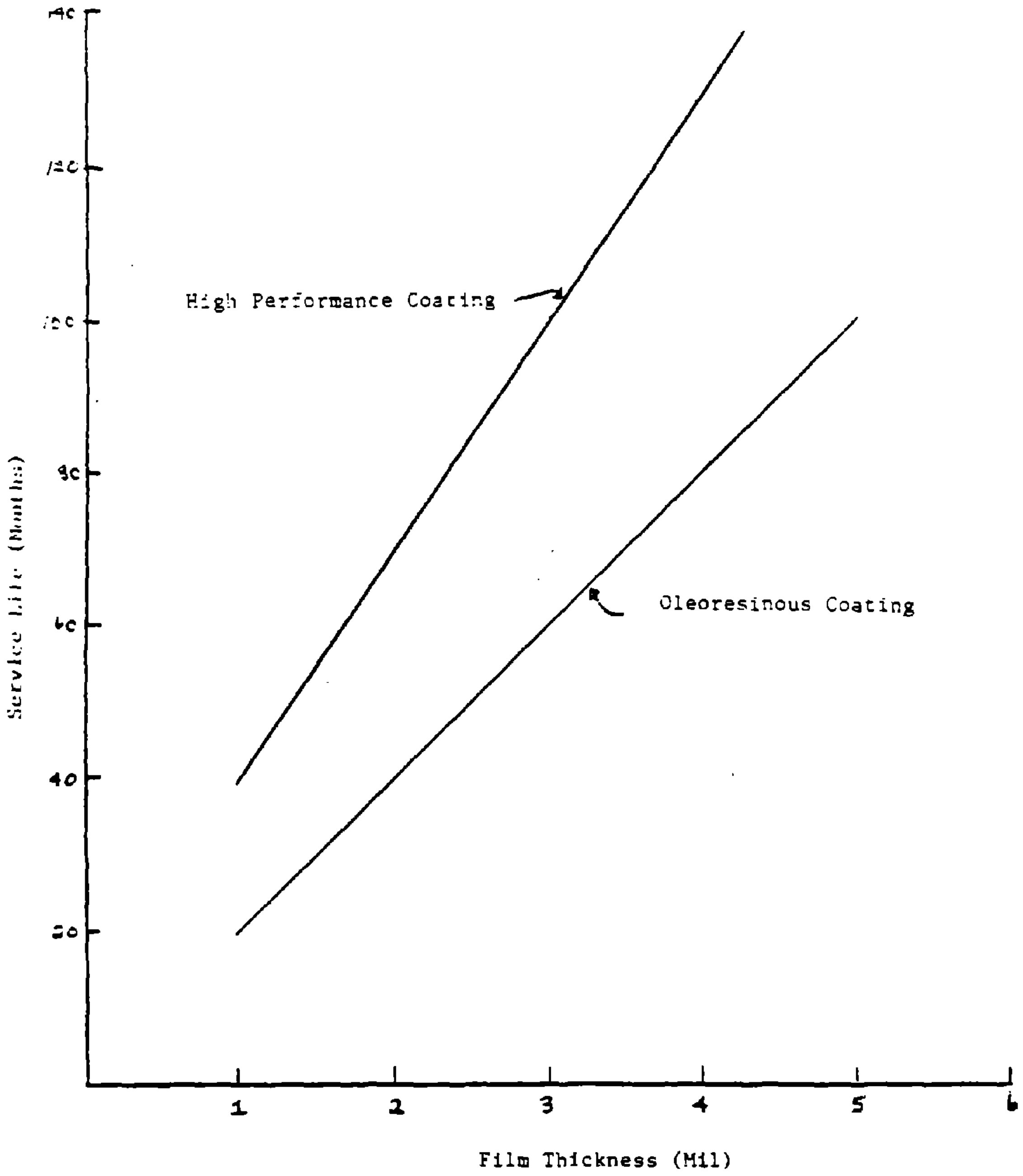


Figure A-7. Hypothetical Performance-Film Thickness Relationship.

Table A-15. Film Thickness Tolerances Recommended For Paints in Nuclear Power Facilities.

Specified Film Thickness		Spot Test Minimum		Maximum Average Film Thickness		Spot Test Maximim	
mils	(μm)	mils	(μm)	mils	(μm)	mils	(μm)
1.0	(25)	0.8	(20)	2.0	(50)	3.0	(75)
2.0	(50)	1.6	(40)	4.0	(100)	5.0	(125)
3.0	(75)	2.4	(60)	6.0	(150)	7.0	(175)
4.0	(100)	3.2	(80)	7.0	(175)	8.5	(213)
5.0	(125)	4.0	(100)	8.0	(200)	9.5	(238)
6.0	(150)	4.8	(120)	9.0	(225)	10.5	(263)
7.0	(175)	5.6	(140)	10.0	(250)	11.5	(288)
8.0	(200)	6.4	(160)	11.0	(275)	12.5	(313)
10.0	(250)	8.0	(200)	13.0	(325)	14.5	(363)
15.0	(375)	12.0	(300)	20.0	(500)	23.0	(575)
20.0	(500)	16.0	(400)	26.0	(650)	29.0	(725)
25.0	(625)	20.0	(500)	32.0	(800)	36.0	(900)
30.0	(750)	24.0	(600)	38.0	(950)	42.0	(1050)
35.0	(875)	28.0	(700)	44.0	(1100)	48.0	(1200)
40.0	(1000)	32.0	(800)	50.0	(1250)	55.0	(1375)
50.0	(1250)	40.0	(1000)	62.0	(1550)	68.0	(1700)
60.0	(1500)	48.0	(1200)	74.0	(1850)	81.0	(2025)

thickness need to be considered in designing a QA program.

Procedures for determining the conformance of paint film thickness with specification requirements that are considered good practice are SSPC-PA2-73T Method for Measurement of Dry Paint Thickness With Magnetic Gages, Materials Procedure 708.40.00, procedure for the Determination of Structural Painting Film Thickness (West Virginia Department of Highways, Materials Control, Soil, and Testing Division), and Section 560-7.6 Thickness of Coats of Florida Department of Transportation Standard Specifications for Road and Bridge Construction 1979.

The procedure from West Virginia Department of Highways is in Figure A-8. The SSPC procedure is:

> "Make five (5) separate spot measurements (Section 2.2) spaced evenly over each section of the structure 100 square feet (9.3 square meters) in area, or of other area as may be specified. The average of five spot measurements for each section shall not be less than the specified thickness. No single spot measurement (average of three readings - Section 2.2) in any section shall be less than 80% of the specified thickness. Single gage readings of the three readings which are averaged to produce each spot measurement may overrun by a greater amount" (p. 122D, Steel Structures Painting Manual, Vol. 2, Systems and Specifications, 1979 printing)

Spot measurements are the average of three gage readings taken in a small contiguous area.

Florida DOT requires thickness measurements at a frequency of one per twenty-five square feet with each measurement within specification limits. The frequency is increased if a low film thickness is found in order to "map out" the deficient areas.

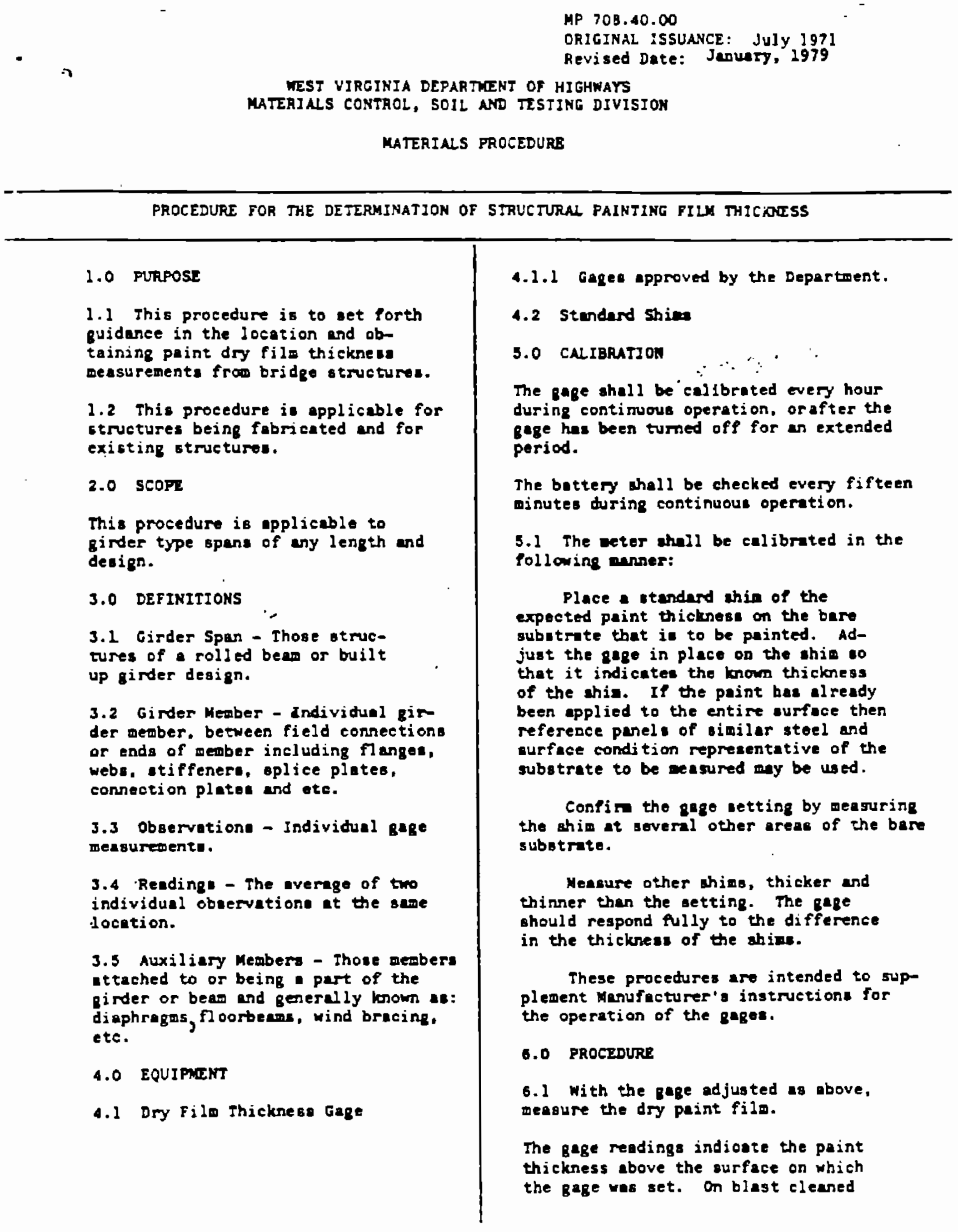
These procedures are considered goo practice because they identify the frequency of measurements and the criteri to be applied in determining acceptability. This is in contrast to other practices found and observed in which the number of measurements to be made was left to the discretion of the inspector.

The proper use of film thickness gages (handling, calibration to compensate for surface profile effects, edge and corner effects on magnetic gages, etc.) are covered in the general good painting practice guidelines cited previously. These supplement the operatio procedures supplied by the gage manufacturer.

The conformation of film thickness should be emphasized in any QA program The data are qualitative and therefore are not dependent on subjective judgement and experience of acceptability. In principle, the film thickness data can be rechecked so that differences b tween a contractor's data and an inspector's data on film thickness can be resolved. Film thickness conformance also is the last step in a QA program; i is the last chance to check quality before final acceptance.

5.0 Coating Contract Provisions

The original research plan for reviewing contracting practices include analysis of contracts for the paintin of bridge structural steel as well as structural steel for water tanks, ships, and power plants. The majorit of contracts actually reviewed were for bridge painting but, based on the few contracts for painting other type of structural steel obtained and reviewed, there are no major difference



MP 708.40.00
ORIGINAL ISSUANCE: July 1971
Revised Date: January, 1979

WEST VIRGINIA DEPARTMENT OF HIGHWAYS
MATERIALS CONTROL, SOIL AND TESTING DIVISION

MATERIALS PROCEDURE

PROCEDURE FOR THE DETERMINATION OF STRUCTURAL PAINTING FILM THICKNESS

1.0 PURPOSE

1.1 This procedure is to set forth guidance in the location and obtaining paint dry film thickness measurements from bridge structures.

1.2 This procedure is applicable for structures being fabricated and for existing structures.

2.0 SCOPE

This procedure is applicable to girder type spans of any length and design.

3.0 DEFINITIONS

3.1 Girder Span - Those structures of a rolled beam or built up girder design.

3.2 Girder Member - Individual girder member, between field connections or ends of member including flanges, webs, stiffeners, splice plates, connection plates and etc.

3.3 Observations - Individual gage measurements.

3.4 Readings - The average of two individual observations at the same location.

3.5 Auxiliary Members - Those members attached to or being a part of the girder or beam and generally known as: diaphragms, floorbeams, wind bracing, etc.

4.0 EQUIPMENT

4.1 Dry Film Thickness Gage

4.1.1 Gages approved by the Department.

4.2 Standard Shims

5.0 CALIBRATION

The gage shall be calibrated every hour during continuous operation, orafter the gage has been turned off for an extended period.

The battery shall be checked every fifteen minutes during continuous operation.

5.1 The meter shall be calibrated in the following manner:

Place a standard shim of the expected paint thickness on the bare substrate that is to be painted. Adjust the gage in place on the shim so that it indicates the known thickness of the shim. If the paint has already been applied to the entire surface then reference panels of similar steel and surface condition representative of the substrate to be measured may be used.

Confirm the gage setting by measuring the shim at several other areas of the bare substrate.

Measure other shims, thicker and thinner than the setting. The gage should respond fully to the difference in the thickness of the shims.

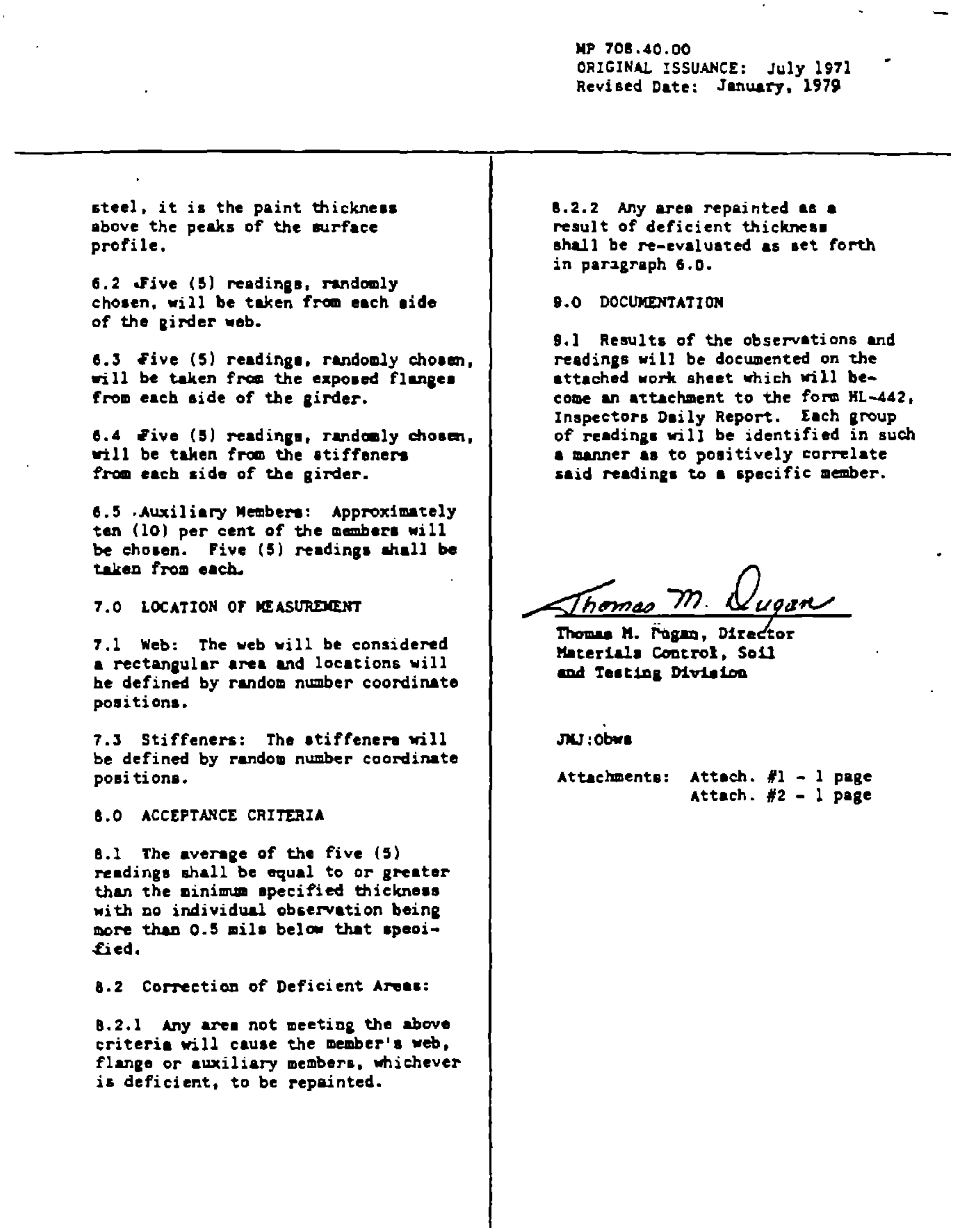
These procedures are intended to supplement Manufacturer's instructions for the operation of the gages.

6.0 PROCEDURE

6.1 With the gage adjusted as above, measure the dry paint film.

The gage readings indicate the paint thickness above the surface on which the gage was set. On blast cleaned

Figure A-8. Reproduction of West Virginia DOH Paint Thickness Procedure



MP 708.40.00
ORIGINAL ISSUANCE: July 1971
Revised Date: January, 1979

steel, it is the paint thickness above the peaks of the surface profile.

6.2 Five (5) readings, randomly chosen, will be taken from each side of the girder web.

6.3 Five (5) readings, randomly chosen, will be taken from the exposed flanges from each side of the girder.

6.4 Five (5) readings, randomly chosen, will be taken from the stiffeners from each side of the girder.

6.5 Auxiliary Members: Approximately ten (10) per cent of the members will be chosen. Five (5) readings shall be taken from each.

7.0 LOCATION OF MEASUREMENT

7.1 Web: The web will be considered a rectangular area and locations will be defined by random number coordinate positions.

7.3 Stiffeners: The stiffeners will be defined by random number coordinate positions.

8.0 ACCEPTANCE CRITERIA

8.1 The average of the five (5) readings shall be equal to or greater than the minimum specified thickness with no individual observation being more than 0.5 mils below that specified.

8.2 Correction of Deficient Areas:

8.2.1 Any area not meeting the above criteria will cause the member's web, flange or auxiliary members, whichever is deficient, to be repainted.

8.2.2 Any area repainted as a result of deficient thickness shall be re-evaluated as set forth in paragraph 6.0.

9.0 DOCUMENTATION

9.1 Results of the observations and readings will be documented on the attached work sheet which will become an attachment to the form HL-442, Inspectors Daily Report. Each group of readings will be identified in such a manner as to positively correlate said readings to a specific member.

Thomas M. Dugan

Thomas M. Dugan, Director
Materials Control, Soil
and Testing Division

JMJ:Obws

Attachments: Attach. #1 - 1 page
Attach. #2 - 1 page

Figure A-8. (Con't). Reproduction of West Virginia DOH Paint Thickness Procedure.

Attachment #1

TABLE I

RANDOM NUMBERS

.858	.092	.865	.125	.263	.176	.551	.711	.355	.698
.575	.417	.242	.316	.950	.819	.444	.323	.331	.179
.567	.288	.835	.635	.596	.174	.866	.685	.056	.173
.053	.391	.739	.002	.159	.423	.629	.631	.979	.399
.140	.324	.215	.358	.653	.193	.215	.667	.627	.595
.574	.601	.623	.685	.339	.485	.055	.627	.458	.137
.936	.569	.757	.308	.025	.836	.200	.055	.510	.655
.603	.910	.944	.281	.539	.371	.217	.892	.324	.284
.215	.355	.645	.450	.719	.057	.287	.146	.135	.903
.761	.683	.771	.338	.928	.654	.815	.570	.539	.600
.669	.222	.115	.447	.658	.989	.921	.924	.560	.447
.562	.036	.302	.673	.911	.512	.972	.576	.838	.014
.431	.791	.454	.731	.770	.500	.980	.183	.365	.012
.399	.966	.356	.183	.797	.503	.180	.657	.077	.165
.464	.747	.299	.530	.675	.646	.385	.109	.780	.699
.675	.654	.221	.777	.172	.733	.324	.659	.079	.587
.279	.707	.372	.485	.340	.680	.928	.397	.337	.564
.338	.917	.942	.965	.838	.805	.278	.639	.906	.939
.316	.935	.403	.629	.130	.575	.195	.887	.142	.488
.011	.283	.762	.928	.102	.058	.902	.850	.569	.977
.683	.441	.572	.486	.732	.721	.275	.023	.088	.402
.493	.155	.530	.125	.841	.171	.794	.850	.797	.357
.059	.502	.933	.055	.128	.655	.043	.293	.792	.739
.956	.729	.370	.139	.306	.658	.183	.464	.457	.863
.240	.972	.495	.693	.350	.642	.188	.135	.470	.733

Figure A-8 (Con't). Reproduction of West Virginia DOH Paint Thickness Procedure.

BRIDGE PAINTING DATA

Attachment No. 2

AV	AV	AV	AV	AV	AV	AV

AV	AV	AV	AV	AV	AV	AV

AV	AV	AV	AV	AV	AV	AV

AV	AV	AV	AV	AV	AV	AV

Date ____________________

Signature ______________________________

Figure A-8 (Con't)

between the two classes of contracts or contracting practices.

Overall, it is felt that the contracting practices and contract provisions are adequate to insure the quality of work intended and needed to get the service life expected of high performance coatings. The cleaning and painting specifications included in the contracts are clear and end result directed. The key to achieving the quality described in these specifications is exercise of the inspection function.

The bulk of highway bridge painting contract provisions and specifications are incorporated by reference to a state's standard set of specifications for road and bridge construction. These establish the contractual relationship between the State and the contractor in terms of bonding requirements, work scheduling and progress, acceptance of work, authority of the project engineer and his inspectors, right of inspection, condition of default, contract period, and payment schedules.

The general contract provisions are the same from State to State. This commonality is due to an informal sharing and review process with minor exceptions in which each State, as a matter of courtesy, distributes its standard specifications for road and bridge construction to the other states. This leveling process is also aided by contract guidelines distributed by the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration.

Some specifications for the paints and associated cleaning, scheduling, and film thickness requirements also demonstrated this sameness.

5.1 Analysis of Contract Provisions and Practices

Contracts and contracting practices were reviewed in terms of bidding requirements, method of award, enforceability, cleaning and painting specifications, incentive and penalty clauses, and time and cost overrun provisions. The results of this analysis follow.

5.1.1. Bidding Requirements.

The qualifications to be met in order to bid a job are primarily measures of business stability and capability with only an indirect assessment of "quality or work" included, if at all. The measures include things like possession of required licenses, amount and type of equipment, capital, work load, experience, credit rating, ability to get bonded, and age of business. The size of the job that one can bid is scaled to the values of these business measures.

This type of economic assessment of a contractor's business is also used by surety companies to determine if a contractor is bondable, i.e., an acceptable risk.

The experience category contains some elements of measuring the quality of work done or delivered but it is mainly a listing of jobs as a demonstration of ability to handle work similar in size, complexity, and materials for a particular job or bid qualification level.

Conceptually, one would like to have a mechanism of rating the quality of the work delivered by a contractor, i.e., identify the "good" contractors and the "bad" ones. In practice, this is difficult if not impossible to do. First, work quality is difficult to define objectively especially for projects as large and complex as bridge construction and cleaning and painting structural steel. Second, the element of arbitrariness in ranking or categorizing potential contractors by work quality leaves the process open to legal and political pressures that would undermine the intent. Changes in personnel in work crews or "management techniques" can always be used as an argument that poor performance in the past is no longer indicative of current capability.

Even if a mechansim were available to rank contractor performance as part of a bid qualification scheme, that ranking would not be sufficient alone to determine qualification status. There still would remain a distribution in quality among "acceptable" contractors. The bottom line is qualified or not; there is no ranking of qualified contractors.

5.1.2 Method of Award

The practice in selecting the winning bid for a project is simple. The award goes to the lowest cost proposal from among the qualified bids submitted by law.

The intent of this selection criterion is to minimize the cost to the public. The criterion is not perfect and it is open to abuse such as intentional underbidding to get an award and then seek cost increases through contract modifications. This certainly occurs.

There is support that the low bid criterion can work as intended if vigilance is exercised in enforcement of specifications through inspection. The theory is that the use of consistent inspection standards and acceptance criteria from project to project (with allowance for differences due to the materials and system design) will eliminate opportunities to "cut corners" or deviate from the agreed upon qualities of the work as described in the contract. Potential bidders, knowing beforehand that specifications will be enforced, will have to respond with realistic cost estimates.

5.1.3. Enforceability

The enforcement of the contract and adherence to specifications is the responsibility of the project engineer. The scope of his authority includes interpretation of plans and specifications, acceptance of quality and quantity of work done, and a general determination of the fulfillment of a contract. The State also maintains a right to approve subcontractors selected by the prime contractor.

The inspector performs the immediate confirmation of compliance with specifications. He is empowered to stop work that he feels is outside the bounds set by the contract and specifications but he cannot change or modify specifications. The engineer makes the decision where differences between the inspector and contractor occur. In addition, inspector acceptance of work done does not relieve the contractor from a responsibility to do the job "right". In effect, inspector acceptance is not sufficient proof of the quality of work done, at least in a legal sense.

A performance or contract bond is required of the contractor in an amount equal to the total bid price. As written, the engineer or the state has the authority to declare a contractor in default and to, thereby, call in the bond. Reasons sufficient to place a contractor in default are listed in the standard provisions including a blanket statement of ..." for any other cause, fails to carry on the work in an acceptable manner."

The options available to the bonding company (or surety) are to (1) find another contractor and complete the work within the original bid price or, (2) allow the State to find another contractor and pay any costs over and above the original contract amount.

Although the standard provisions, taken at face value, give the State or engineer the authority to decide default, the acceptance of that judgment by the surety is not automatic. The bonding company reviews the circumstances and determines for itself if the default is justified. If its analysis is contrary to the State's position, resolution can involve legal suits.

The State also exercises a right of final inspection and acceptance before final payment is made and the contractor relieved of his responsibilities.

Final inspection and acceptance are critical points in a project. Conversation with different State's DOT personnel indicated that redress of work deficiencies that become evident after this acceptance is not existent. The finality of this probably is a pragmatic statement of the difficulties and costs involved in legally proving fraud or latent defects over which the contractor had control. This possibility, however, is included in the standard provisions.*

5.1.4 Cleaning and Painting Provisions

The provisions that detail the cleaning and painting of the steel are covered by reference to standard specifications or special provisions. The items covered by reference include:

1. A description of the locations and portions of the steel and structure to be cleaned and painted.
2. Drawings and plans showing the location of steel to be cleaned and painted.
3. Surface preparation, degree of cleanliness, and profile required.
4. Qualified paints (QPL) and general provisions of acceptance.
5. Paint application methods allowed.
6. Dry film thickness specifications for each coating and total system.
7. Schedule requirements for painting after surface preparation and between paint applications.
8. Weather conditions (temperature, humidity, precipitation) limiting cleaning and painting.
9. General statement about the type and extent of paint film defects considered unacceptable.

The provisions that cover the cleaning and painting are considered sufficient in that they include key elements involved in describing the end points conceptually associated with paint and painting quality.

5.1.5 Incentive and Penalty Clauses

No incentive clauses (payments) exist in the standard specifications reviewed. As far as it is known, there is no legal barrier to having such provisions; it is just not practiced.

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*"The clause is..."The contractor, without prejudice to the terms of the contract, shall be liable to the Department for latent defects, fraud or such gross mistakes, as may amount to fraud, or as regard the Department's right under any warranty or guaranty." LA DOT, 107.22; GA DOT 107.20

..."The Department reserves the right, should an error be discovered in the partial or final estimates, or should proof of defective work or materials used by or on the part of the Contractor be discovered after the final payment has been made, to claim and recover from the Contractor or his surety, or both, by process of law, such sums as may be sufficient to correct the error or make good the defects in the work and materials." (FL DOT, 7-16).

The penalty clause in the standard specifications is not labelled a penalty; the terminology used is "liquidated damages." Failure to complete the contracted work within the allotted time activates the liquidated damages clause.

The amount of money charged against the contractor if the job is overrun in time is determined by the bid price and charged on a per day basis for each day that completion is late. The schedule of liquidated damages used is reproduced in Table A-16.

5.1.6 Cost and Time Overruns

The cleaning and painting of structural steel is priced on a lump sum basis for the whole job, i.e., quotes do not use a unit cost based on square feet cleaned and painted. This is in contrast to other types of road and bridge construction work in which unit prices are used and payment is made based on the actual number of units delivered.

Increases in cost for cleaning and painting the steel as described in the contract are not allowed. Additional work due to changes in the plans or scope of work on the part of the State is paid for at agreed upon rates at actual total cost for the contractor plus a percentage add on.

Time overruns reduce the net payment to the contractor through the liquidated damages presented in Table A-16.

Extensions of the contract period can be granted at the discretion of the engineer. Justifiable reasons for time extensions are not treated explicity; the contractor can petition the engineer for a time extension. Guidelines are more work than described in the contract is required to do the job correctly or "reasons beyond the control" of the contractor.

5.2 Best Practice

The quality of cleaning and paintin of bridge structural steel is defined in a contract by end results or qualities. These end results (degree of surface cleanliness, paint film thicknesses, and paint film appearance and defects) are given independent of consideration of the effort involved in delivering work o the quality so defined. In addition, th quality factors associated with cleaning and painting bridge structural steel are not measurable in a quantitative sense except film thicknesses. Because of this, interpretation of the contractual requirements for steel cleaning and applied film characteristics is subjective

It is considered, then, best practice to have a pre-bid conference at which the work to be done as seen and de fined by the State (through a designated engineer) is presented to potential bidders. Details of the inspection procedures and inspection standards and crite ria to be used in monitoring the quality and progress of the work can be demonstrated and emphasized. This procedure will not eliminate the subjectiveness inherent in judging the work quality but it will help minimize differences in interpretations between the contractor and the responsible engineer(s) and, thereby avoid delays and conflicts that might impair the cooperation necessary to successfully complete a project. One can also expect the bids subsequently submitted to better reflect the effort involved and to have less variance.

A pre-bid conference might also serve as a forum in which the contractor can, at least, offer input to the adequacy and advisability of the specifications proffered by the State. Such input and involvement of painting contract

Table A-16. Schedule of Liquidated Damages.

Original Contract Amount		Daily Charge	
More than	To and Including	Calendar Day or Fixed Date	Working Day
0	$25,000	$30	$42
$25,000	50,000	50	70
50,000	100,000	75	105
100,000	500,000	100	140
500,000	1,000,000	150	210
1,000,000	2,000,000	200	280
2,000,000	-------	300	420

in the specification preparation process was emphasized by painting contractors as a method to help improve the field reliability of coatings (see, for example John B. Conomos, "Field Painting of Bridge Structures, A Contractor's Point of View," Proceedings of the First World Congress in New Coatings Systems for Bridges and Steel Structures, New York, November 3-4, 1981).

6.0 Qualifying Contractors, Painters, and Inspectors.

This section deals with the qualification of painters and inspectors since it is felt that qualification of the contractor is properly an assessment of the character and stability of his business. The requirements for bid qualification (e.g. equipment, capital, experience, and ability to get bonding) are considered adequate for this.

One instance of a qualifying procedure for painting contractors was discovered. This is a franchising operation for the industrial maintenance painting market developed through efforts of a group of paint manufacturers, application equipment manufacturers, and contractors. Initial qualification concentrates on general measures of business integrity similar to bid qualification review: years of experience, work record, ethics in terms of reputation and "standing behind work", number of employees, equipment inventory, and yearly income. Training in quality assurance is supplied using the requirements for painting in nuclear power facilities as a guideline. This is supplemented by periodic training through seminars on management and technical aspects of painting (See J.L. Cleveland, "First Franchises Awarded", American Painting Contractor, vol. 58, no. 3, 41-42, 44, 46 (1981); "Certified Painting Services Presents Quality Assurance Workshop," American Painting Contractor, vol. 58, no. 12, 26-27 (1981).

6.1 Qualifying Painters

The craftsmanship of painters is important and necessary in the delivery o a properly applied paint film. This rather obvious point is reinforced by t fact that coatings manufacturers expect painters to make adjustments to the pai (e.g. thinning) and adjustments in thei application procedures to get the paint applied under a variety of field conditions. Although specifications usually cover the question of proper applicatio by reference to the manufacturer's recommendations, these recommendations ar not adequate for the scope of climatic conditions encountered in field work. The operational criteria are to make adjustments as necessary to get a film applied that will meet the end point specifications (film thickness, adhesion, appearance, and uniformity).

6.1.1 Painter Training

The rudiments of cleaning and paint application form a minimum basis for qualifying painters. As with any trade most of these are obtained through on the job training and experience.

A formal exposure to the technology behind the practice is beneficial because an understanding of why certain procedures are followed in different circumstances helps one to adapt to new situations beyond specific experiences. That is, experience is necessary in developing craftsmanship in a trade but without an understanding of why something works in some cases and not in others, one can also be limited by experience. Formal training supplements and complements work experience.

Formal training in surface preparation, equipment operation, and paint application is part of a union painter's apprenticeship. Abrasive blast cleaning and spray application of paints appropriate to structural steel painting is included in the program but it is a minor part. The emphasis is in house painting procedures. The apprenticeship training is three years long.

Federal training opportunities in painting are available to open shops through a curriculum being developed through the Painting and Decorating Contractors of America (PDCA) and Associated Builders and Contractors, Inc. (ABC) (see, "Manpower and Training Committee Writes Guidelines for Training Manual," American Painting Contractor, November, 1979, 72-74).

The training is classroom oriented and involves comprehension of material demonstrated by a written test. Completion of an entire program for a trade takes the same time that union programs traditionally take.

Details of these training programs (union and open shop) were not obtained in the course of this research study. Both are broad in scope since they cover the whole painting trade. Because of this, practices appropriate to cleaning and painting structural steel with high performance type coatings form only a segment of the training.

Training in paint application equipment handling, operating principles, and troubeshooting is also available from application equipment manufacturers like Binks Manufacturing Company and The DeVilbiss Company.

ASTM Subcommittee D01.43 on Coatings for Power Generation Facilities has prepared a guide for qualifying, certifying, and training painters.* It is [illegible] *Manual of Coatings Work for Light-Water Nuclear Power Plant Primary Containment and Other Safety-Related Facilities*. As now developed, only an assessment of ability to apply paint per se is included in the qualification and certification scheme. This committee is continuing to develop certification requirements covering surface preparation and mixing of paints before application. The guideline also includes an outline of recommendations for a training program covering examination of surfaces, surface preparation equipment and procedures, application equipment operating principles and procedures, causes of and remedies for film defects, inspection equipment operation and use (which for a painter are his quality assurance tools), and equipment maintenance. This guide is considered best, current practice.

The key elements of the guide are:

1. Journeyman status.
2. Demonstration of painting ability by applying coatings to a test specimen such that the dry film thickness is within specified ranges and free of defects such as runs, sags, dry spray, and pinholes.
3. Inspection of the applied film and measurement of film thickness done jointly by the contractor and owner (i.e. State or engineer) or their designates.

Journeyman is used here in a broad sense as one who has learned a trade. For union painters, the distinction between apprentice and journeyman can be used. For non-union painters, the classification is more difficult to make. One method that can be used is to require the same number of years of experience an apprentice must have before he can achieve journeyman status. When training programs such as the one being developed by the PDCA are complete or available,

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*This work is now part of ASTM Committee D-33 on Protective Coating and Lining Work for Power Generation Facilities.

completion of such training as a requirement, perhaps, can be added.

The test speciman is a steel plate of approximately fifty square feet on which "typical" structural features like a section of pipe and "I" beam are welded. It is intended to be representative of the different shapes and configurations the painter will encounter on real structures. Figure A-9 illustrates the test panel's features.

The painter is supplied with equipment in proper working order and paint properly mixed. He is evaluated on dry film characteristics. Recommendations are given in the guide for allowed variability in film thickness but no specific guides are given for quality and acceptability in terms of type and extent of film defects. Actual acceptance criteria for certifying a painter are to be mutually agreed upon by the contractor and owner or their designates.

This qualification procedure is adaptable to highway bridge construction and maintenance. Test panels can be designed to include the features common to bridge construction or the specific type of bridge to be painted. The acceptance criteria for film thickness naturally follows from the specification requirements and the inspection procedures and data analysis to be used on a project. The type and extent of film defects considered acceptable is an undefined area, at least a priori. Classification of defects found and their extent can be made, however, with a decision as to their acceptability left to judgment and experience. This is no different than field practice.

The qualification procedure is not burdensome and is based on skills and work quality that can be reasonably expected. Of course, it is not a guarantee that work of the quality demonstrated in qualifying will be delivered throughout a project. Inspection plays the chief role in providing quality consistency. The qualification gives assurance of some minimum level of skill and experience. It is adaptable to different projects and products.

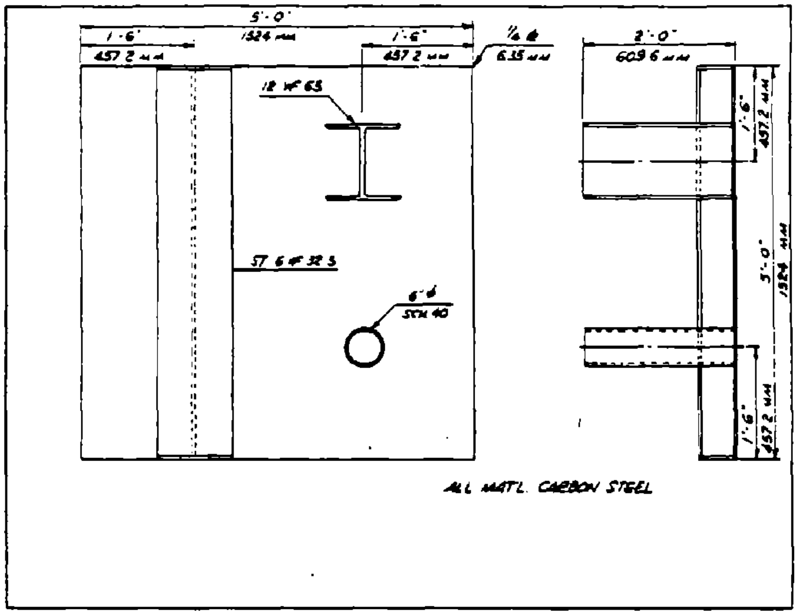
There is a precedent for qualifying workers on bridge projects, although the qualification is for welders (see Louisiana Standard Specifications for Roads and Bridges, 1977 edition, Section 815.02 Qualification of Procedures, Welders and Welding Operators). Again, qualification amounts to a demonstration of the ability to do the work.

6.1.2 <u>Inspector Training and Qualification</u>

Inspection of the cleaning and painting of structural steel is the operational heart of a QA program. The items and processes to be included in the inspection function have been discussed under the QA recommendation for surface preparation, paint application, and final film examination.

Although inspection is an important and necessary element in field reliability of any protective coating, it is emphasized in discussions about the use of high performance coatings because of their lower tolerance to deviations in surface preparation and application than the oleoresinous systems they are to supplant (see, for example, Berger, 1977). This greater reliance on inspection, then, requires training of inspectors so that the equipment, procedures, and standards they use are used properly.

The general body of knowledge and accumulated experience known as "good painting practice" that has been referenced earlier also addresses the in-



Item	Area, ft² (m²)	Weight, lb (kg)
Plate	50 (4.6)	255 (115.6)
ST 6 WF 32.5	15 (1.4)	162.5 (73.6)
Pipe	6 (0.6)	38 (17.2)
12 WF 65	12 (1.1)	130 (58 9)
Total	83 (7.7)	585.5 (265.6)

Figure A-9. Test Panel Used for Painter Qualification (Manual of Coating Work for Light-Water Nuclear Power Plant Primary Containment and Other Safety Related Facilities, ASTM, 1979, pp. 72).

spector's duties and procedures. These are:

1. Steel Structures Painting Manual, Vol. 1 Good Painting Practice, Chapter Five. "Inspection". (1979 printing).

2. ASTM D3276 Standard Recommended Guide for Paint Inspectors.

3. Manual of Coating Work for Light-Water Nuclear Power Plant Primary Containment and Other Safety-Related Facilities, Chapter 5 "Inspection."

4. "Durability of Coatings Applied to Steel Structures, Chapter Five Inspection of Coatings During and After Application, West Virginia Department of Highways, FHWA/WV-80/005.

5. "Inspectors Short Course: The Painting of Structural Steel", Florida Department of Transportation.

Of these, the guidelines in the manual for coatings work in nuclear power facilities address training and qualification of inspectors. The others concentrate on outlining the inspector's duties, procedures, and equipment. In addition, the FHWA is in the process of revising a training course for bridge paint inspectors developed under contract (Contract No. DOT FH-11-9691, "Training Course for Bridge Painting Inspectors").

The training suggested for coating inspectors in the nuclear coating manual is not treated in detail. The scope includes all the aspects of cleaning and painting: blasting equipment, abrasives, paint materials, application equipment, inspection tools and equipment, specification reading and interpretation, common application problems and film defects and their cause and remedies, inspection documentation, and safety. The training is the same suggested for painters.

Qualification of inspectors is basically a demonstration of the ability to use and operate inspection tools and equipment in a field environment. e.g. psychrometers, film thickness gages, and efflux viscometers). For nuclear power plant work, the criteria to be used in establishing proficiency is left to the discretion of the facility owner or his designates.

It is felt that the best practice in training inspectors is to concentrate the operation, use, and care of inspectio equipment and the employment of visual standards for judging quality characteristics of cleaning and painting that cannot be measured. This training includes calibration of equipment, limitations of use, and data manipulation (e.g. determination of dew point or relative humidity from wet and dry bulb temperatures).

The when, where, how often, and acceptance limits placed on the things an inspector observes and measures are considered engineering functions and elements of quality control. That is, it is the project engineer's duty and responsibility to translate the specifications into a set of operational definitions, procedures, and check points for the inspector.

7.0 Overcoating Zinc Rich Primers

There are two major concerns in over coating zinc rich primers. One is the cleaning of weathered primer to remove zi corrosion products and atmospheric contaminants. The other is the occurrence o bubbling and blistering in freshly applie overcoats. Of these two, the bubbling ph nomenon was the more common problem encountered in talking with people, in gene ral, about topcoating zinc rich primers a in the site visits made.

7.1 Cleaning Zinc Rich Primers

The cleaning of a zinc rich primer surface is part of normal painting procedures. The length of time the uncoated primer is weathered and the nature of the weathering environment affects or dictates the type and degree of cleaning.

Theory attributes two benefits to the zinc salts formed through atmospheric exposure. One is the salts form a barrier film on the zinc particles' surfaces. This film reduces the reactivity of the zinc itself, thereby increasing (potentially) the coating's useful lifetime. The other benefit is the corrosion products fill the pores in the zinc primer, aiding the coatings barrier properties in retarding corrosion and, secondarily, reducing the frequency of bubbling in topcoats.

The zinc salts formed in atmospheric exposure also have disadvantages associated with them. (Tator, 1976). They can interfere with the adhesion of a topcoat or intermediate coat. Water soluble zinc salts, if not removed, can induce osmotic blistering and peeling of the topcoat from the primer since organic topcoats are not impermeable to moisture. Increased zinc corrosion rate under wet conditions is also possible.

Water washing or pressurized water blasting can remove the salts. The porous nature of the primers complicates the cleaning since water and salts may become trapped in the labyrinths. Water washing is also used as part of surface preparation of zinc primers exposed to sea salt spray. Visual evidence of salts ("white rust", white deposits, salt crystals) is used as an indicator of the need to wash the primer surface.

Deposits of water insoluble zinc salts like zinc carbonate and zinc hydroxide can interfere with overcoat adhesion depending on their concentration. If they are present as a powdery deposit, then normal good painting practice would require that they be removed. Pressurized water blasting can remove such deposits through abrasive action.

Hence, best practice requires water washing or water blast cleaning of untopcoated, weathered zinc rich primers. Visual evidence of the presence of salts, either zinc corrosion products or atmospheric deposits, confirms the need. The porous nature of the films presents the possibility that contamination not visually detectable is present so washing is necessary routinely as a fail safe measure.

For freshly applied zinc rich primers, which are overcoated within a few days after application, the need for water washing is diminished. Contamination by airborne salts from ocean spray, of course, remains a concern and possibility. Examination of the surface just prior to overcoating to check for such contamination as well as normal dust and dirt is still required by general good practice.

Zinc rich primers are prone to dry spray more than other types of coatings since they are predominately composed of non-film forming material. Overcoats are not to be applied to dry spray as part of normal good painting practice since intercoat adhesion is lowered and the interface is then subject to early failure. Abrasive sanding of surface areas is used to remove dry spray and overspray deposits.

7.2 Bubbling in Overcoats

The prevalent problem of bubbling of freshly applied overcoats has been recognized and discussed for several years in th coatings industry. The source of this application problem is the porous nature of zinc rich primers. The air contained in the pores is displaced (or is to be) by the overcoat. Depending on the relative rates at which the viscosity of the coating changes and the air bubbles move through the film, the bubbles can become entrapped in the film at varying depths. Of course, the rate at which the bubbles move through the wet film is dependent on its viscosity.

The occurence and severity of overcoat bubbling is aggravated by field conditions of ambient and surface temperature, wind speed and direction as well as the application procedures and material adjustments by the painter (e.g., wet film thickness deposited per pass, gun to substrate distance, evaporation rate of thinning solvents, etc.). The degree of porosity of zinc rich primers can, then, be expected to vary spatially over a bridge structure reflecting changes in film morphology in response to the variety of conditions encountered over the course of a painting project. This variability in porosity may account, at least in part, for some of the haphazard occurrence of the problem.

In general, procedures and material adjustments that retard the rate of drying will help alleviate permanent bubbles and their associated defects like craters and pinholes from paint films.

Recommendations have been developed that constitute a set of procedures that may eliminate or reduce the occurrence of overcoat bubbling. These have been presented and discussed by Tator (Tator, 1976), Padavich (Padavich, 1980), and NACE in Publication 6H180 "Topcoating of Zinc-Rich Primers for Atmospheric Exposure." These standard remedies are:

1. Weather the zinc rich primer.
2. Accelerate the cure and drying of zinc rich primer.
3. Application of a barrier or tie coat.
4. Application of a wash primer.
5. Application of a mist coat.
6. Application of a thinned overcoat.
7. Application of solvent to the primer before overcoating.

Weathering of the zinc rich primer in theory reduces the porosity and, ther fore, the amount of air to be displaced. The corrosion products of the zinc dust fill in the voids and pores. The practicability of this approach is difficult t assess because the weathering process, i rate, and the nature of the zinc product as well as their dependence on different environments is not fully understood. One has no control over weathering so it reliability is nil. Schedules and contract periods, of course, do not allow one the luxury of waiting for the primer to weather for some unknown, unspecified time.

The acceleration of the cure or drying of the zinc primer is not germane to the bubbling induced due to the porous nature of zinc rich primers. This procedure reflects concern about the loss of solvents or water by the primer either through evaporation or as a by-product o curing reactions like the hydrolysis of alkyl silicates (i.e. ethanol and other alcohols). The loss of these materials by a primer that has been topcoated "toc soon" leads to degradation of intercoat adhesion manifested by peeling. This is a genuine concern but it is not associated with the overcoat bubbling discusse here.

The use of barrier coats, tie coat or a wash primer are essentially the sa mechanistically. These types of coatin have two purposes in overcoating zinc ri primers. One is to provide a surface that is compatible with the intended topcoat. The other is to fill in and seal the pores of the primer so that bubbling in the topcoat is avoided. The bubbling in these intermediate layers is minimized by their thin film (thinner than topcoats) so bubbles have less of a distance to travel to reach the film surface and burst. The overcoating of film defects in these intermediate coats with the topcoat to give a final coating system of acceptable apperance is also a factor in practice that leads to acceptance of this technique.

In light of the assessed best technology in qualifying and approving coating systems as integral units, the intermediate coat (however it is named) must be part of the qualified system beforehand. Because of this, the use of an intermediate coating on an as needed basis is not good practice despite the fact that laboratory testing and early exposure results from the SSPC project on topcoating zinc coatings have shown little difference in performance between primer-topcoat combinations with and without an intermediate coat (Keane, 1981, pp. 29, 54). The coatings in this study were not prepared under field conditions and the degree of correlation between the laboratory tests and field exposures and the field exposures and service performance is not known.

The use of an intermediate coat on a spot basis also introduces problems associated with schedule adjustments, inventories, and QC/QA.

The distinction between mist coat and thinned topcoat in practice is not rigorously maintained. In principle they are different.

A mist coat represents an application of the overcoat in a thinner than specified thickness. This is done so that the transport distance for bubbles is reduced and, thereby, the severity of bubbling and bubble retention reduced. Once the mist coat has displaced the air and sealed the pores, more topcoat is applied to bring the thickness within specification.

The descriptions given for the mist coat film structure do not picture it as a continuous, non-porous film. Because a mist coat describes a general application technique, in practice the continuity and morphology of the mist coat film will vary so that no one simple picture sufficies. Mist coating itself is no guarantee of bubble free overcoats.

Thinning of the topcoat is an obvious procedure to try, given the generally accepted belief on the cause of bubble retention. The increased solvent level maintains a low viscosity longer in the deposited film so that air bubbles can rise through and out of the coating before it sets. The amount of thinning is not known beforehand so adjustments are made on a trial and error basis tempered by experience. In principle, the coatings manufacturer is to recommend thinning solvents, an upper limit on the amount of thinning to avoid precipitation of coatings components (e.g., "pigment shock") and a dry to recoat schedule.

A second application of topcoat is required to compensate for the reduced volume solids concentration in the thinned topcoat approach. Film thickness specifications prevail. The recoat time, in theory, is short enough (e.g., one-half to one hour) so that application of more topcoat can be done with rigging already in place.

Spraying the surface of the zinc primer with solvent displaces the air. Paint application is to follow before the solvent evaporates completely. The retained solvent is to aid the penetration of the paint into the pores and, thereby, aid adhesion. The solvent diffuses through the coating and evaporates. This method is most applicable to inorganic zinc rich primers and crosslinked organic zinc rich primers although the extent of crosslinking (degree of cure) in the latter at the time of solvent application is a source of concern and caution to avoid extraction of components or swelling.

The applicability of this technique to thermoplastic organic zinc rich primers in general cannot be supported due to the criticality of solvent selection, film dissolution, and annealing of polymer that may encapsulate the zinc particles and, thereby, reduce the coating's effectiveness in galvanically protecting steel.

The bubbling of coatings applied onto zinc rich primers is a field application problem that occurs sporadically. It is dependent upon the composition of a coating through the sensitivity of its drying characteristics to field conditions of temperature and wind which vary day to day and during a day. The skill and experience of the painter also has an impact on the occurence and elimination of the problem. There is not always a technical "fix", because the phenomenon is not fully understood (i.e., its occurrence is not known beforehand and standard remedies do not always work).

7.3 Overcoating Alkyl Silicate Zinc Rich Primers.

The precautions and problems in overcoating zinc rich coatings given above apply to alkyl silicate zinc rich primers. This section highlights a special consideration for alkyl silicate zinc rich primers, namely the evolution of alcohols, usually ethanol, forme by the hydrolysis of the silicate.

Based on the specifications reviewed, the predominate inorganic zinc rich binders are those based on ethyl orthosilicate. It is used at varying degrees of hydrolysis (e.g., 40% and 80%) in formulating a product. In theory, hydrolysis is completed in the deposited film by reaction with water absorbed fro the atmosphere.

Two problems can arise with such systems. In one, the primer can be topcoated before the degree of hydrolysis and subsequent crosslinking has progressed to a point that the mechanical strength of the primer is sufficient to withstand the stresses imposed upon it as the topcoat dries. This can be manifested by a flaking or peeling of the coating system by cohesive failure in th primer layer (a layer of primer is expected to adhere to the topcoat).

The other failure that can be induced by premature topcoating of an alkyl silicate zinc rich primer is loss of intercoat adhesion. In this case, solubility and diffusion of ethanol through the topcoat or intermediate is important. For vinyl resin based coatings, this is a particularly sensitive problem since ethanol is not a solvent for vinyl resins. The ethanol can, then, pool and be retained at the interface or precipitate the vinyl resin in the interface region. In either case, intercoat adhesion is degraded. Peeling and flaking of the topcoat from the primer can result.

The development and promotion of zinc rich primers that are insensitive t topcoating after short "dry to topcoat" times is being pursued and, is, of course, a desirable product feature (Gelfer, 1981; Ginsberg, 1981). Mechanistic studies of film formation in alkyl silicates using changes in density, mechanical properties, and thermal stability have generated data that support a view that properties are generated within hours of film deposition with the major mechanism being solvent evaporation and not hydrolysis and condensation (Ginsberg, 1981). The subsequent rate of hydrolysis and alcohol evaporation is expected to be too slow to cause early and rapid failure of the type described above.

The initial degree of alkyl silicate hydrolysis was not given in these studies; the results are more likely applicable to ethyl silicate polymer at the eighty per cent hydrolysis level. The applicability to alkyl silicate zinc rich primers in general must be established through additional experimentation. The fact remains that field failures of topcoats over alkyl silicate zinc rich primers have occurred with the cause attributed to a lack of cure in the primer (see, for example, Tator, 1978).

The best technology in overcoating the alkyl silicate coatings is to follow the manufacturer's guidelines in dry to topcoat times. The effect of temperature, humidity, and wind on the drying of these primers is not known other than in a qualitative sense. Because of this, upper limits rather than lower limits of dry to recoat times should be used to guide overcoat application schedules.

8.0 Defining and Correcting Field Failures

The information base to be used in defining and correcting field failures was to be composed of case histories. The research plan identified several potential sources of such information: court proceedings for suits involving alleged coating failures, analytical and forensic laboratories, departments of transportation, bridge authorities, technical service departments of coatings manufacturers, and research and technical organizations. Only a few cases were identified, however, as a result of inquiries made.

The original intent of the investigation of coating system failures was the establishment of relative frequencies of failures with cases classified by causes. Example classifications are:

1. Surface preparation, e.g. inadequate by design, lower quality than specified obtained, and inadequate definition of quality desired.
2. Coating system, e.g. mismatch of coating system to the service environment, inadequate thickness by design, and lower film thickness obtained than specified.
3. Application procedures, e.g., use of wrong equipment, scheduling, improper mixing and thinning, and climatic conditions.
4. Inspection, e.g., lack of training, lack of vigilance, insufficient number of inspection and measurement points (inspection tasks poorly designed).
5. Unknown.

The operational definition of failure adopted for this facet of the research study was failure to achieve an expected or design service life. Failures or problems during the application of coatings were originally excluded from consideration since they were within the scope of another project task (Task B - Review Application Procedures). Failures of interest then would be catastrophic in extent either spatially over a bridge's surface area or economically in degrading life cycle cost benefits anticipated.

With a knowledge of the relative frequencies of the causes of field failures, the elements involved in field painting of structural steel that need to be addressed to improve reliability are easily identified. A large number of cases are needed to correctly apply such an approach. Unfortunately, only a few cases were identified. The information base then for this section is small and reliant actually on general principles and guidelines that are known in the general body of knowledge of coatings technology and affirmed, at times, by individual experience and intuition.

8.1 General Findings

The consensus feeling among DOT personnel interviewed on coatings failures is failures are due to application shortcomings and not due to inherent weaknesses in materials. The application shortcomings are related to the quality and thoroughness of surface preparation and paint application (film thickness uniformity, film thickness compliance with specifications, and freedom from film defects).

This generalization is already a part of painting lore applicable to oleoresinous and high performance coatings. For example, as an introduction to a discussion on causes and prevention of paint failures, a NACE task group (Task Group T-60-22, Why Coatings Fail, NACE Publication 6D170) estimates that something on the order of seventy per cent"... of all coating failures have resulted from poor or inadequate surface preparation before application of the protective coating." Tator, in a presentation on painting highway steel which included zinc rich paints, concluded that premature failures predomi nantly are caused by "...substandard surface preparation and deficient pain thicknesses." (Tator, 1968) Specifications were considered adequate but i spection lax. Hence, it is concluded that what needs to be done to get reliable coating systems is known; one then must do what is necessary to insure it is done, i.e., inspect.

8.2 General Procedures

Given some failure in a coating system (the effect), one wants to dete mine its cause. These failures can in volve film defects generated and observed during application (the project life span) or ones that become evident after the coating system is placed in service.

There are practical, legal, and economic reasons that support the effort necessary to identify the cause o causes of the problem encountered. An immediate one is to rectify the problem so that design qualities wanted can be achieved in the coating system when it is accepted and placed in service (application stage related problems). Another is to make modifications in specifications, application procedures, or inspection to achieve d sign level qualities in future work. The legal and economic reasons for establishing a cause and effect relation ship for failures are driven by the ec nomic reasons: who is to pay for the cost to correct failures.

The best practice to be followed defining failures in terms of cause an effect is a common sense approach with a strong flavor of the "scientific method":

1. List possible causes of the failure or failures observed.

2. Make observations and collect data that can eliminate some causes or support others to reduce the list of possible causes to one cause or a list of fewer causes with ranking to reflect their probability.

In this procedure, the second stage (data collection) is to be emphasized. For application problems, the availability of data (of same form) will aid the project engineer in overcoming inexperience in judging field painting quality in terms of what is acceptable on the basis of "reasonable and customary practice" and reducing reliance on recommendations of coatings manufacturers and painting contractors. It will help determine if the painting contractor can be reasonably held to specifications since the causes may be within his control (i.e., effort involved does or does not constitute work beyond scope of the contract and "reasonable and customary practice").

The soundness of the cause and effect relationship, if legal procedures are brought to bear, will rest on the data and its analysis to reduce possible causes to one. Under field conditions, there are a great many factors that contribute to a coating's success or failure. Many but not all are known. They will vary widely in intensity and duration over a cleaning and painting project life span so the task of establishing cause and effect is difficult and subject to interpretation. Hence, in practice, a cause and effect may not be unequivocally established; most probable is, perhaps, a better description.

8.2.1 Sources of Cause and Effect Relationships.

The starting point in the analysis of field failures is the generation of a list of possible causes. Source of such information are:

1. General discussions of cleaning and painting structural steel such as (a) Hess's Paint Film Defects, H.R. Hamberg and W.M. Morgans, eds., Chapman and Hall Tbd., London, 1979, (b) NACE Publication 6D170 Causes and Prevention of Coatings Failures, (c) Steel Structures Painting Manual, Vol. 1 Good Painting Practice, Chapter Eighteen "Causes and Prevention of Paint Failure" (1979 printing), (d) "Durability of Coatings Applied to Steel Structures", Report No. FHWA/WV-801005, pp. 91-114, West Virginia Department of Highways, and (e) Paint Handbook, Chap-18 "Application Techniques", pp. 18-19-18-28, and Chapter 19 "Troubleshooting and Inspection", G.E. Weismante, ed., McGraw-Hill Book Company, New York, 1981.

2. Technical service departments and representative of coatings manufacturers.

3. Technical service departments, representatives and troubleshooting guidelines from manufacturers of cleaning and spraying equipment.

4. Experience of personnel involved with paint systems like materials engineers and maintenance engineers.

5. Published case history reports of observed failures, their investigation, and resolution carried in the Industrial Maintenance Painting section periodically in the American Painting Contractor magazine.

The general presentations of paint failures and their causes referenced in item 1 immediately above approach paint film failures broadly. Environmental and weathering factors that ultimately limit the useful life of any coating that has been applied "properly" are included in the discussions as well as failures attributable to defects in cleaning and application. The latter is the subject of concern here.

Defects or failures in a coating film detectable during the painting job are items one expects to be correctable by adjustment in the procedures used by a painter. Defects like running, sagging, or blistering provide short-term feedback to the painter and inspector. The adjustments made fall within the realm of skill and workmanship. Inspection also provides feedback in terms of the types and extent of defects accepted in contrast to the contract specification requirements of no defects or no "excessive" amount of defects. This practice at least tacitly recognizes that under field conditions one cannot obtain a defect free film over the surface area of the bridge.

The detailed analysis of problems arising during the application stages indicated above is to be invoked when conventional adjustments to application procedures fail to give acceptable results. Claims under such circumstances are made that paint materials themselves are deficient (i.e., a paint film of uniform properties and defect free cannot be applied by reasonable and customary techniques) or the quality acceptance levels are beyond "normal" ranges and trade practice. This analysis scheme then, based on the information gathered, may result in an acceptance of a job "as is" despite flaws since current technology cannot eliminate them. An example of this is bubbling of topcoats over zinc rich coatings.

8.2.2 Analysis Methods

The gathering of data to eliminate some possible causes and increase the probability of others is the second ste in dealing with coating failures. Investigation of the failure is done in two phases. In the first, inspection procedures are used, including study of inspection reports and project logs. In the second phase, which may not be needed depending on the results of phas one, analytical methods (chemical and physical) are applied to the examinatio of interfaces and paint films. Failure handled here are performance related ones like rust development and peeling of paint films.

The methods used in the first phase of investigating a coating system failure are essentially the same used in inspecting a job in progress. Information is wanted that describes the type of failure e.g., rusting and peeling), location, and extent. The major data and procedures are:

1. Measurement of film thickness, total and individual layers, using magnetic gages and destructive gages.

2. Examination of the steel in area at and adjacent to failure sites to establish the degree of cleanliness under the coating or at failure sites (chemical stripping, removal of film by cutting or peeling, examination under chips, examination with a Tooke gage tc estimate profile and presence of old paint layers, etc.)

3. Examination of the underside of paint chips or flakes for evidence of dust, dirt, old paint that was to have been removed,

4. Visual examination for film defects like pinholes, blisters, and overcoated dry spray.

5. Examination of project diaries and daily inspection reports to establish the nature of the weather conditions that were prevalent at the time

surface preparation and coating application of chemical and physical methods of materials analysis (e.g. infrared analysis, x-ray diffraction, electron microscopic analysis). These tools might be applied to the determination of proper mixing ratio of paint components (e.g. curing agent component in two package epoxy) or the nature of contaminants found in interfaces. These techniques and that analysis and interpretation of their data are specialized areas. Hence, the best practice is to retain the services of a laboratory that has the equipment and experience in forensic analysis.

8.3 Select Cases

Brief summaries of a few case histories of protective coating system failures found in the course of the project are given here.

8.3.1 Nassau Sound Bridge, Florida*

The Nassau Sound Bridge is located over the Nassau Sound River near the Atlantic Ocean so it is in a marine environment. The specifications for the cleaning required a near white quality of cleanliness (SSPC-SP10) with silica sand used as the abrasive. The paint covering was a three coat, qualified and approved system: self-cure, inorganic zinc rich primer, a vinyl type intermediate layer, and a vinyl finish coat. Film thickness requirements were: primer - three to five mils above the profile; intermediate - one to two mils; topcoat - three mils. Laboratory tests on paint batches used indicated that the materials were within specification requirements.

The cost for cleaning and painting was $106,520. After approximately fifteen months of service, it was estimated, based on inspection, that fifteen per cent of the painted surface area was showing rust (total surface area was about 118,000 square feet). The areal density of rust on different spans ranged from five to ninety percent.

It was concluded that the cause of the failure was surface preparation less than,(paint applied over dry spray) specified and paint thickness deficiency. Rust, rust scale, and old paint were found under the zinc rich primer. The range of primer thickness found was one-half to six mils; for the intermediate, it was one-half to three mils. The topcoat had a range of one to six mils. In addition, the inspecting engineer estimated that visual evidence of primer dry spray was on twenty-five percent of the painted area.

For the purposes of this study, it is noted that the causes for the observed failure are all amenable to current inspection techniques.

8.3.2 Atchafalaya River Bridge, Morgan City, Louisiana*

The paint system used on the Atchafalaya River Bridge in Morgan City was a shop applied inorganic zinc rich primer with a vinyl topcoat. Field repair of damaged primer was done with an epoxy-polyamide type organic zinc rich primer. Surface cleaning in the touch up areas was near white abrasive blast. The design thickness for the primer was three to five mils with the topcoat at a minimum of five mils.

The failures observed in this case were:

1. Topcoat peeling from the primer predominately over areas where the or-

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*Information obtained from R.R. Ramsey, Florida DOT.

*Information supplied by A.L. Dunn, Louisiana DOTD.

ganic zinc rich primer was used; this occurred within one year of application.

2. Topcoat showing cracks and porous structure; cracks developed within two years of exposure.

3. Bleed-through of a material from the organic zinc primer sufficient to discolor the topcoat; the material would turn white with exposure.

Rust development was not cited in the inspection reports and memos for this case history.

The phenomenon of bleed-through from the organic zinc rich primer was dismissed by the coatings manufacturer as cosmetic with no anticipated effect on performance. The intercoat adhesion failure over the organic zinc primer argues against this.

Film thickness measurements indicated a wide variance from the specification range. Some areas were measured at eighteen to thirty-five mils. The coatings manufacturer attributed film cracking to such excessive thickness. One inspection report indicates that solvent odors were detected in freshly peeled topcoat but it is not known if those films also were the thicker ones. Prolonged solvent retention, however, is possible; factors are film thickness, nature of the solvent, temperature, and drying in the surface region of a film.

All the coatings were from the same manufacturer. The problems encountered emphasize that the combination of materials to be used in a project must be tested and approved beforehand. Paints from the same manufacturer are not a guarantee of compatibility. Recommendations and guidance from coatings manufacturers must be critically evaluated since the bulk of their knowledge about the materials is based on laboratory experience. Their response to field problems may be only an extrapolation of laboratory experience and not a reflection of field experience.

8.3.3 Red River Bridge, Alexandria, Louisiana

The cleaning and painting project fo the Red River Bridge was all field work The cost was $506,466. The primer was an epoxy-polyamide zinc rich with an epoxy topcoat. The degree of abrasive blast cleaning specified was near white The primer and topcoat were each to hav a three mil thickness.

Within eighteen months of the final inspection, the topcoat in areas was peeling from the primer. Although no total area or per cent area defective was reported, the spots with peeling varied from pinhole size up to estimate of five square feet. The failure occurred on the superstructure.

Other defects noted were cracks in the topcoat on some areas of the bridge and loss of the total paint system in some areas with rust development.

Closer examination of the coating system, prompted by the peeling, revealed a film thickness distribution of wide variance with a portion below specification minimums. For example, out of one hundred seventy-seven (177) measurements, the primer thickness was less than three mils in sixty-eight (68 measurements; the topcoat was less than three mils in twenty-six (26) locations In addition, two hundred fifteen (215) measurements of total thickness out of eight hundred and twenty (820) were below six mils; forty-two measurements indicated a thickness of three mils or less. Film thickness up to twenty mils was also noted.

During the course of the painting, untopcoated primer on parts of the superstructure developed visible rust.

Examination under 10X magnification matched rust spots with pinholes in the primer film. The length of exposure after which this rusting became evident is not known based on the information reviewed.

The exact cause of the detamination problem was not established. The list of possible causes was:

1. Topcoat applied over dry spray.
2. Topcoat applied over contaminated surfaces (dust, dirt, pigeon droppings, chalky primer).
4. Primer not cured due to low temperatures or condensation and rain that leached some coating components or both (based on weather records).

For the most part, the causes associated with the paint failure are items that are included within the inspection task. In principle then, this failure was avoidable with best, current technology.

8.3.4 Bridges in Maine*

A brief summary of observations on the performance of inorganic zinc rich primers plus vinyl topcoats on some bridges in Maine is given in Table B-17.

The peeling of the vinyl topcoat from the primer is a common failure but the delamination is localized and not symptomatic of the entire system. In all cases, the bridges had no visible signs of rust even in areas where the primer alone was exposed.

Color change in the topcoat was noted in two cases. This is attributed to insufficient pigment or UV stabilizer loading to compensate for the vulnerability of vinyl resins to degradation in sunlight.

The reports from which the information in Table A-17 was extracted were inspection reports done as part of experimental projects to evaluate the inorganic zinc primer and vinyl topcoat system. Failure analysis was not their intent.

8.3.5 Bridges in Arkansas*

Performance and evaluation information taken from inspection reports for a select number of bridges in Arkansas is condensed in Table A-18.

The modes of coating failures denoted are listed mainly to indicate the type of failures that can occur. The extent of these failures was not large (rusting was typically less than one percent of the coated area). Some were attributed to cleaning and painting procedures that inspection could rectify (failure to remove old, red-lead paint, lack of primer in some areas) while others were limited by the formulations (color change and chalking).

8.3.6 Paint Case Histories

Cases of paint failures were difficult to obtain. One source of such case histories, though, is a series in the American Painting Contractor magazine reported in the Industrial Maintenance Painting section. There are cases from the files of KTA-Tator Inc., a coatings consultant company. Some of these have been used as reference material in the foregoing. Reading and review of the cases is helpful in practicing the best technology because they reinforce the need to follow good practice by demonstrating the consequences of not doing so. The methods and equipment used to investigate failures serve as guides in analyzing yet future problems.

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*Information supplied by David S. Leyland and Frederick M. Boyce, Maine State Department of Transportation.

*Information supplied by Wendell Williams, Arkansas State Highway and Transportation Department.

Table A-17. Some High Performance Coatings in Maine.

Bridge	Coating System	Exposure Duration (mo.)	Failure Mode	Cause and comment
I-95 Overpass Cider Hill Rd.	Inorganic Zinc (3 mils) + vinyl (5 mils)	18	topcoat peeling	none given; localized peeling
I-95 overpass Cutts Rd.	Inorganic Zinc (3 mils) + vinyl (5 mils)	17	topcoat peeling	none given; localized peeling
I-95 overpass Beech Ridge Rd.	Inorganic Zinc (3 mils) + vinyl (5 mils)	18	topcoat peeling	none given; localized peeling
Van Buren R.R. Bridge	Inorganic Zinc + vinyl	9	topcoat peeling	vinyl too thick, ∿ 1 mils) or surface unclean; limited to one flange
		34	color change	PVC too lo
Rt.1A, Harrington	Inorganic Zinc + vinyl	40	topcoat peeling &	none given
			color changing (brown → pink)	none given
			top coat cracking	occurs ove Al filled, epoxy mast

Table A-18. Some High Performance Coatings in Arkansas

Bridge	Coating System	Exposure Duration (mo.)	Farline Mode	Causes & Comments
No. 613	Inorganic Zinc (2pkg.) + vinyl (blue)	32	color change chalking	formulation
No. 3300	Inorganic Zinc + vinyl (blue)	18	chalking peeling rust	some areas not cleaned to near white; some areas without primer.
No. 3301	Inorganic Zinc + vinyl (blue)	12	chalking peeling rust	minor & localized
No. 2899	Inorganic Zinc + vinyl (blue)	6	peeling (localized)	application in "marginal conditions"
No. 1253	Inorganic Zinc (2pkg.) + vinyl (yellow)	44	peeling (localized)	old paint not removed
No. 2526	Inorganic Zinc + vinyl (green)	27	color change	green + bluish tint; UV instability
No. 1412	Inorganic Zinc (2pkg) + vinyl (green)	57	chalking cracking color change	
No. 2212	Inorganic Zinc (2pkg.) + vinyl (aluminum)	41	some rust	

9.0 Conclusions

The conclusions presented here are organized around an assessment of the best technology currently applied in the use of high performance coatings in protecting structural steel. It is based on the findings from the tasks that define the scope of the research study undertaken.

The process of using high performance coatings on bridges has been compartmentalized as shown in Figure A-10.

9.1 Product Qualification

The best practices in a qualifying scheme should include establishing a qualified products list (QPL) which incorporates field testing as well as laboratory testing, coating systems qualified as single complete units, and specifications based on performance qualifications.

9.2 Procurement

The paint to be used on a particular project, must be a system that has been qualified and approved by the State. Designation of the product identification is sufficient for procurement since the composition supplied must be the same as the composition originally approved. Methods and criteria used to assure qualified product uniformity are discussed in the next section under elements of quality control and quality assurance.

9.3 Materials Quality Control and Quality Assurance

By definitions adopted from ASTM sub-committee D01.43 - "Coatings for Power Generation Facilities."

Quality control - administration and engineering procedures employed to attain the desired level of quality assurance.

Quality assurance - the verification of the conformance of materials and methods of application to the governing specification in order to achieve a desired result.

9.4 Surface Preparation and Inspection

The minimum degree of surface cleanliness for steel that is to receive a zinc-rich primer is near-white (SSPC-SP1(The use of a near white surface cleanliness condition with high performance coatings besides zinc-rich primer systems is also recommended. In any case, no less than commercial blast quality is acceptable for such coatings.

The best practice in inspecting surfaces for cleanliness and profile is to use the visual standards at the point of inspection and to make profile measurements.

9.5 Paint Application and Inspection

In the area of paint application climatic and substrate conditions conducive to the actual handling and application of the paint, and the properties of the applied film must be considered. For the most part, these procedures and checks are adequately covered under the guidelines of good painting practices. Weather and substrate conditions used to establish acceptable painting conditions are air temperature, humidity, wind, steel temperature, and surface moisture. Best practice requires that these parameters be measured or determined at the job site periodically throughout a work day.

Inspection of the mixing and thinning of high performance coatings is particularly important especially in multipackag paint systems (e.g. epoxy-polyamide paint and zinc rich primers).

Inspection of paint application equipment, especially oil and water traps to prevent contamination, that may not be detectable until visual examination of the applied film.

Scheduling is also very important in

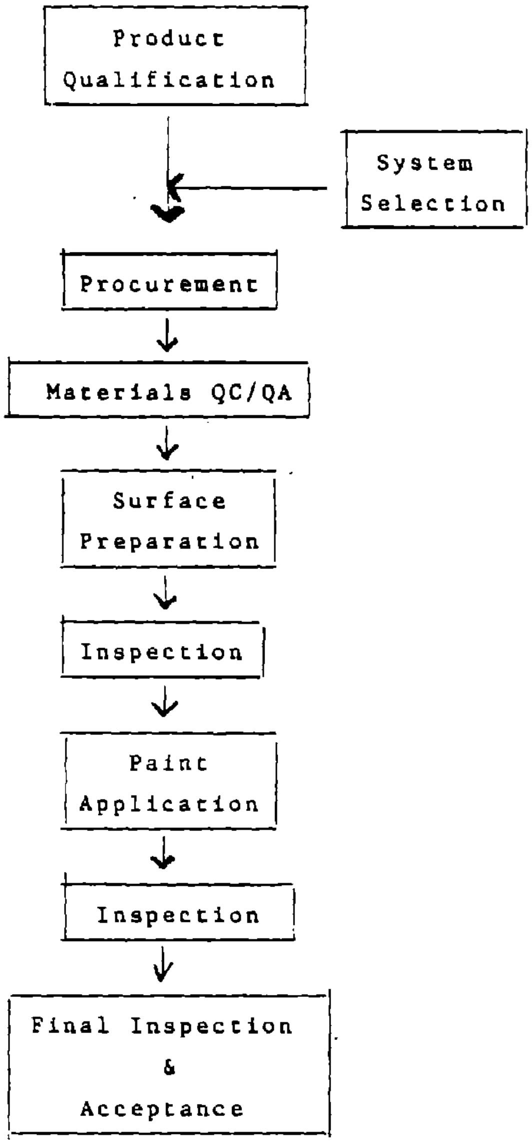

Figure A-10. Schematic Outline of the Painting Process.

in the application process, as the schedule reflects the elapsed time between surface preparation and coating application, as well as elapsed time between application of different coats.

The measures of quality for a paint film are thickness, thickness uniformity, color and gloss uniformity, and adhesion, and the extent to which it is free of defects like runs, sags and pinholes.

9.6 Final Inspection and Acceptance

The practical difficulties in correcting work already in place reinforces the need to inspect as work is in progress. The quality of cleaning and painting of bridges is defined in a contract in terms of end results. Interpretation of the contractual requirements then involves subjective judgment. Because of this, it is considered best practice to have a pre-bid conference at which the work to be done is defined by the state and presented to potential bidders. Details of inspection procedures and operational standards and criteria to used to monitor and accept work quality can be demonstrated and explained. This will not eliminate the subjectiveness inherent in judging work quality but it will minimize differences in interpretations between contractors and the state.

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