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CHONG CYCLE, DURABILITY ISSUES AND ACCELERATED TESTS OF BRIDGE COATINGS

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ABSTRACT

Fundamental research in durability of materials and structures have shown great potential for enhancing the functionality, serviceability and increased life span of our civil and mechanical infrastructure systems and as a result, could contribute significantly to the improvement of every nation's productivity, environment and quality of life. This paper is mainly aimed at developing innovative short-term laboratory tests, which allow accurate, reliable prediction of long-term performance of coating materials in steel bridges. It is especially needed for new coating materials since such data are hard to come by. Additionally, the intelligent renewal of aging and deteriorating civil and mechanical infrastructure systems includes efficient innovative use of high performance composite materials for structural and material systems including nano materials and smart and high performance materials. In this paper in addition to bridge coatings the NSF initiative on durability modeling and accelerated tests, as well as research needs are presented.

Keywords: Chong cycle; surface engineering; bridge coatings; accelerated tests.

1. INTRODUCTION

The intelligent renewal of aging and deteriorating civil and mechanical infrastructure systems includes efficient innovative use of high performance composite materials for structural and material systems including nano materials [1] and smart and high performance materials [2~4]. As an example, the annual bridge maintenance and rehabilitation costs billions of dollars; therefore reducing corrosion is a critical task for bridge engineers and owners in order to ensure a sustainable critical infrastructure. Coatings have been applied over steel bridges to reduce corrosion which affects the structure integrity and load carrying capacity of bridges as well as ultimate failure; the coating durability of course is a critical issue for bridge maintenance. Field testing takes long time to determine the lifetime of bridge coatings; therefore, any reliable accelerated laboratory test method within relatively short time would be very beneficial for estimating the long term durability of coatings over steel bridges. A more realistic laboratory accelerated test, named by the research communities as the Chong Cycle, has been developed to predict the long-term field performance of bridge coatings. In conjunction with a powerful evaluation technique, the relative performance of various bridge coatings can be easily distinguished as described below.

2. DURABILITY ISSUES

Demands for better-performing, longer-lasting, safer, more economical, and more environmentally friendly structures and machines are constantly pushing the envelope of technological capabilities engineering practice [3, 5, 6, 7]. As

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a result there are relentless moves towards close tolerances and use of realistic life-cycle design, condition-based maintenance, and performance-based design. In this environment engineering designer is faced with the problem of finding useful and relevant materials property data use in the design of machines and structures which are expected to provide top performance over extended period of time. He or she will typically have access to “hard” data, i.e., repeatable and reproducible results from short term laboratory tests, such as simple hardness, fatigue, uniaxial yield and fracture tests; and even results from somewhat more complex standard tests, such as fracture toughness or short-term salt-fog or ultraviolet (UV) chamber exposure tests. The designer usually also has some more “soft”, qualitative information on how a material has performed in the past under a combination of time, temperature, mechanical load, environment, etc. in the same or similar application. The skilled designer will usually be able to draw from his or her experience of connections between sets of “hard” and “soft” information for one particular material to make educated estimates of different material, which gives somewhat similar results in short term tests, will perform under not-too-different sets of long-term complex mechanical and environmental loading conditions [5~7]. This approach has served reasonably well in the past but has several shortcomings relative to the new demands on tight design for performance. For example it does not deal well with synergistic interactions of cyclic stress and long-term corrosion. For creep of metals and viscoelastic materials, use of the Larson-Miller parameter and similar approaches serve as semi-empirical ways to add the effect temperature and time, but similar parameters are lacking for most other situations. It also does not readily allow for comparison of different classes of materials, for which the short-term test results vary substantially, for example steel and polymer-matrix composites. This inhibits or delays the adoption of new materials for many critical applications [7].

With this general background in mind, a number of NSF program directors held informal discussion over a period of time resulting in an initiative [5]. Some of the questions considered were the following:

Have recent advances in the fields of modeling, computation, understanding of basic materials properties, sensing, control, probability analysis, etc., reached the stage where we really can do better than outlined by the problem set above, where we can begin to predict long-term performance, from short-term tests by quantitative approaches? And where we can confidently operate with lower safety margins or safety factors and closer prediction of life to failure or time until maintenance is necessary?

Do we understand the different processes well enough to be able to closely predict their long-term synergistic interactions, such as the combined effects of stress, corrosion and temperature variations?

Is there some basic generic approach, which has general applicability in diverse cases, maybe, including model-based simulation and uncertainty and probability considerations?

Do we have some quantitative or semi-quantitative ways of dealing with new materials, new combinations of external loadings and environmental effects, or changes in these factors during life of a machine or structure?

Are there any new short-term tests or NDE techniques that need to be developed to provide some of the necessary information in a useful manner? And what new research should we try to stimulate in order to expedite development in this field? What are the long-term field data available and how do them compare with the research results of proposed methods?

Durability of new materials involves the synthesis, laboratory and field testing, accelerated tests, modeling, etc. Table 1 illustrates the size effects and mechanics [8] involved.

Table 1
Scales in Material Systems

Materials	*Structures*		*Infrastructure*
Submicro-level Molecular scale	Meso-level Microns	Macro-level Meters	systems integration Up to km scale
-nano-mechanics -nanotechnology	-meso-mechanics, MEMS -interfacial mechanics	-beams -columns	-bridge systems -airplanes

The discussions initially resulted in the support of a workshop focused on problems in the infrastructure materials area, funded by NSF and organized by the Board on Infrastructure and the Constructed Environment under the

National Advisory Board of the National Research Council of the Academy [8]. From the report of this workshop and additional discussions an NSF research initiative was subsequently developed.

The workshop was held at the National Academy of Sciences on August 24 and 25 of 1998. Its role as a reconnaissance-level assessment of models and methods that are being used, or it could be used, to determine the long-term performance of infrastructure materials and components [9]. The objectives were:

> *define the objectives for infrastructure-based research that would use accelerated testing computational simulations to determine life-cycle performance; assess the state of the knowledge base to identify gaps and overlaps in research activities; establish outcome-oriented metrics for setting research priorities; and identify promising lines of research and collaborations.*

The participants agreed that a “root cause” of the deterioration and failure of any system is related to materials but that accelerated-testing methods, while they may potentially be used to rank the performance of materials in real-world systems, are not at present sufficiently reliable to system-life predictions.

The workshop proposed that development of useful life-prediction models for infrastructure would require some of the following advances [9]:

- a better fundamental understanding of infrastructure materials and systems, including degradation modes and spanning all size scales;
- a better understanding of the relevant characteristics of the operating environment development of standardized test methods and databases;
- development of sensors for monitoring systems during construction and use; and incorporation of economic models in life-cycle cost analyses.

The workshop also suggested that major obstacles to adaptation of life-cycle prediction modeling accelerated test procedures for infrastructure applications are two interrelated factors: poor integration of the relevant engineering community into materials-based infrastructure and concerns about risk and liability. It expressed the opinion that “practicing engineers have little opportunity to develop the trust in simulation models and accelerated laboratory tests as they have in their many empirical field observations.”

The workshop concluded that...”life-prediction models and accelerated-testing procedures have potential to increase the deployment of new materials in infrastructure applications and to improve traditional materials ... “Predictably, it also suggested that NSF should do more to” ... support materials research directed to understanding the combined effects of degradation mechanisms and applying that understanding to quantitative predictions of system life ... “and, because of the large variations between sectors, NSF should” ... evaluate each infrastructure sector and attempt to organize its research ... “for easy formulation of research needs and ready technology transfer to practice.

The NSF Initiative, NSF 98-42 [5] actually predated the Academy workshop by a few months. It was developed principally in the Civil and Mechanical Systems Division (CMS) of NSF’s Engineering Directorate but with significant input from colleagues at the Federal Highway Administration and State Departments of Transportation (DOTs), especially CALTRANS in California, as well as the Force Office of Scientific Research (AFOSR).

Its stated aim was: “... developing innovative short-term laboratory or in situ tests which allow a reliable prediction of long-term performance of materials, machines and structures ...” based on understanding of the fundamental nature of deterioration processes and innovative ways to model processes as they affect life and long-term performance.

The Initiative aimed to give preference to high risk/high-payoff research by individual investigators and small groups. While most of the deterioration processes of interest clearly were those associated with environmental effects and exposure to overloads, over speeds and other unanticipated conditions, there was no clear or implied limit on the phenomena or materials groups was intended, in line with NSF’s general approach, to encourage innovative thinking in the community. Similarly, application areas were not specified, although it was suggested that some relevant one units of the constructed infrastructure, transportation systems and units, and manufacturing machinery. Some possible research topics were suggested [5]:

- multiple interactive effects and deterioration mechanisms
- accelerated techniques, related instrumentation and model validation to long-term field data determination of service life from wear tests and modeling

- deterioration of structural materials and protective coatings (e.g. polymeric coatings on bridges as a function of environment)
- failure mechanisms of composite materials (e.g. reinforced-concrete failure and corrosion protection systems)
- size effects in testing, instrumentation and modeling
- relevant statistical methods and reliability
- comparison of models with long term field data

Awards have been made in these areas and the findings have been presented in a book [6].

3. THE CHONG CYCLE

Various accelerated laboratory test methods have been developed to evaluate the relative performance of bridge coatings, especially for newly reformulated low volatile-organic-compound (VOC) content and high solid bridge coatings. Prior to 1990, salt-fog test was the primary method for testing coatings. Later, bridge engineers and coating industry have found that the salt-fog testing, as designated in the American Society for Testing and Materials (ASTM) B117 method, does not accurately predict the field performance of many of the new low-VOC coating systems, particularly for waterborne coatings showing unrealistic premature failures. Subsequently, the inclusion of a dry cycle in the conventional salt-fog test [10~13] reduced unrealistic failures substantially. Cyclic testing methods including several different weathering steps were found to generate more realistic conditions similar to field exposure.

When a dry cycle, pollutants, and UV-condensation (QUV) exposures were incorporated into the salt-fog cycle, a better correlation with field exposure was obtained by various researchers [14~16]. Chong S-L and Peart [17] added a freeze cycle to a salt-fog exposure, the 3,000-hour (h) test (cyclic 6-day salt-fog and 1-day freeze) was used to compare coating performance; this cyclic test in conjunction with a 2,000-h QUV test, resulted in a performance trend similar to that obtained by outdoor marine weathering of 15 different coating systems for steel bridges. They showed that freezing is an important part of weather cycle in cold climates; the volume expansion of water absorbed by a coating at freezing temperatures results in significant mechanical stresses being placed on the coating systems.

Currently the most common test method for bridge coatings, ASTM D5894, includes QUV followed by salt-fog/dry-air cycles that is the method being used in the *American Association of State Highway and Transportation Officials (*AASHTO)/National Transportation Product Evaluation Program (NTPEP). This test method is used to qualify commercial products for use by the State Departments of Transportation in the United States.

Chong S-L [18, 19] created a variation of ASTM D5894 and added a low temperature cycle. The results were better correlated with a natural marine exposure of 28 months than those obtained from salt-fog (ASTM B117), and QUV/cyclic salt-fog. This test cycle was named as “Chong Cycle” by Aragon and Frizzi [20]. Due to the importance of low temperature thermal stress, a new freeze cycle has been added in the International Standard (ISO) 20340 method in accordance with the “Chong Cycle”. The test conditions, techniques, and test results of the Chong Cycle are presented in this paper.

Test Specimens

The coatings used for the comparison of three accelerated laboratory test methods were applied on Steel Structures Painting Council (SSPC) white metal (SP-5) steel panels and panel sizes of 7.5 cm x 15 cm x 0.6 cm (3 inch x 6 inch x 0.25 inch) were used. Whereas, the coatings for studying the relative coating performance were applied on SSPC SP-5 steel panels and panel sizes of 10 cm x 15 cm x 0.48 cm (4 inch x 6 inch x 0.19 inch.) that are the current standard panel dimension for coating evaluation. All the coated test panels were scribed according to ASTM method D1654. A 5.0 cm diagonal scribe was made on the face of all the coated panels; the scribe must be made through the coating film thickness until a straight shining metal line is seen (figure 1). Each panel after the laboratory test was examined by the blister and rust creepage from the scribe.

Test Method

Laboratory accelerated tests

Three test methods used in the comparison for their reliability to predict outdoor performance are listed as follows:

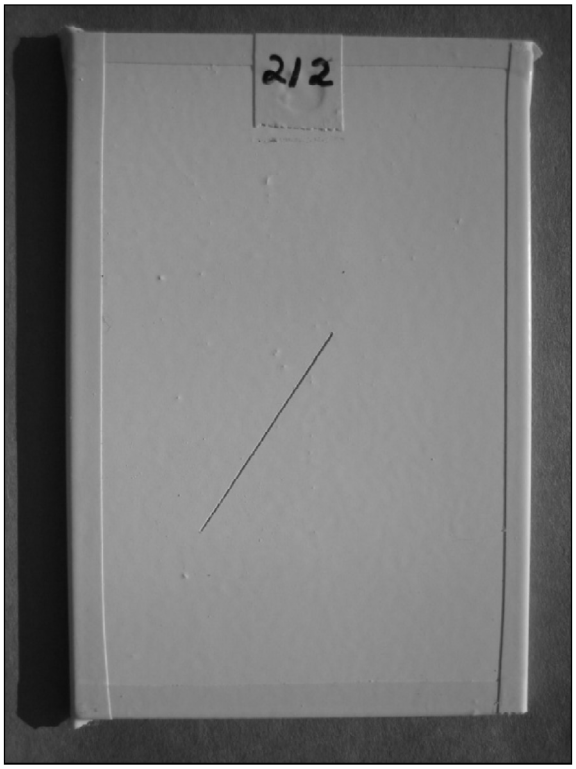

Figure 1: A Coated Test Panel with a Diagonal Scribe

1. Salt-fog: ASTM B117
   Salt solution: 5% sodium chloride
2. Cyclic salt-fog : 1-h wet/1-h dry cycle
   Wet cycle: Harrison mixture (0.35% ammonium sulfate and 0.05% sodium chloride). The collected condensate has a pH of 5.0.
3. The Chong Cycle (figure 2): 70-h freeze/215-h QUV/215-h cyclic salt-fog cycle
   Freeze temperature: -23 °C (-10 °F)
   QUV: UV/Condensation test
      Test cycle: 4-h UV/4-h condensation cycle
      UV lamp: UVA-340
      UV temperature: 60 °C
      Condensation temperature: 40 °C
   Cyclic salt-fog: same as test 2.

Outdoor marine exposure
Location: Sea Isle City, New Jersey
Annual characteristics
Sunshine: 2,840 h
Relative humidity: 51%
Rainfall: 150 cm
Spray sea water once a week: pH = 7.5
Salt content: 2.7%

RESULTS AND DISCUSSION

The new generations of coating systems are mostly quite durable and usually do not develop much surface failures but almost all of them develop some degree of scribe creepage after weathering; therefore, using scribe

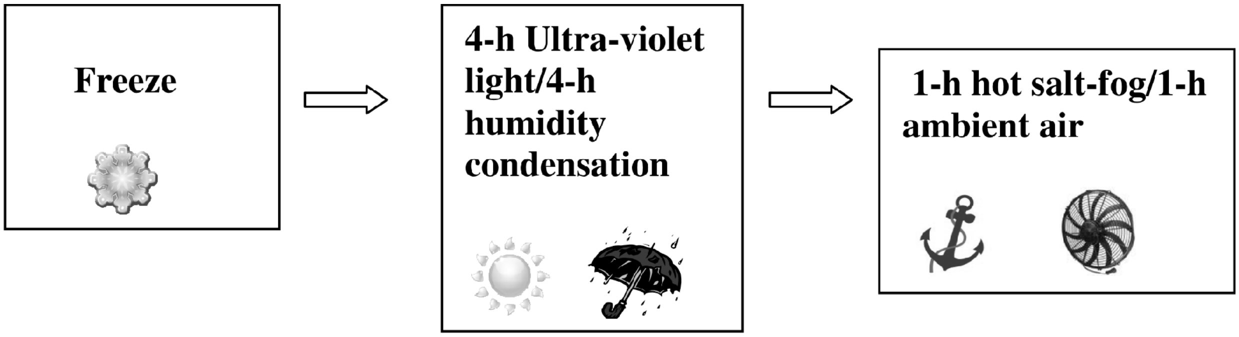

Figure 2: The Chong Cycle

creepage as an evaluation parameter is a more sensitive and rapid way to compare the performance of different coatings systems. A typical creepage developed at scribe is shown in figure 3. Creepage used for coating evaluation is the average distance of surface blistering and rusting that have progressed from the scribe line, a nondestructive technique. It should be stated here that scribe creepage is only one parameter for predicting coating performance; however its early development under most of test conditions makes coating evaluation possible in a relatively short time.

In 1990, the Federal Highway Administration/Turner-Fairbank Highway Research Center (FHWA/TFHRC) followed the ASTM D 1654 to obtain rust creepage values that generally increase with test time, but the plot of scribe creepage as a function of test time showed no particular mathematical pattern [17]. In 1999, the measurement technique was refined by Weaver [21] to take scribe creepage measurements by a ruler at equal length intervals along scribe line and the creepage values were then averaged. It is interesting and encouraging to see a linear relationship existing between mean creepage and test time using this technique. However, this method is tedious and time consuming. Later, the measurements became even more repeatable when the ASTM method D7087-05a was developed by the FHWA/TFHRC to measure scribe creepage [22]. It is a more quantitative and rapid method. This method includes tracing creepage area along a scribe, scanning trace, and saving scanned image on a computer. The creepage area was then integrated by computer software and divided by two times of scribe length to obtain mean scribe creepage. A strong linear correlation phenomenon has been found between rust creepage developed at scribe and test time for numerous previously conducted tests. When linear regression analysis was used, virtually all of the R^2 values were found to be greater than 0.9 by Chong S-L and Yao [23~25]. R is correlation coefficient; R^2 of 1.00 is defined to be the perfect linear fit. This evaluation technique is highly powerful and useful for comparing coating performance.

A study was conducted at FHWA in 1995 to seek a more reliable laboratory test method to predict the field performance of bridge coatings. Twelve different coating systems (table 2) were tested by Chong, S-L [18, 19] by 3 different test methods; all of the coating systems contained VOC contents less than 340 g/L (2.8 lbs/gal). When rust creepage at scribe (scribe creepage) was used to plot against test time, a linear line was generally obtained. To compare accelerating rate of the test methods, the mean scribe creepage of eight different coating systems at each 500-h test interval were plotted versus test time in figure 4. The salt-fog test caused slightly larger creepage (i.e. more corrosion) than did the cyclic salt-fog test; the freeze/UV-condensation/cyclic salt-fog test produced the least amount of scribe creepage among 3 test methods. On the other hand, the linear regression correlation of 3 laboratory test results with outdoor exposure results were investigated using 8 coatings systems and 12 coating systems separately. Four coating systems (No. 1, No. 3, No. 10, and No. 12) showed early severe failures in the salt-fog test, the exposure of these panels was terminated after 2,000 hours. For 8 coating systems after 2,000-h tests, the correlation coefficients for 3 tests were found to be 0.30, 0.81, and 0.89 showing improvement in correlation moving from salt-fog test to cyclic salt-fog test to freeze/QUV/cyclic salt-fog test. To further demonstrate the reliability of the freeze/QUV/cyclic salt-fog test for predicting coating performance, the 3,000-h test results for 12 coating systems were compared to those obtained by the cyclic salt-fog test. The correlation coefficients were 0.87 and 0.67 (table 3) showing a greater degree of improvement by the freeze/QUV/cyclic salt-fog test. The results of this correlation study strongly suggest that the Chong Cycle, freeze/QUV/cyclic salt-fog test, is comparatively a much more reliable laboratory accelerated laboratory method to predict the field performance of the coating systems in a salt-rich marine environment.

Figure 3: Rust Creepage Developed at Scribe After the Test

Table 2
Coating Systems Evaluated

No	*Description*	*Dry Film Thickness, Micrometer (mil)*	*VOC (g/L)^{a}*
1	Solvent-borne Calcium Sulfonate/Alkyd, 2 coats	125/100 (5/4)	276/288
2	Solvent-borne High-solid Epoxy	200 (8)	180
3	Water-borne Acrylics, 3 coats	75/75/75 (3/3/3)	132/109/109
4	Water-borne Acrylic Epoxy, 3 coats	75/75/75 (3/3/3)	134/133/133
5	Moisture-cured Solvent-borne Zinc-rich Urethane/ Urethane/Urethane	63/125/200 (2.5/5.0/8.0)	336/336/336
6	Moisture-cured Solvent-borne Zinc-rich Urethane/Urethane/Urethane	63/125/200 (2.5/5.0/8.0)	336/250/250
7	Moisture-cured Solvent-borne Zinc-rich Urethane/Water-borne Urethane/Water-borne Urethane	63/125/200 (2.5/5.0/8.0)	336/24/24
8	Solvent-borne Epoxy Mastic/Polyurethane	125/50 (5.0/2.0)	84/288
9	Solvent-borne Epoxy Urethane Mastic/Polyurethane	125/50 (5.0/2.0)	327/288
10	Water-borne Inorganic Zinc Potassium Silicate/Water-borne Acrylic/Water-borne Acrylic	63/88/88 (2.5/3.5/3.5)	0/237/241
11	Solvent-borne low-VOC Epoxy/Acrylic Modified Epoxy	138/50 (5.5/2.0)	308/282
12	Water-borne Zinc-rich Epoxy/Water-borne Acrylic/ Water-borne Acrylic	75/75/75 (3.0/3.0/3.0)	86/230/230

(a) 120 g/L = 1 lb/gal.

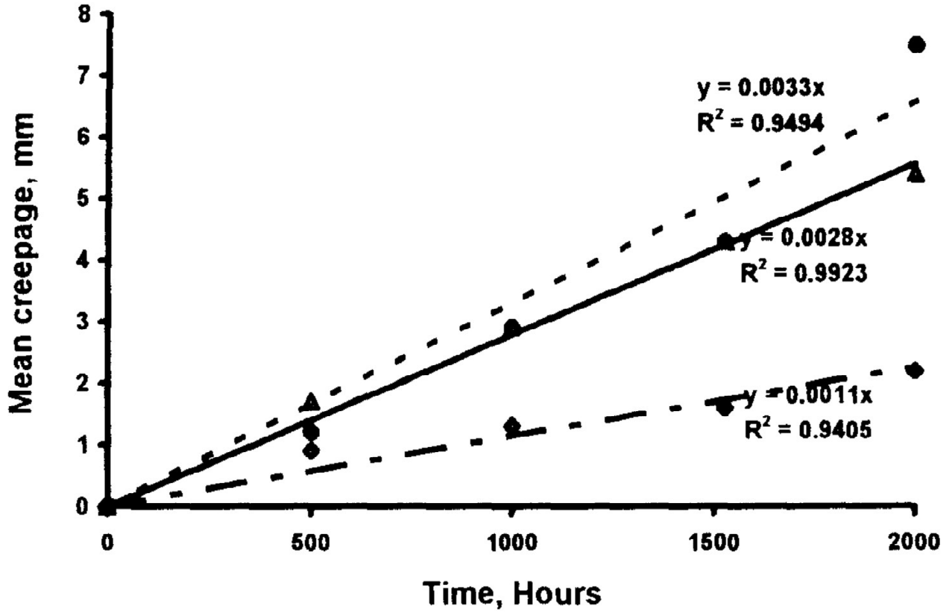

Figure 4: Mean Creepage of 8 Coating Systems after Exposure times of 500, 1,000, 1,500, and 2,000 Hours of Salt Fog Test, Cyclic Salt fog Test, and Freeze/UV-condensation/cyclic

salt fog test, Line symbols for salt fog test, for cyclic salt fog test, and

— – — – for freeze/UV-condensation/cyclic salt fog test (the Chong Cycle)

Table 3
The Correlation Coefficient for Developed Scribe Creepage between laboratory Tests and 28-month Salt-accelerated Outdoor Exposure

	Test No. 1 Salt fog testa	*Test No. 2 Cyclic salt fog testb*	*Test No. 3 Chong Cycle*
8 coating systems[c]	0.30	0.81	0.89
12 coating systems[d]	-	0.67	0.87

a. ASTM B117, salt solution: 5% sodium chloride

b. 1-h hot salt-fog/1-h dry cycle, salt solution: 0.35% ammonium sulfate + 0.05% sodium chloride.

c. Tests were performed for 2,000 hours. Calcium sulfonate, acrylics, inorganic zinc, and zinc-rich epoxy were not included in the analysis.

d. Tests were performed for 3,000 hours.

These results suggest that all the natural stresses – UV, temperature, humidity, rain, cold, and thermal variations – must be included in a laboratory test in order to simulate outdoor exposure conditions. Due to the importance of low temperature stress and the results obtained by the Chong Cycle, a new freeze cycle has been added to the International Standard (ISO) 20340 method. A freezing phase at -20 °C for 24 hours is replacing the dry cycle in the original Norsok cycle. The exposure cycle used in ISO 20340 lasts a full week (168 h) and includes:

1. 72-h QUV - Alternating periods of 4-h UV at (60 ± 3) °C and 4-h condensation at (50 ± 3) °C.
2. 72-h salt-fog
3. 24-h freeze at (-20 ± 2) °C (essential part of Chong Cycle).

To ease operation, the test hours in the Chong Cycle were later changed to 9 days (216 hours) for both UV-condensation cycle and salt-fog/dry air cycle, and freeze cycle was changed to 68 hours. As a result, each test interval for obtaining creepage data is still 500 hours. In general, freeze cycle is about one-third as long as the other two cycles. Salt solution can be either sodium chloride or Harrison mixture depending on field conditions where candidate coatings will be exposed. Nevertheless, all three cycles must be included in the test and the test conditions must remain the same when coating comparison is made. In terms of creepage growth, the acceleration of the

Chong Cycle is approximately 12 to 16 times as compared to normal bridge conditions. This means that the Chong Cycle compresses the time scale 12 to 16 times in terms of predicting the long term performance. Chong Cycle has been used later for more coating evaluations, various coating systems can be compared in terms of creepage amount developed at scribe, i.e., their corrosion rates [23~25]. Overall, zinc-rich coatings systems were found to outperform barrier coatings such as acrylic and epoxy coating systems. A chart (figure 5) shows the relative performance of some bridge coating systems using scribe creepage as a determining factor. The coating systems presented in figure 5 are described in table 4; they are several zinc-rich and waterborne coating systems. In this study, the salt solution used in the Chong Cycle was 5% sodium chloride. The coating durability is considered to be proportional to the incubation time that is the extrapolated test time when creepage equals to zero and inversely proportional to the line slope (26). The coatings on top perform poorer than the bottom ones; more specifically the coatings located at the bottom right region of the figure are more durable coatings for protecting steel surfaces than those located at upper left region. Therefore, it is very easy to differentiate the coating durability from this type of plot. This new methodology is described in detail in the paper by Chong S-L and Yao [26] which contained much more test data. Furthermore, rust creepage at scribe at longer test time may be extrapolated from the linear plot of scribe creepage versus test time. In other words, an accelerated laboratory test may be shortened in terms of time since the corrosion degree at scribe at longer time can be predicted from the plotted line to a certain extent. Zinc-rich coating systems typically developed a much lower amount of scribe creepage than did other type of coating systems after the accelerated test; suggesting that they are much more durable than epoxy, acrylic, and polyurethane coating systems. In the other words, zinc-rich coating systems will be the best systems to protect steel bridges from corrosion in a salt-rich environment because of their higher durability.

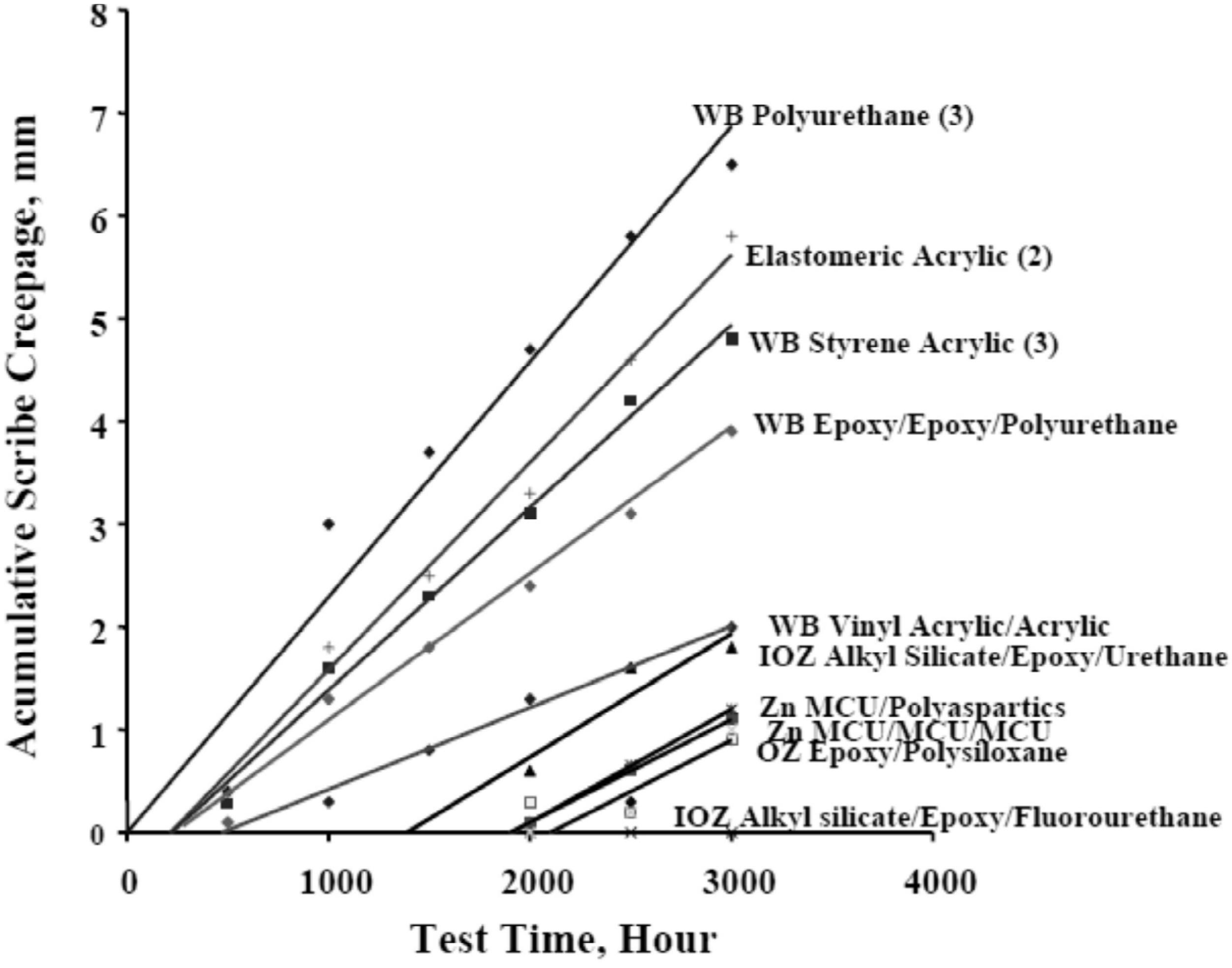

Figure 5: Plot of Scribe Creepage of Various Coating Systems over SP 10 Steel Surface Versus Laboratory Test Time

Table 4
Description of Coating Systems in Different Types

Coating Description	*Nominal Dry Film Thickness, Micrometer (mil)*	*VOC Content[a], g/L*
IOZ[b] Alkyl silicate/ Epoxy/Polyurethane	75/100/50 (3/4/2)	288/195/264
IOZ Alkyl silicate/Epoxy/Fluorourethane	75/75/75 (3/3/3)	288/195/532
Zn[c] MCU [d]/MCU/MCU	75/75/75 (3/3/3)	340/340/420
OZ[e] Epoxy/Polysiloxane	100/150 (4/6)	326/216
MCU Zn/Polyaspartics	75/200 (3/8)	340/289
WB[f] Styrene Acrylic (3)[g]	50/50/50 (2/2/2)	67/67/56
WB Vinyl Acrylic/Acrylic	75/50 (3/2)	64/130
Elastomeric Acrylic (2)	150/150 (6/6)	0.01/0.01
WB Epoxy/Epoxy/Polyurethane	50/50/50 (2/2/2)	180/180/276
WB Polyurethane (3)	50/50/50 (2/2/2)	192/192/250

a: Labeled by supplies, b: Inorganic zinc, c: Zinc, d: Moisture-cured urethane.

e: Organic zinc, f: Waterborne, g: Number of coats.

4. CONCLUSION

We have briefly traced the background for the NSF Durability Initiative and its subsequent development. It was issued in response to a perceived need and the response from the community. One may think of the "materials tetrahedron promulgated by an Academy report in 1989 [27] where performance, as the ultimate "materials characteristic", is shown linked to microstructure/composition, properties, and processing in a Microstructure/ composition, processing and property are interlinked to the apex of the tetrahedron. Since that time, we have understanding of most of the interrelationships in the base triangle. Durability Initiative and the results presented in a workshop demonstrate that we are now well on our way to also develop reasonable understanding of the connections of the apex of the tetrahedron, performance, to the topics in the base triangle. The need and rational for short-term accelerated tests to predict realistically long-term performance of structures and materials are presented. This is especially needed for new materials including coatings and nano-materials.

The test results demonstrated that the Chong Cycle test produced more realistic coating performance as compared to outdoor salt-rich exposure results than the conventional test methods. The Chong Cycle consists of freeze cycle, UV-condensation cycle, and salt fog-dry air cycle. The freeze cycle added in the Chong Cycle is considered as a necessary cycle for testing coating systems. Using this test cycle in conjunction with the plot of scribe creepage versus test time, relative coating performance can be easily distinguished from the linear lines obtained. The coatings on top perform poorer than the bottom ones; more specifically the coatings located at the bottom right region of the figure are more durable coatings for protecting steel surfaces than those located at upper left region. This combined technique apparently makes coating durability study much more effective, relative coating performance is easily observed. All the test results show clearly that zinc-rich coating systems perform much better on steel surfaces than the barrier coatings including acrylics, epoxy, and polyurethanes.

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