PERFORMANCE EVALUATION OF PROTECTIVE PAINTING
SYSTEMS ON STEEL BRIDGES

Project Number ST-2019-3

Final Report

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ABSTRACT

The purpose of the research work presented herein was to develop a simple and yet reliable laboratory test procedure in an accelerated corrosive environment in order to identify a better coating system for steel bridges in the State of Alabama. It is an established fact that among the many factors contributing to the environmental degradation of protective coating on bridge steel, the two most prominent parameters relevant to structures in the State of Alabama are the corrosive salt component of the marine environment and ultraviolet radiation.

An environmental chamber was designed to simulate a wide range of corrosive environments, especially the sea coast environment. The chamber performed accelerated corrosion testing. Exploratory testing was done to study the influence of each variable on the degradation rate. Based on these exploratory tests, an optimum combination of test variables was identified and laboratory testing was carried out on commercial products supplied by the Alabama Highway Department and leading manufacturers. Additionally, paint performance under high temperature was also considered, since the Alabama climate encompasses a wide spectrum of temperature variations. Data were collected on approximately 500 standard paint testing panels, and curves were plotted. Definite distinct performance patterns were observed from various combinations of test parameters. Based on GRAFKIT curve fitting software, empirical equations were obtained with standard deviations.

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I. INTRODUCTION

1.1 Statement of Problem

There are about 330,000 steel bridges in the United States (1). In order to protect them from corrosion, thousands of these are coated every year, while in a great number of cases others have to be repaired and renovated because of inferior or inadequate corrosion protection. Financial costs for corrosion control expenditure in this country amounts to several billion dollars annually. Protective coatings on exposed steel have been a major concern, not only in this country but throughout the world. Despite numerous advancements and perpetual product developments, repainting of deteriorated bridge steel continues to be a national problem. Identification and then selection of effective and durable protective coating systems for steel bridges is a major engineering challenge.

New protective coating products are entering the market regularly. In order to control and regulate these products, the Federal Highway Administration (FHWA) has a qualified products list to assist highway agencies in assessing their reliability and adequacy. Unfortunately, in some instances it is too easy for the new products, that are not of required standards, to get on the FHWA list.

Repainting existing structures in less than ideal conditions, is a highly labor intensive operation and is always a costly endeavor. It is of prime importance that the initial painting be done with the best possible coating system so that repainting can be delayed as much as possible. The major differences between initial painting and repainting are listed

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Numerals in the parentheses denote the reference number.

in Table 1 (2). Figure 1 (3) shows the factors that influence the
performance of coatings and should be considered for the selection of a
coating system.

Table 1. Initial Painting Versus Repainting (2).

Category	Initial Painting	Repainting
What to paint	Predetermined	Survey and analysis required
Funding	Capital funds	Maintenance funds
Schedule	Construction and erection deadlines	Not set, often deferred
Application conditions	Shop, controlled environment, easy access	Field site, weather factor, scaffolding, etc.
Metal surface	Uniform, clean metal	Variable, contaminated
Paint selection	Data, guides available	Few guides, no performance data

Selecting the best available coating material for corrosion
protection, especially when FHWA products list is of no or very little help
in the process of decision making regarding the selection of a coating
system, is a chief concern of the Alabama Highway Department.
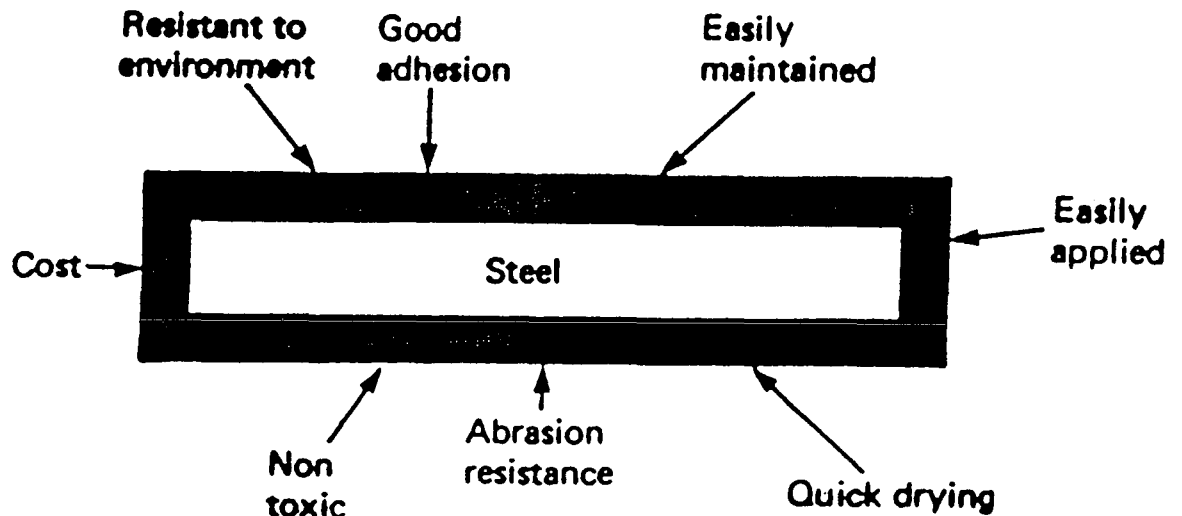
Figure 1. Requirements of a Good Coating System (3)

1.2 Study Objectives

The objective of this study is to develop a simple yet reliable, at least in a qualitative sense, laboratory test procedure in an accelerated corrosive environment for evaluating coating systems and possibly establish a quality control program. Currently several standard testing methods are available such as ASTM B117 salt spray (fog) testing, ANSI/ASTM B287 acid-salt spray testing, ASTM D1735, ASTM D2247, ASTM B368, ASTM D2485 and others (4,5), plus some modified accelerated proprietary testing

procedures developed by the automobile and space industries. Most of these testing procedures not only require costly sophisticated apparatuses but also demand long-term observations. For example, the above-mentioned testing procedures require up to 700 hours of testing time in an accelerated corrosive environment. Specific sub-objectives or tasks that were undertaken to accomplish the goals are as follows:

a. To identify critical parameters which influence the rate of corrosion,

b. To design an environmental chamber that simulates a marine environment, and

c. To develop a laboratory testing procedure for evaluating coating products in the shortest possible time without costly trials.

II. BACKGROUND AND LITERATURE REVIEW

2.1 Background

Research on accelerated corrosion testing devices and techniques spans a period of fifty years. The salt spray test was first suggested by Capp (6) in 1914 as a method of testing protective coatings on steel to determine their probable performance in sea coast atmospheres. The test was found to be less representative than originally anticipated because the natural exposure conditions found in marine areas are dependent upon distances from the seashore. Since then great strides have been made to minimize the inverse proportionality relationship between the degree of accleration and the reliability of the results. Generally, the acceleration factor cannot be expressed numerically (e.g. x 10), as indicated by K. A. Chandler (3) and it usually varies with the particular alloy or coating being tested. It is very difficult to predict coating material life with these accelerated short-term tests. These tests can give results for obtaining correct coating sequences.

Reliability of test results decreases with increasing acceleration and a shorter test period. This is particularly true if the test environment deviates in its chemical composition from that in the actual case. As suggested by Wrangler (7), a fundamental principle in the choice of short-term tests in the laboratory is that the corrosion environment and its qualitative chemical composition, should essentially be the same as that in the actual case. In the past researchers attempted to produce a certain acceleration of the corrosion process by intensifying some dominating environmental factor such as temperature or the concentration of a certain corrosive agent.

2.2 Literature Review

Engineers do not necessarily need an in-depth knowledge of corrosion mechanisms and processes. However, a broad understanding of the principles involved is useful. At this time it is appropriate to explain corrosion in a generalized sense.

Corrosion may be defined as an inadvertent attack on a material through reactions with surrounding mediums resulting in damage caused by such a process. The resulting compounds formed from the above process are referred to as corrosion. Deterioration by physical causes is called erosion. Certain unique mechanical properties, such as strength, hardness, and ductility, make steel a very good construction material. Corrosion can attack and make the metal into a powdery, friable compound resulting in the deterioration of the metallic construction or component. The degree to which this occurs will depend on the rate of the corrosion reaction. The reaction for the conversion of metallic iron to rust can be written as (3):

$$4\ Fe + 3H_2O + 2H_2O \longrightarrow 2Fe_2O_3 \cdot H_2O \qquad (1)$$
$$\text{(rust)}$$
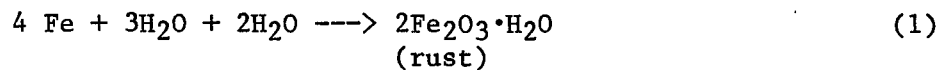
Corrosion may take on a variety of forms that range from a fairly uniform wastage resulting in general loss of thickness of cross-section, to a highly localized attack resulting in pitting and perforation or in cracking and fracture. Figures 2 (3) and 3 (3,8) show a general uniform attack pattern and localized corrosion respectively. Figure 3a depicts various forms of pitting while Figure 3b portrays a deep pit with relation to average metal penetration and the pitting factor. Figure 4 (7) illustrates different types of corrosion.

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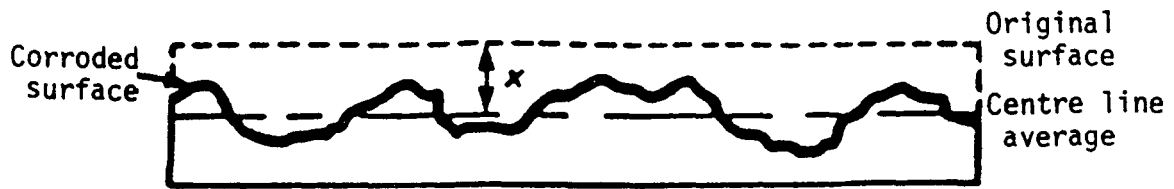
Figure 2. General Corrosion; "x" Indicates the Average Corrosion Loss (3).

It is necessary to devote more attention to metallic corrosion and its control nowadays than earlier, due to:

A. An increased use of metals within all fields of technology.

b. A more corrosive environment due to the increasing pollution of air and water.

c. The use of metallic constructions of more slender dimensions which do not tolerate corrosive attacks to the same extent as did the heavy constructions used in the past.

According to Herbert H. Uhlig (8), the importance of corrosion studies is three-fold. The first is the financial losses incurred because of corrosion. The second area is improved safety of structures which, through corrosion, may fail with catastrophic consequences. Examples are bridges, pressure vessels, metallic containers for toxic materials, and airplane components. Third is conservation, applied primarily to metal resources. The world's supply is limited, and the wastage of them includes corresponding losses of energy associated with the production and fabrication of metal structures.
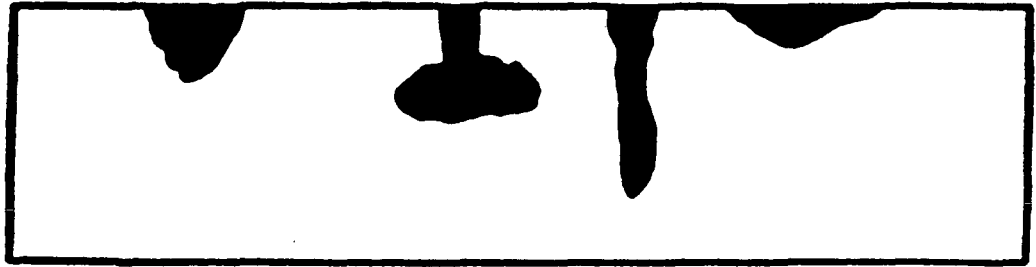
Figure 3a. Localized Corrosion, Forms of Pit (3) .

Pitting factor $= \frac{p}{d}$

Figure 3b. Sketch of Deepest Pit (8)

OXIDE FILM OR NOBLE METAL

General attack

Pitting

Intercrystalline corrosion

Layer corrosion

POROUS Cu

BRASS (Cu + Zn)

Selective corrosion

Graphitic corrosion

LOAD   STRESS

CRACKS

Stress corrosion cracking (SCC)

Corrosion fatigue

Crevice corrosion

Deposit corrosion
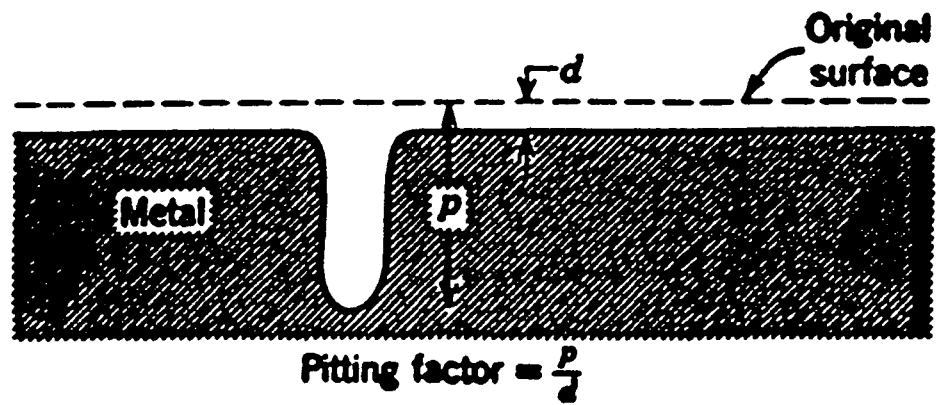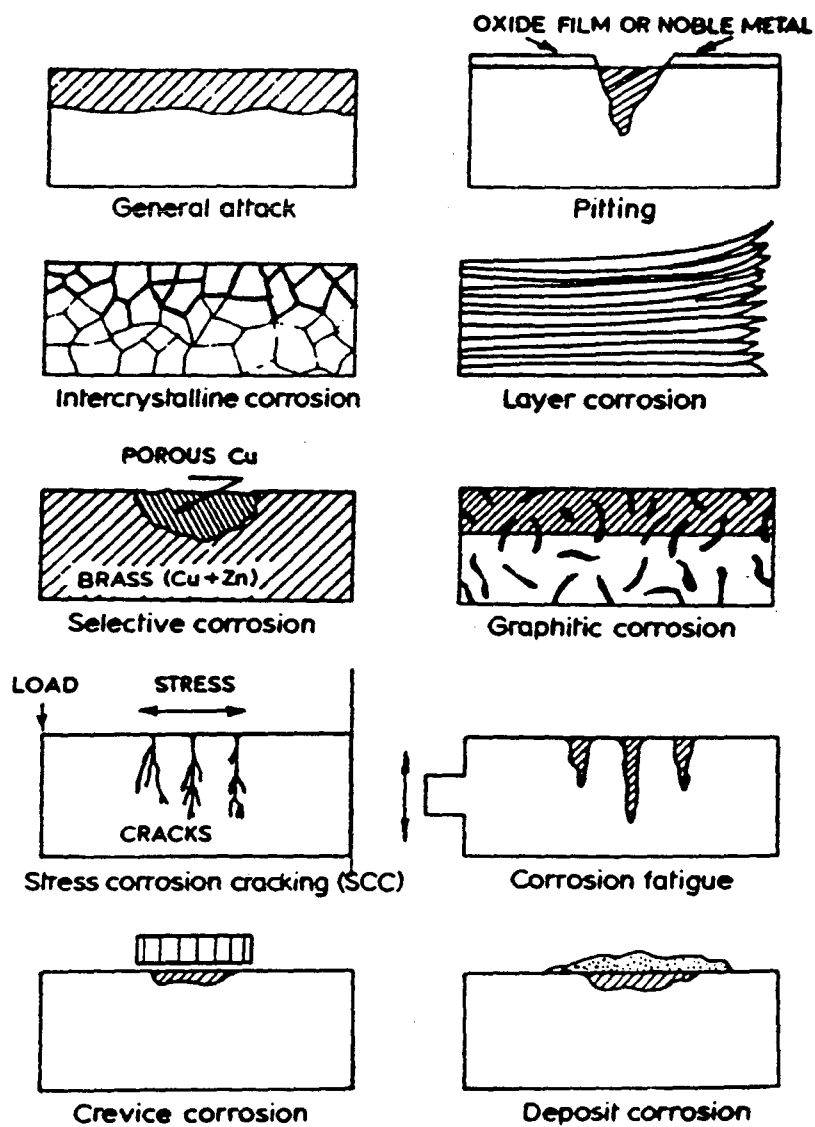
Figure 4.   Schematic Illustrations of Different Types of Corrosion (7).

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Cost of corrosion and its control experienced by one pulp and paper company was estimated to be $20 million annually (9). The total combined losses due to corrosion in the United States alone are estimated conservatively to be about $70 billion annually, or 4.2% of the gross national product (GNP) (10). Studies of the cost of corrosion to Australia (11), England (12) and other countries have also been carried out. In each country studied, the cost of corrosion is approximately 3-4% of the GNP.

It is obvious that in the development of new corrosion resistant materials and coatings for surface protection it is not possible or practical to resort immediately to a long-term model or to field tests. Using accelerated laboratory tests is a good place to start. These should be used and applied in such a way that the results have the highest possible implication for the practical application. Suppliers and users of corrosion control coatings are showing increased interest in rapid quantitative measurement techniques for detecting and assessing early coating failure and in using accelerated tests for better selection. The demand of these developments (13) is fueled by the large economic losses resulting from corrosion, the high costs resulting from coating failures, the mandatory displacement of traditional coatings by new, less familiar coating systems and the inadequacy of currently available accelerated testing procedures (14,15).

After Capp (6), during the 1920s, Nelson and co-workers (16,17,18,19) developed artificial weathering machines and investigated various exposure cycles. An interesting illustrated review of this early work has been done by Gardner (20). Standard methods for operating weathering equipment (21) and preparing and evaluating test panels (22) were developed and published

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by the American Society for Testing and Materials (ASTM) during the 1930s.
Clearly, the problem of defining and measuring some important fundamental
properties and test variables had not been specifically addressed and
almost no evidence was seen of any effort to formulate a comprehensive
strategy in order to differentiate various coating systems. During the
1970s, the National Aeronautics and Space Administration (NASA) was
involved with several other research laboratories in accelerated corrosion
testings of coating systems for performance evaluation purposes. The
launch facilities at Kennedy Space Center (KCS) located on Florida's
Atlantic coast require greater corrosion protection than that needed inland
because of constant exposure to salt spray and fog. For such launch sites
and other related facilities a coating was developed at Goddard Space
Flight Center, Greenbelt, Maryland.

The Statue of Liberty's designer, French sculptor Fredric Auguste
Bertholdi, once boasted that his creation would last as long as the
pyramids of the Nile. But over the first hundred years, corrosion has
taken its toll on the steel skeleton structure. The Statue of Liberty
Foundation began the search for the coating that would protect this
national treasure for the next hundred years. The coating chosen was based
on inorganic zinc technology which was originated in NASA research and
tested around the world over ten years.

During the early 1980s in Japan (23), tests were carried out on
protective paints to study the effect of the number of coats applied, film
thickness, surface preparation and corrosive environment on the durability
of paints used on steel bridges. In Canada (24), comparative laboratory
salt spray resistance and accelerated weathering durability tests as well

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as chemical and physical analyses of the coating systems were performed. During this period the Pennsylvania Department of Transportation and the Federal Highway Administration sponsored research (25) to evaluate performance of environmentally acceptable coating systems for structural steel in accelerated and outdoor exposure tests.

III. CHAMBER DESIGN, INSTALLATION AND OPERATION

3.1 Chamber Design

To determine the best coating product, through accelerated corrosion
testing, a Harshaw/Filtrol environmental chamber was selected and UV source
was added on the top lid. The chamber has the ability to simulate a marine
environment. This modified chamber has salt solution level control
reservoir and humidifying tower level control reservoir containing salt
solution and distilled water. The function of the latter is to keep the
required level of fluid in the humidifying tower which connects the
saturated air line to the uni-fog dispersion tower that helps in
maintaining the appropriate humidity in the chamber. Numerous valves,
pressure gauges, thermometers, etc. are provided for easy handling and for
generating a desired environment in the chamber. Several controlled drains
exist for the expended salt solution to leave the chamber. A schematic
diagram of the environmental chamber is shown in Figure 5 (43). The
interior of the chamber is lined with an inert PVC lining, so no metallic
parts were used inside the chamber. A plexiglas tower was designed on the
cabinet with heater control and meters, a dry bulb thermometer, two cabinet
heaters, and an oil and water extractor and with air regulators. Plastisol
coated specimen support racks and two fiberglas support bars along with
slotted polyprophylene support panels were provided for holding test
panels.

The environmental chamber has the capability of intensifying the
variables that significantly affect the corrosion rate; for instance, there
is an option of varying the temperature over a wide range. Six high power
mercury light bulbs were installed in the chamber to produce ultraviolet

rays for the purpose of simulating UV-radiation effect of the sun. Design and position of these light sources ensure the uniform generation of UV-light in the chamber. In order to produce salt spray (fog) uniformly within the entire chamber, a uni-fog dispersion tower and atomizer nozzle were installed with special considerations. For example, the inclusion of an adjustable cone, as shown in Figure 6, ensures the uniform distributon of fog inside the chamber. This constant generation of UV-light and fog afforded an opportunity of utilizing the full chamber space and thus allowing testing of a large number of samples in one run. In addition, uniformity in these parameters eliminate the chances of errors attributed to the inconsistency in the values of variables from one location to another inside the chamber. The slope of cabinet roof ensures that the condensation on the roof does not drop on to the specimens.

In all salt spray (fog) testing, the control was empirical and, therefore, it was absolutely essential that all significant variations in both test specifications and testing techniques be eliminated completely to avoid or to minimize the run-to-run variability. This environmental chamber was so designed that all the known cabinet variations had been eliminated and, if operated properly, it can be assured that the test conditions and results can be reproduced from test to test.

3.2 Installation and Operation

The chamber installation and operational procedures are given in Appendix B.

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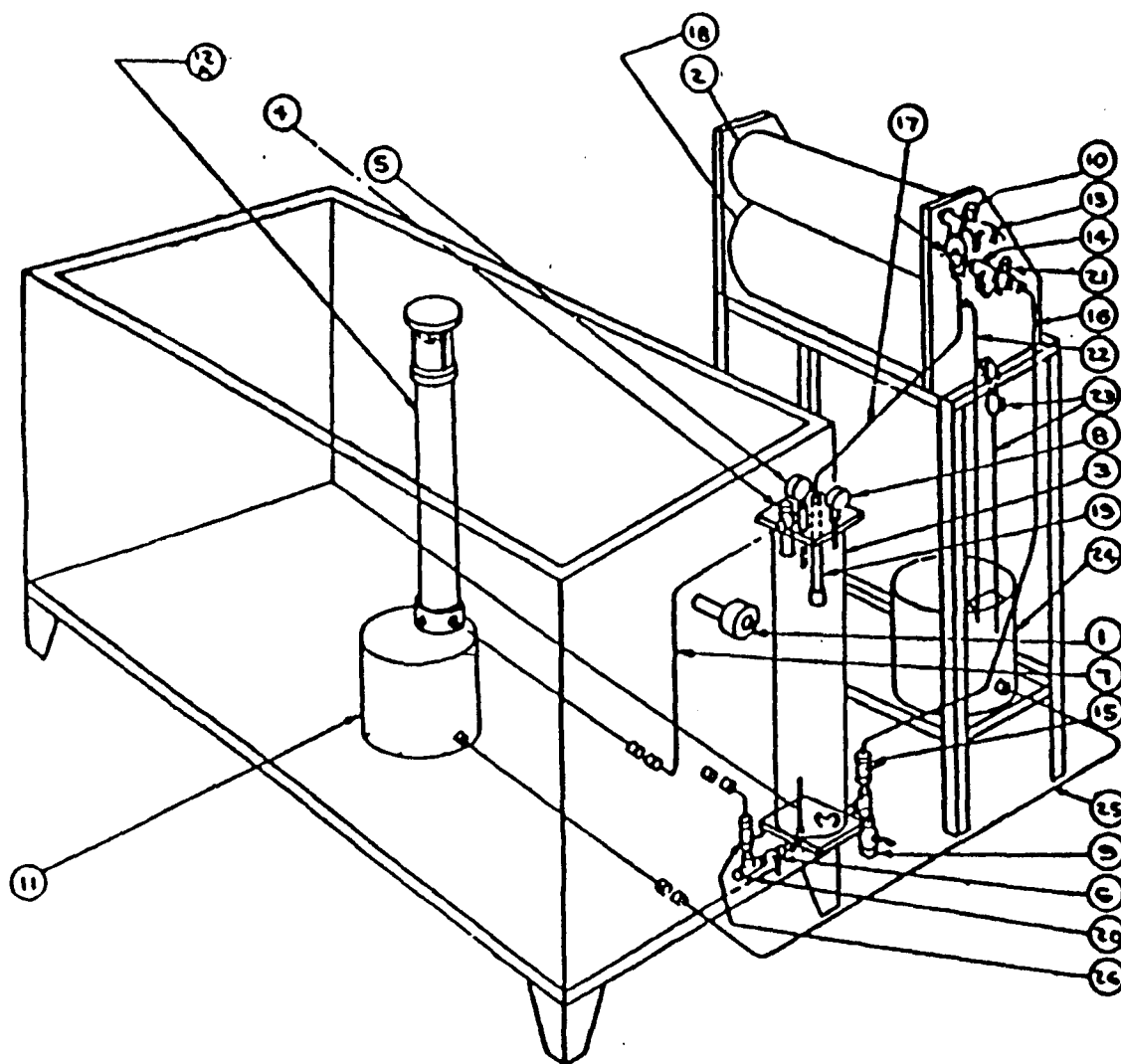
1. Cabinet Temperature Control
2. Humidifying Tower Level Control & Reservoir
3. Humidifying Tower
4. Humidifying Temperature Control
5. Humidifying Tower Pressure Gauge
6. Humidifying Tower Air Valve
7. Saturated Air Line
8. Humidifying Tower Temperature Gauge
9. Humidifying Tower Drain Valve
10. Filler Plug, Water
11. Internal Salt Solution Reservoir
12. Unit—Fog Dispersion Tower
13. Pressure Release Valve
14. Humidifying Tower Water Control Valve, Upper
15. Humidifying Tower Water Control Valve, Lower
16. Humidifying Tower Water Line
17. Air Control Valve & Line, Water
18. Salt Solution Level Control Reservoir
19. Air Control Pipe Assembly
20. 1/4" Air Supply Connection
21. Filler Plug, Salt Solution
22. Air Control Line, Salt Solution
23. Salt Solution Control Valve & Line
24. External Salt Solution Distribution Box
25. Salt Solution Connecting Line
26. Purge Control Valve & Line

Figure 5. Schematic Diagram of Environmental Chamber

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Figure 6. Details of Atomizer Nozzle

2 — Vertical Dispersion
3 — Tube & Throttle

4 — Atomizer Nozzle

6 — Cover & Adapter Flange

7 — Nipple (Air)

5 — Centering Nipple (Suction)

10 — Spacer Washer

11 — 1/4" Plastic Tube Fitting — Female

12 — 3/8" O.D. Plastic Tubing

8 — Strainer Assembly

9 — Internal Reservoir
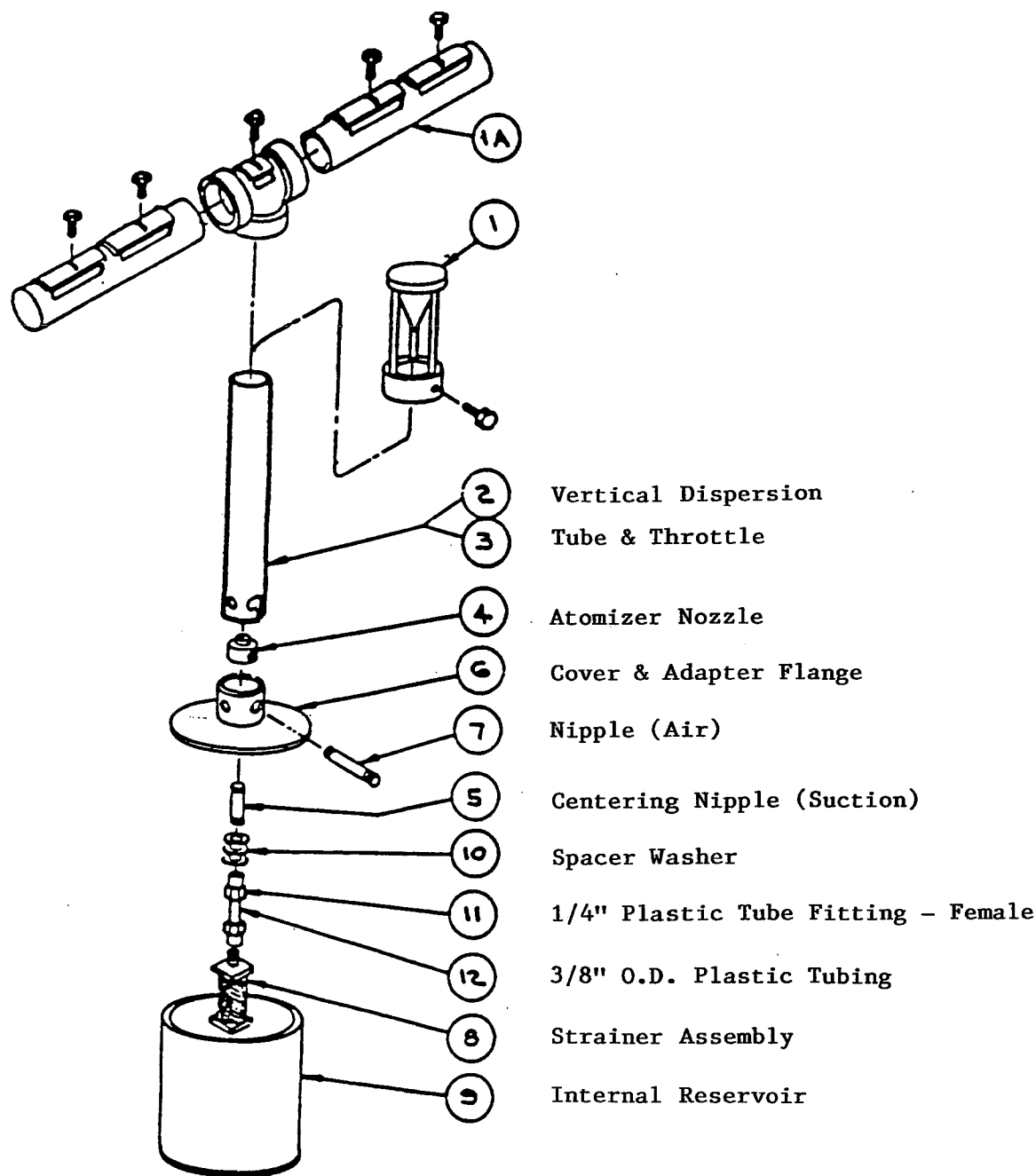
IV. THEORETICAL CONSIDERATIONS AND TESTING PREPARATION

4.1 Test Panels

Test specimens used are 3" x 6" x 1/8", A36 steel, plate panels
meeting the specifications of ASTM D609-73, Type 1 (26). It is a well
known fact that surface preparation is extremely important for the bonding
of coating to a substrate. Research carried out at Naval Research
Laboratories (27) has shown that 90% of all coating failures occur due to
inadequate pre-treatment methods. There are several surface preparation
methods, depending upon the type of coating to be applied and its intended
use. There is always a danger of poor results if the wrong type of anchor
pattern is employed. The shape of the profile, obtained by surface
preparation, is called anchor pattern. For example, if a good adhesive is
applied to a deeply undercut pattern, although the coating will be well
anchored mechanically, the anchorage may be stronger than the inherent
strength of the coating. Under differential expansion the movement could
then tend to shear the coating at the peaks of the pattern. On the
contrary, a poor adhesive on a smooth surface will break loose under mild
mechanical attack. National Association of Corrosion Engineers (NACE) has
formed a task group to study the effectiveness of the various surface
preparation methods. Figure 7 (8) describes typical anchor pattern
profiles.
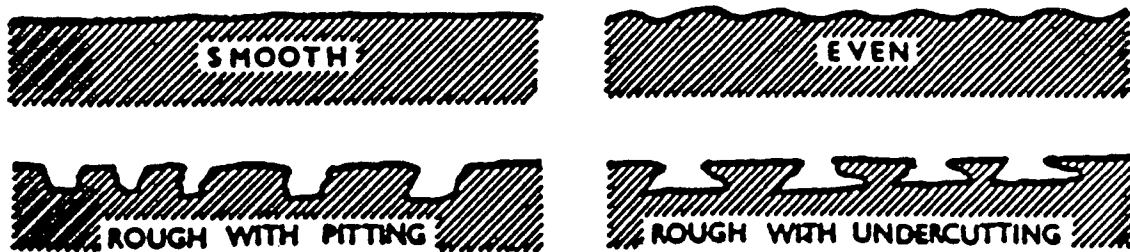
Figure 7. Typical Anchor-Pattern Profiles(8).

The main objective of the surface preparation is to produce effective and maximum adhesion for the coating by providing a direct contact between the paint and the base metal. It has a general two-fold purpose. Surface preparation removes any contamination from the substrate, eliminating metal oxides, old coatings, dirt, chemical fallout and similar contamination. Secondly, it increases the surface area by increasing the surface roughness. The intent of this was to increase the amount of exposed surface area per unit of actual area and thus increase the effective adhesion surface. (It should be noted that a coating that is naturally adhesive will require only a little mechanical anchorage to the metal, whereas a coating with poor adhesive properties will require good anchorage.)

The test panels were cleaned to meet the requirements of Structural Steel Painting Council specification, SSPC-6, commercial blast cleaning. The anchor patterns thus obtained were measured by Keane-Tator surface profile comparator to verify whether the prepared surfaces meet the shop cleaning guideline, 521.03(b) 16 of special provision number 196, Alabama

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COATED SURFACE

1/4" — scored surface

1/8"

1/16"

1/32"

6"

3"

COATED
SURFACE

A   A

3"

Total
thickness

Finishing coat

Undercoat(s)

Priming coat

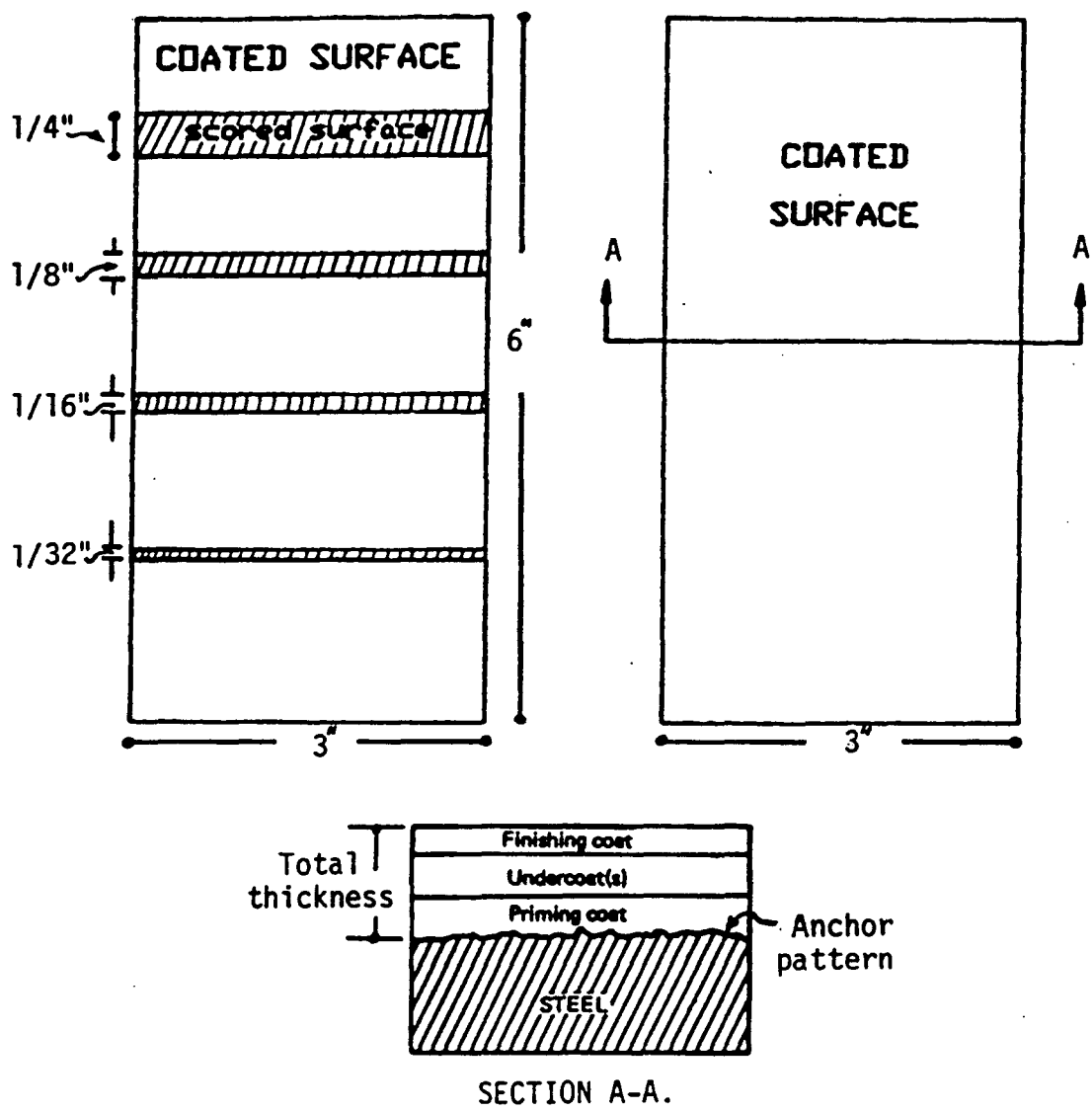Anchor
pattern

STEEL

SECTION A-A.

Figure 8. Standard Test Panels

Highway Department Standard Specification. In order to assess sacrificial protection, the coating of each duplicate specimen was scored to the base steel with a series of lines 1/32, 1/16, 1/8, and 1/4 inch wide, by means of a special scribing tool (28). Scribing was not done lengthwise as suggested in Ref. (28), simply because specimens were exposed flat and not with an angle, so the question of running of solution droplets along the scribe did not arise. Figure 8 shows the standard test panels and its cross-section.

4.2 UV-Intensity Simulation

It is of interest to estimate the extent of the effect of UV-light on the rate of corrosion. The European weathering literature divides the solar UV spectrum into three ranges. UV-A is the energy in wavelengths between 400 nonometers (nm) and 315 nm. UV-B is the 315-290 nm range, while UV-C includes the solar radiation below 290 nm, which never reaches the earth's surface. According to G. W. Grossman (29), this classification is very convenient and useful. The 400 nm upper limit for UV-A is the
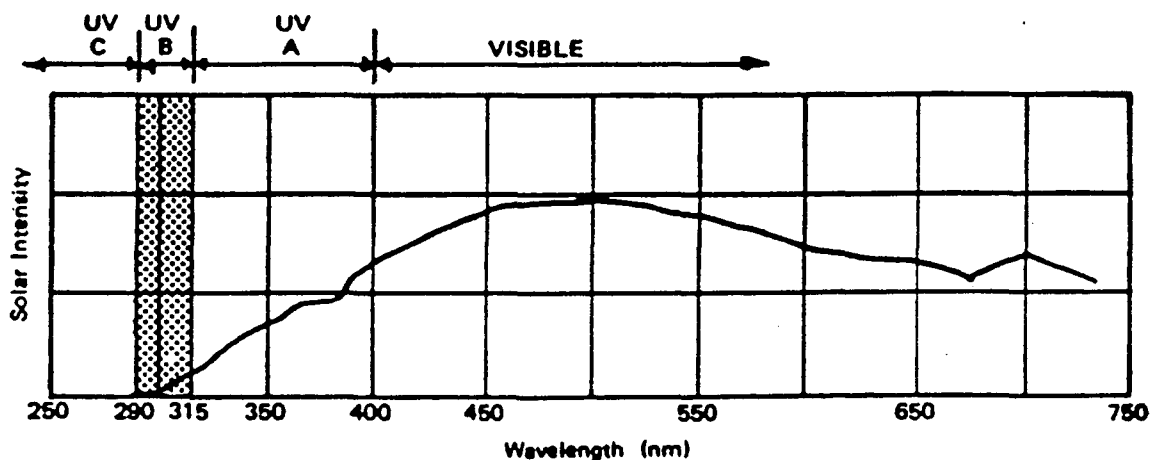

Figure 9. Division and Classification of Solar Ultraviolet Spectrum (29)

generally accepted boundary between visible light and ultraviolet energy.The UV-C boundary of 190 nm is a sharp cutoff of solar radiation at the earth's surface caused by ozone absorption. Figure 9 (29) illustrates the division and classification of solar ultraviolet spectrum.

The quantum theory explains the different effects of these ranges. Light energy is transmitted in discrete units called photons. The energy in photons is inversely proportional to wavelength. The sun emits radiation in wavelengths well below 242 nm and the energy of photons in wavelengths below 242 nm is high enough to dissociate oxygen to create ozone. Ozone, in turn, is a highly effective UV absorber, absorbing all solar radiation below 290 nm so that energy in such wave lengths never reaches the earth's surface. Ozone partially absorbs UV-B so that the amount of UV-B in sunlight varies with solar altitude. At solar altitudes between 60^0 and 90^0, the maximum amounts of UV-B reach the earth's surface. Scott (30) has shown what occurs when the UV-B is excluded from sunlight by wintertime atmospheric filtering. However, the observed reduction in degradation could be partially attributed to reduced temperature stress. The ozone cutoff in sunlight and quantum effect make it possible to reproduce the effects of sunlight with relatively low cost. The UV-stress obtained with the mercury bulbs emitting UV-B is comparable to noon midsummer sunlight on a clear day. Increasing UV stresses by employing UV-C radiation is not acceptable for evaluating materials, as suggested by Stieg (31). Using UV-C is not only uneconomical but also unnecessary, as UV-B has the capability of doing the job. According to Ref. (24), natural exposure is limited to about six hours of UV-B daily by the earth's rotation, while there are no constraints on the duration of the UV-B exposure in the laboratory.

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UV-intensity data were collected in ambient conditions by means of digital UV-meter, and variations in different types of daily weather were observed. This can be reproduced adequately in the chamber for simulation purposes. The utlraviolet meter used is Spectroline DM-365N, designed by Spectronics Corporation in New York. The maximum value recorded outdoor was about 1800 uW/cm^2. It can be argued that, as the UV-intensity in the chamber is about 340 units less than the peak outdoor value, there may not be any amplification of this parameter. This is simply not true because of the fact that peak value lasts only for a limited time in the ambient weather, as shown in Figures 10 through 12. Secondly, there would be no UV-light when weather is cloudy. On the contrary, in the chamber a reasonably high value was maintained during the entire testing period. Thus the magnification was achieved through constant value of about 1460 uW/cm^2 throughout the testing. Variation in UV-intensity, especially during exploratory testing, was introduced by changing the level of racks holding specimens, i.e., by increasing or decreasing the distance of specimens from UV-light source.

4.3 Discussion on Test Parameters

In this research work, variables, other than UV-intensity and temperature, are classified into three categories:

1. Solution variables.

2. Specimen variables.

3. Test procedure variables.

4.3.1 Solution Variables: The composition of the corrosive medium must be controlled, even with respect to unintentional impurities, since analytically pure chemicals often have a different effect from the
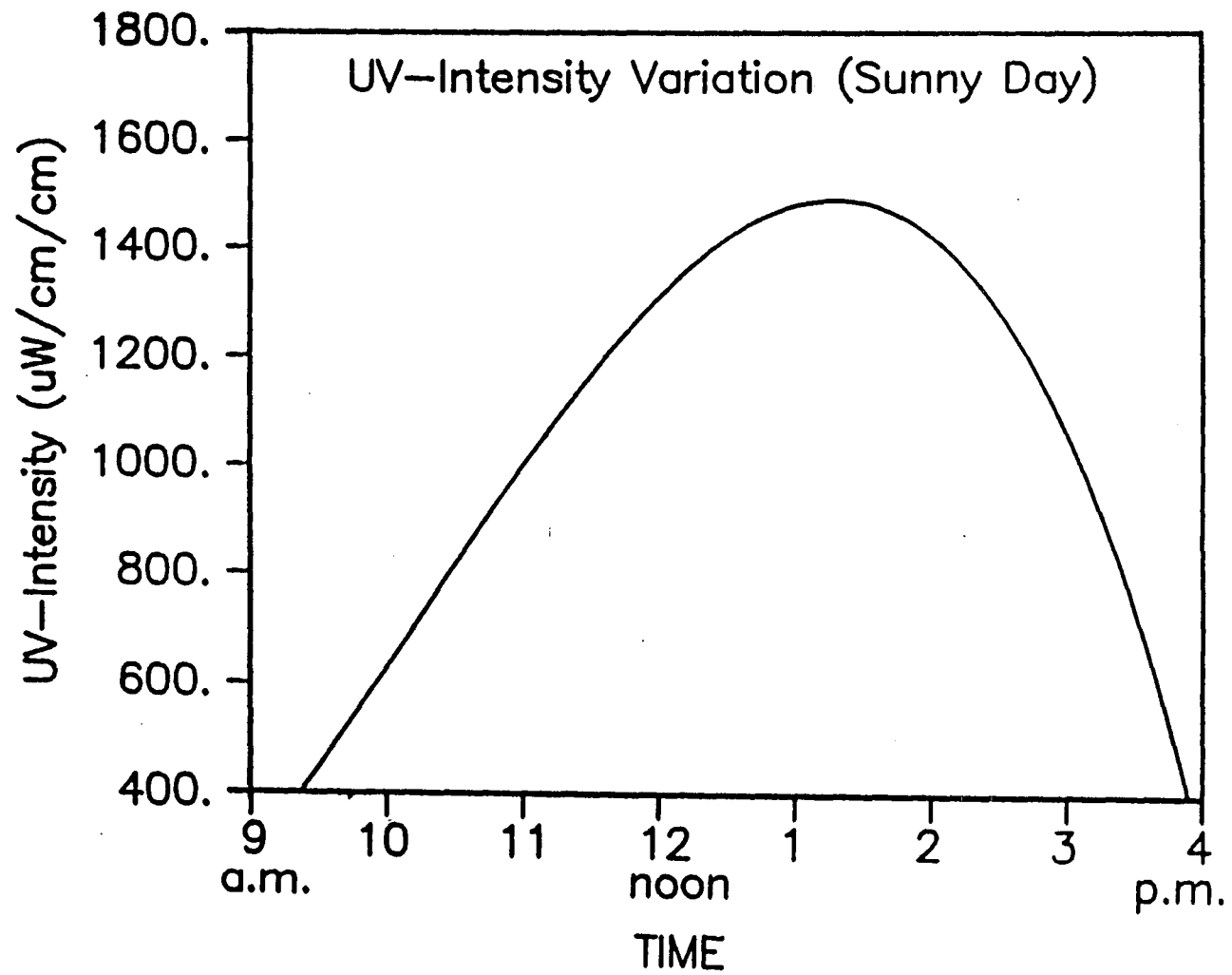
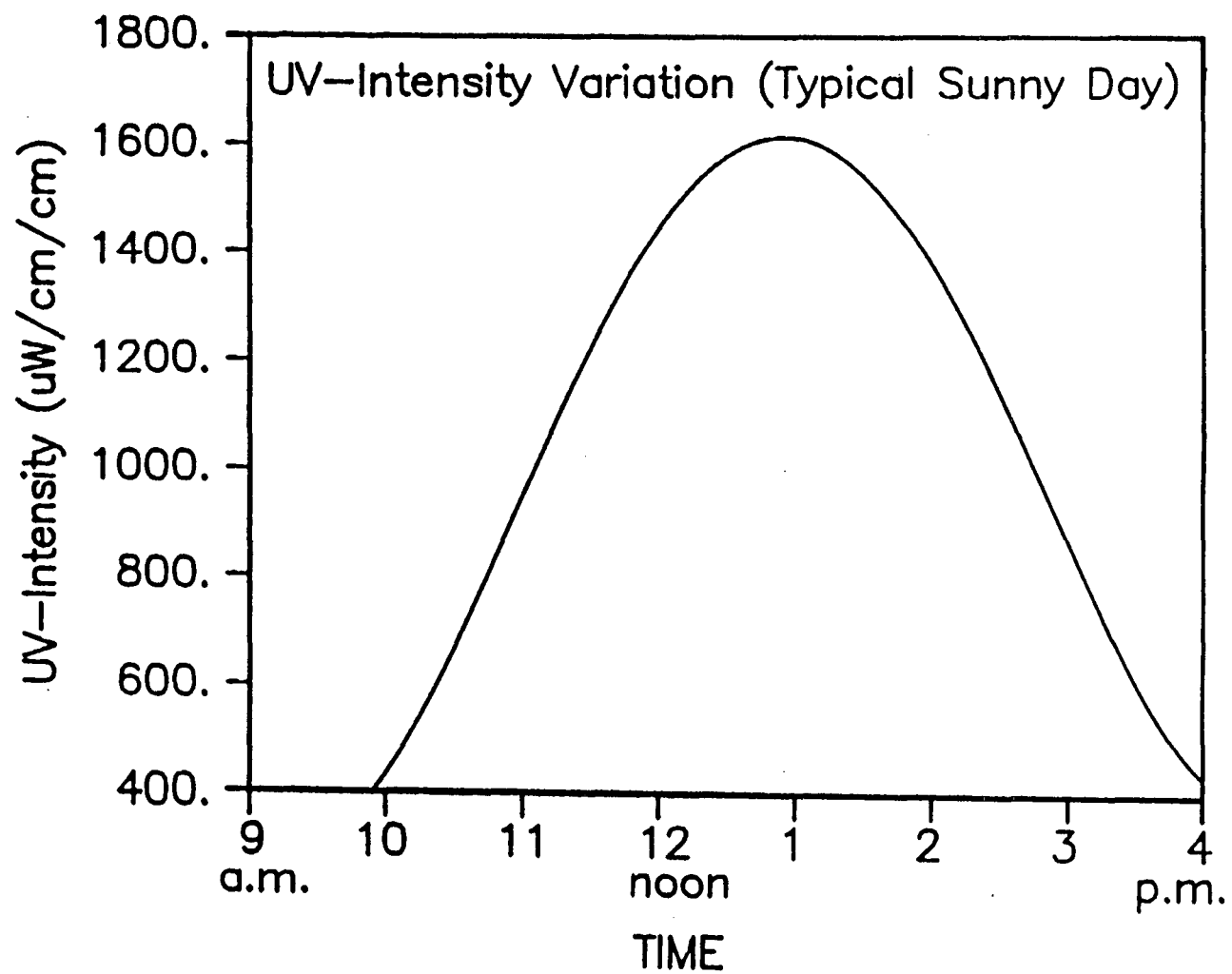Figure 10.   UV-Intensity Variation (Sunny Day)

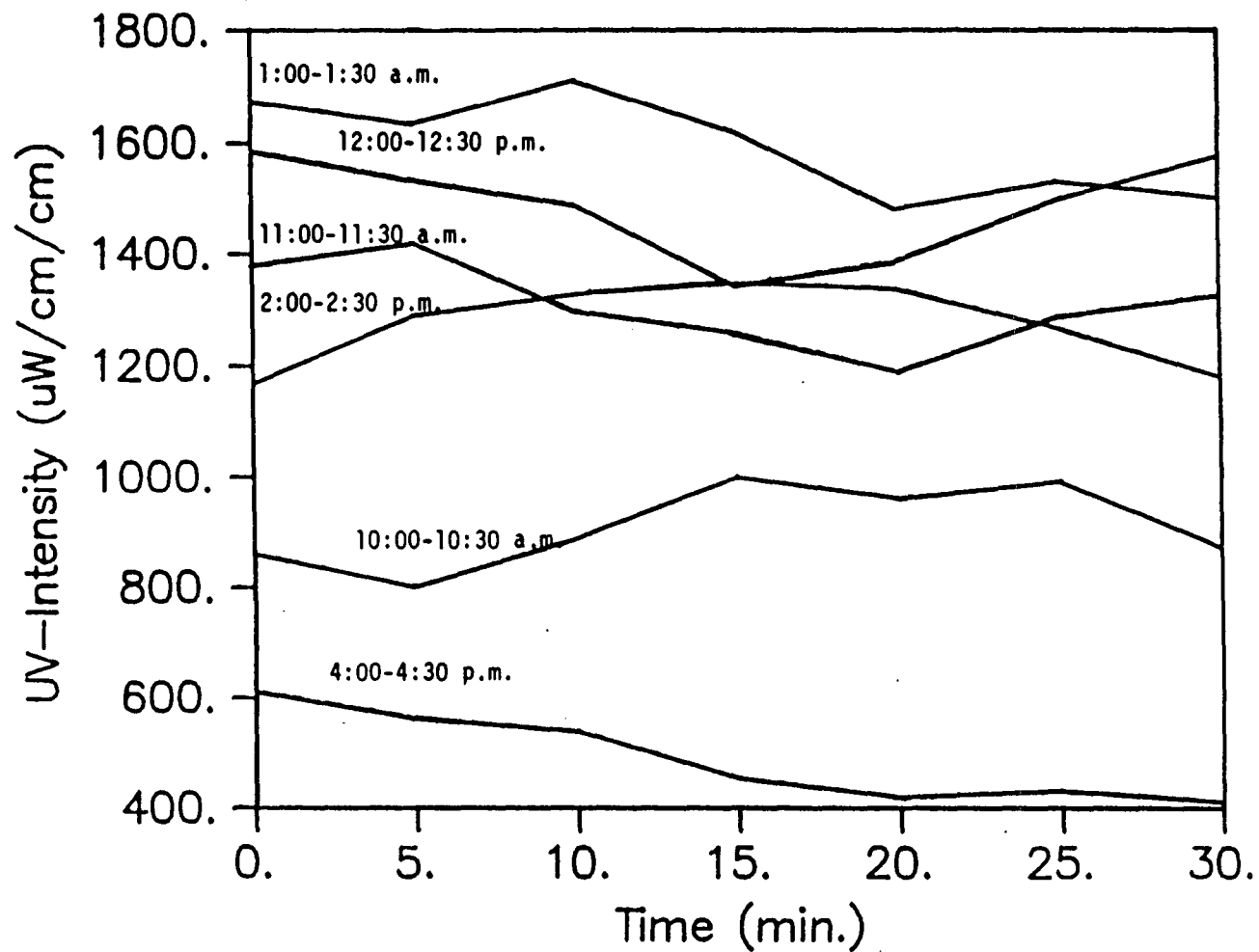Figure 11. UV-Intensity Variation (Typical Sunny Day)

Figure 12. UV-Intensity Variaiton in Ambient Condition (Over a Period of 30 Minutes)

polluted solutions encountered in practice. That is why ordinary tap water was not used, although suggested by Waldron (32) in the preparation of salt (fog) solution. Also, it is inconvenient to carry out a laboratory test in natural sea water which has to be transported a long distance, stored, and which may not have a constant composition. Furthermore, acceleration in the testing may not be achieved by natural sea water due to its high pH value, i.e., low acidity. It is, therefore, usually customary to carry out laboratory test aimed at testing corrosion in marine environments with artificially produced sea water. This will give a far more reproducible environment than water taken directly from the sea.

The salt solution to be used on the test specimens in the chamber was prepared by dissolving 5 parts by weight of sodium chloride salt (NaCl) in 95 parts of distilled water. Then one gram of copper II chloride ($CuCl_2 \cdot 2H_2O$) was added to each 3.8 liters of salt solution and the solution was mixed thoroughly by means of a mechanical arrangement having a rotating shaft, connected to a motor, which rotated the shaft at various speeds for mixing the solution. The pH of the salt solution was adjusted by the addition of acetic acid and was measured electrometrically as per ANSI/ASTM B368-68 specification (33). The presence of copper chloride substantially increased the corrosivity of the solution, thereby shortening the test period.

Greater amount of salt contents, beyond optimum value, were not used to increase the severity. The use of copper chloride, acidification with acetic acid and the application of slightly elevated temperatures were practiced instead. It was established by exploratory testing, which will be presented next, that the use of salt content more than 5% was

impractical because of the danger of clogging nozzles and secondly excessive salt might create non-uniformity in the fog. This non-uniformity inside the chamber may yield erroneous data. As suggested by Portevin and Herzog (34), density, fineness and uniformity of the spray were taken into consideration. Humidity, in the testings, was not a variable and it waskept to a constant equivalent or slightly greater than that of the solution being sprayed, as proposed by Darcey (35) and Champion (36). If the humidity is too low the mist tends to lose water and become a dry fog which is less corrosive and may cause choking of jets. If the humidity is higher, then the fog will become diluted. Perryman and Hadden (37), in the 1950s, carried out research regarding optimum relative humdity for maximum corrosion.

4.3.2 <u>Specimen Variables</u>: Consideration was given to quality control regarding specimen preparation, testing and their performance evaluation. Coatings were applied either by spray or by hand in such a way that the formation of air bubbles was avoided. Air bubbles can cause adhesive failure early during the testing. From the strong intercoat adhesion view point, top or finish coat were applied when the primers were fully cured. The curing time and formation of dry film thickness (DFT) depends upon the environmental conditions, during and after application, which were kept under control. The DFT was maintained uniform throughout the panel, and as a check, three readings were taken at different points on the panel to measure DFT, by a magnetic dry film thickness measuring gauge.

4.3.3 <u>Test Procedure Variables</u>: Exposure time, temperature of the chamber, angle of exposure of panels with respect to UV-light source, UV-intensity level and number of interruptions, especially at exploratory

testing stage, for data collection purposes are the parameters that were kept identical for all the samples to be studied for comparative analyses. Before evaluation, specimens were removed from the chamber and cleaned and dried so that true nature and extent of corrosion could be ascertained. Wet and dry cycles were employed simultaneously. However, during the final stages of the testing, unsynchronized cycles were also used as suggested by W. R. Tooke of Tooke Engineering Associates, Atlanta, Georgia (38). This was to study the effect of UV-light alone on the degradation rate, because it can be argued that presence of fog inside the chamber may lessen the UV-intensity.

V. EXPLORATORY TESTING AND TEST PROCEDURE

5.1 Exploratory Testing

The basic actions in weathering are known and quantified. The time a material is exposed, temperature, UV-intensity and water (with certain pH) are the primary variables in natural weathering. Reproducing them exactly in the laboratory can provide acceleration by eliminating idle time. Further acceleration is possible by maximizing UV-light, water and temperature effects within certain limits. The experimental work performed indicates that the most important factor in accelerated laboratory weathering is the proper balancing of these factors.

In an accelerated environment, there is always a danger that speed may be purchased at the expense of validity of these tests, since a proper balance of accelerating factors is somewhat difficult to obtain. In order to find the optimum combination of test variables, such as salt concentration, pH of solution, chamber temperature and UV-intensity, and in turn to avoid either concentration or dilution of the salt (fog) solution, exploratory testing is a must. This is to establish the boundary within which the simulation can be achieved at higher acceleration rates without the distortion of results. It was realized that the use of salt solution of varying pH, during exploratory testing, is advantageous to cover the full possible variation of concentrations, since it frequently happens that particular ranges of concentration are especially corrosive to some coatings.

In this study, exploratory testing was performed on a wide range of protective systems; for example, Alabama State Highway Department bridge paint system, Texas Department of Transportation (D.O.T.) system, Florida

D.O.T. system, Louisiana D.O.T. system, Georgia Highway Department system, and others were tested with several combinations of test variables. Testing was done with pH values ranging from 3.4 to 3.0, salt percentage 4%-6%, UV-intensity 800-1460 uW/cm^2 and temperature from 95-105^{0}F. Curves are plotted based on current ASTM specification (39) regarding evaluation of the degree of rusting on painted steel surfaces. Scale and description of rust grades with respect to percentages of area corroded are illustrated in Figure 13 (39). Figures 14 through 16 show results of exploratory testing. These figures were drawn by using GRAFKIT curve fitting software; the resulting polynomial, values of constants, correlation coefficients, R, specimen type, etc. are listed in Table 2. On the basis of exploratory testing optimum values of parameters were established. For example, 5% of salt (5 parts by weight of sodium chloride salt in 95 parts of distilled water) is the optimum value, because when 6% of the salt was used salt deposition on samples was observed. Waldron (32) agrees that high concentrations have little advantage in increasing the attack. He claims that the 20% solution gives a lower temperature coefficient owing to its lower oxygen solubility. It was expected that the maximization in UV-intensity would expedite the corrosion rate up to some extent. In the latter phase of the exploratory testing UV-intensity values ranging between 1380-1460 uW/cm^2 were used instead of 800 uW/cm^2, which was used initially.

5.2 Special Considerations in Accelerated Tests

The two principal incentives for accelerated corrosion tests are the ability to conduct tests in a standard environment, thereby eliminating uncontrolled variables such as those which exist in natural environments, and the opportunity to obtain meaningful test results within a relatively

Figure 13. Examples of Area Percentages (39)

Exploratory Testing Results For Georgia System

Variables	Test I	Test II
pH	3.2	3.0
Temp. °F	102	104
Salt %	5	6
UV-Intensity (uW/cm^2)	1280	1350
D.F.T.(mils)	6	6

——— Test I , plain
—·—·— Test II, plain
— — — Test I , scored
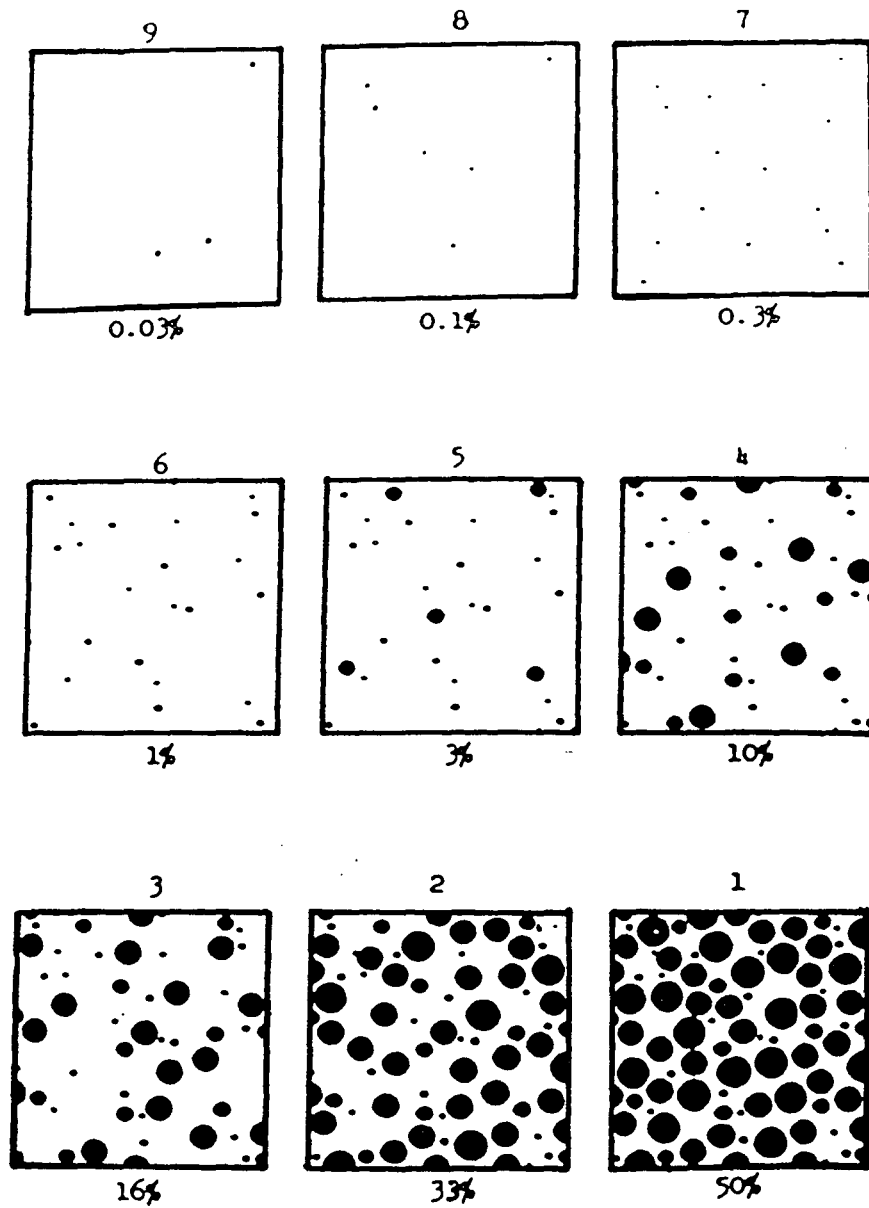--------- Test II, scored

Y-axis: % of Panel Area Corroded
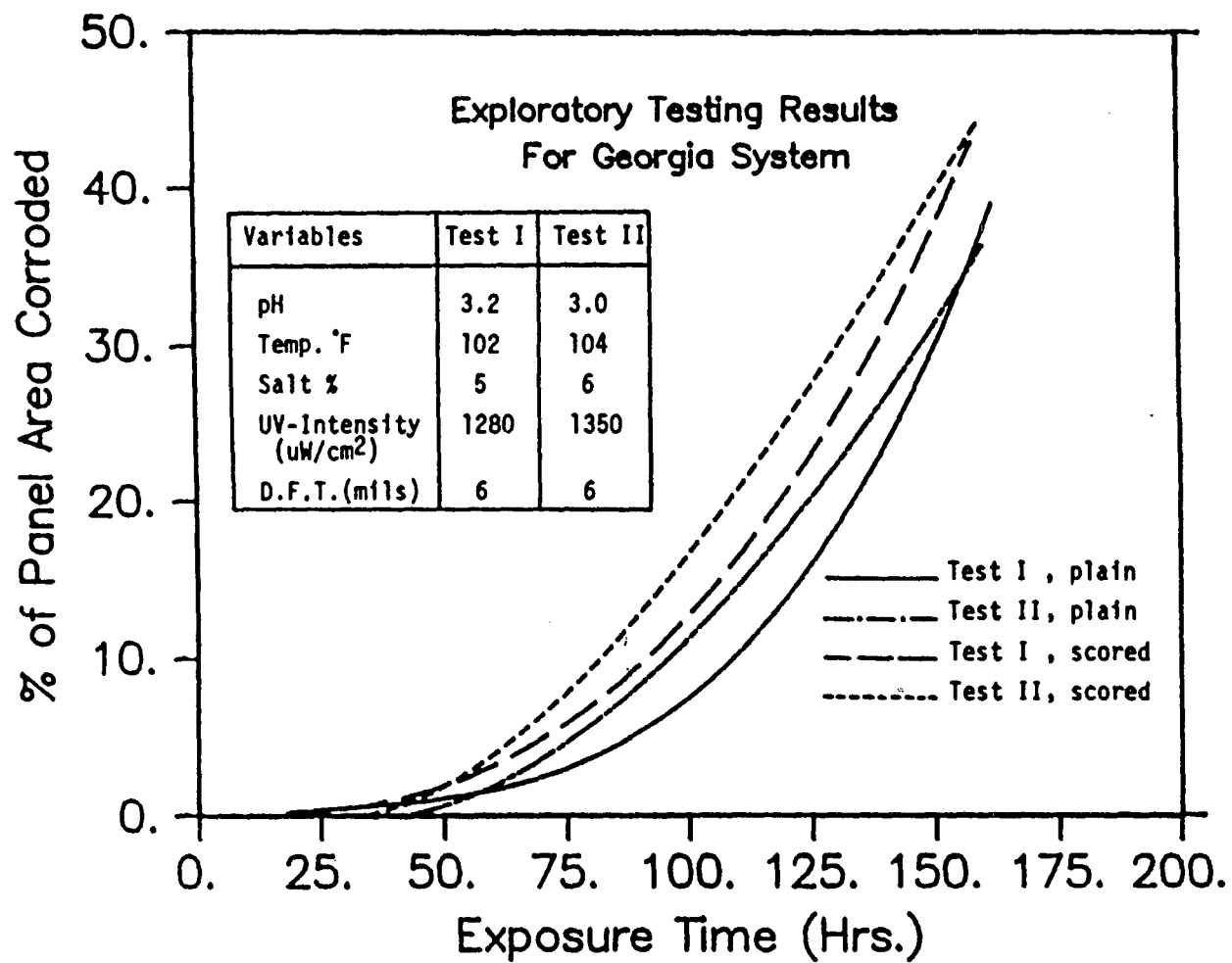
X-axis: Exposure Time (Hrs.)

Figure 14. Exploratory Testing Results for Georgia System
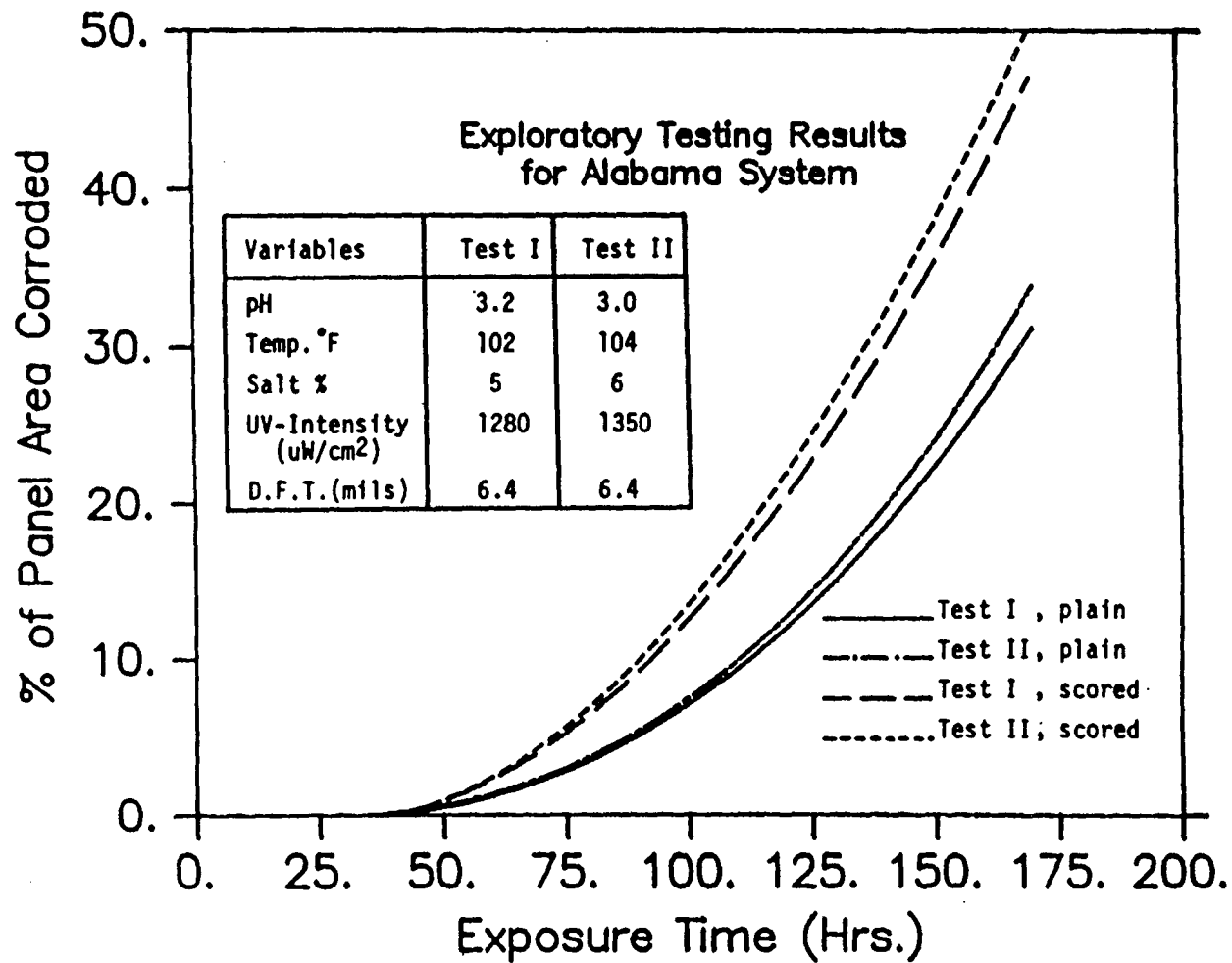
Figure 15. Exploratory Testing Results for Alabama System
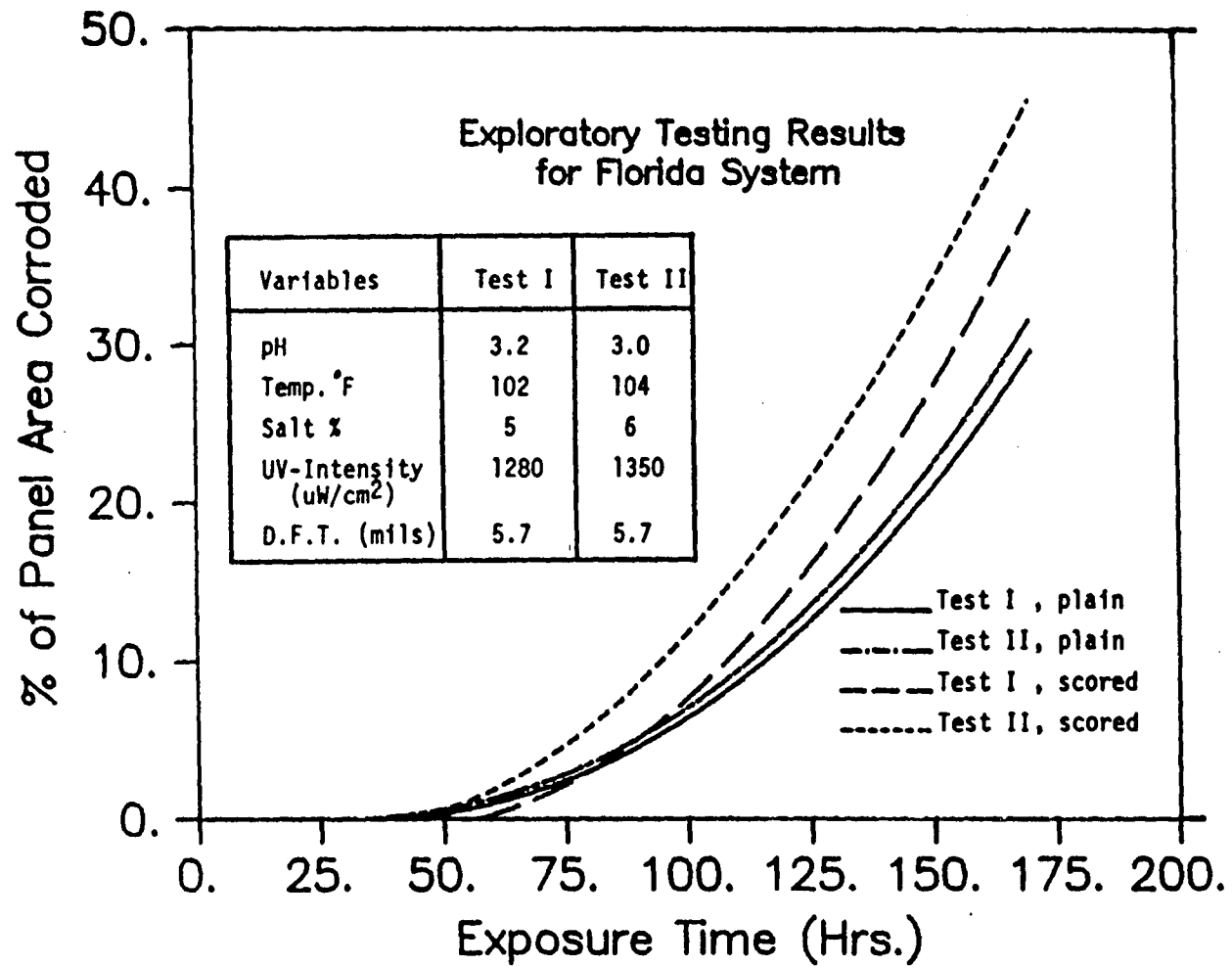
Figure 16. Exploratory Testing Results for Florida System

Table 2

Constants and Standard Deviations of Cubic Polynomial
for Figures 14, 15 and 16

$Y = A + BX + CX^2 + DX^3$; where X = Exp. Time (Hrs.), Y = % Corrosion

Figure Number	Specimen Type	Test Number	Constants				Coefficient of Correlation, R
			A	$B(10^{-2})$	$C(10^{-4})$	$D(10^{-6})$	
14	Plain	I	−0.638	6.29	−13.23	15.1	0.984
		II	1.62	−15.1	27.7	− 2.95	0.997
	Scored	I	0.355	− 3.23	9.51	6.06	0.990
		II	1.97	−19.4	42.7	8.74	0.996
15	Plain	I	0.561	− 5.58	9.76	2.41	0.998
		II	0.420	− 4.36	7.77	3.73	0.998
	Scored	I	1.43	−13.8	26.4	− 1.49	0.998
		II	1.72	−15.9	30.0	2.28	0.998
16	Plain	I	0.646	− 5.76	8.87	2.67	0.999
		II	0.381	− 4.07	7.21	3.55	0.998
	Scored	I	2.16	−15.6	20.1	0.964	0.996
		II	1.72	−15.5	27.4	− 1.81	0.998

short time. The latter applies particularly to the inspection and quality control of coated parts or materials. The availability of a test giving prompt quantitative results is of a great convenience in preparing manufacturing specifications involving metallic coatings. One of the most difficult problems lies in the desire to obtain quick reliable information, from accelerated tests, on the probable life of a system in natural environment. Although efforts are not directed towards predicting the life of a coating on the basis of test results, it cannot be over-emphasized the importance of avoiding undue acceleration, which may alter the character of the corrosion and vitiate the results obtained. Since corrosion is a natural process, one should understand that there is a limit to the control which can be exercised to increase reproducibility without seriously interfering with the natural course of action. Exploratory testing afforded an opportunity to know the limits up to which acceleration could be achieved.

The purpose of coating systems, generally, is to provide long-term protection to steel structures, so the evaluation of these materials rely heavily on accelerated laboratory testing. In this study, several primers along with numerous finish coats that are currently in use in many states throughout the country were tested. Consideration was given to the color of the system to be tested, since failures will be more apparent on a finish that shows color contrast with rust. In cases where there are doubts as to whether the method of preparation has affected the results, replicate tests may be desirable. So, replicate specimens were prepared and were tested with contant values along with consequential variation in the test parameters to check the run-to-run variability and to see the

effects of various influencing parameters independently. Extra care should be, and in fact was, exercised in the relative evaluation of systems with large difference in dry film thicknesses, because by increasing the dry film thickness of some of the apparently inferior paints, better performance could have been attained. Therefore, two- and three-coat systems were tested separately and not compared with each other for performance evaluation purposes. Corner effects were also studied because bridges, like offshore structures, are extremely vulnerable to corrosion, perhaps more so since many bridge structures are formed from standard steel shapes, with all of the corners, edges, crevices and surface defects inherent in such shapes (40). Scored samples with the maximum scribed surface width (i.e., 1/4 inch) were meant to study the coatings when damaged. Shop painted structures are susceptible to minor damages because of handling and transportation to the site. On the other hand, the minimum scribed width on scored specimens was intended to simulate micro-cracks in the weld zones due to large temperature variations.

Salt spray tests may be used as absolute tests or as comparative tests. When used as absolute tests, the results can only be compared with others in the same or other cabinets if the test conditions are maintained completely within specified limits. When used as comparative tests, standard samples of known performance are included in each batch of samples tests; under these conditions slight variations in test conditions are less important since the performance of the test samples is compared with that of the standard samples.

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5.3 Test Procedure

5.3.1 General

The test procedure recommended herein is primarily based on various current American National Standards Institute (ANSI)/American Society for Testing and Materials (ASTM) specifications, for example, copper-accelerated acetic acid-salt spray test (33), salt spray test (41) and acetic acid-salt spray test (42). The reason for closely following these standards in order to develop a reliable testing schedule is that all these methods are applicable to salt spray testing of ferrous and non-ferrous metals and can also be used to test inorganic and organic coatings, especially where such tests are the basis for materials or product specifications. Furthermore, these specifications have been used to a considerable extent for the purpose of comparing different materials with an acceptable standard. The recent elimination of many cabinet variables and the improvement in controls have made the three standard testing procedures into useful tools for many industrial and military production and qualification programs.

5.3.2 Laboratory Experimental Technique

The specimens were placed in the chamber just prior to bringing the test chamber to the required temperature and turning on the spray. Storing of test panels in an idle chamber overnight or for another significant length of time has a tendency to affect the test results. The specimens in the chamber were arranged in such a manner that they did not come in contact with each other or with any metallic material or any material capable of acting as a wick. Allowance was made for free settling of fog on all the panels. Racks holding specimens were arranged side by

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side at different levels, so that salt solution from one specimen should not drip on any other specimen. Two clean fog collectors were placed within the exposure zone so that no drops of solution from the test specimens or any other source would be collected. Suitable collecting devices are glass funnels or crystallizing dishes. Funnels and dishes with a diameter of 10 cm have an area of about 80 cm^2. The sodium chloride concentration of the collected solution shall be 5 ± 1 weight percent.

The compressed air supply to the nozzle or nozzles for atomizing the salt solution was checked for oil and dirt and maintained between 10 and 25 psi. The nozzles were directed so that none of the spray could impinge directly on the test specimens. Testing was stopped about every 8-12 hours for inspection and corrosion assessment of test panels. Evaluation of degree of rusting was done according to ANSI/ASTM D610-68 specification (26). Scale and description of rust grades are illustrated in Figure 8. Each time specimens were removed from the chamber for evaluation, they were gently rinsed and then immediately dried to examine the nature and extent of corrosion. Information such as percent of panel area corroded and corresponding exposure time along with other data regarding test variables was recorded.

It should be noted that there is seldom a direct relation between salt spray (fog) resistance and resistance to corrosion in other media, because the chemistry of reactions, including the formation of films and their protective value, oftentimes varies greatly with the precise conditions encountered. This testing approach is considered to be the most useful in estimating the relative behavior of closely related materials in marine atmospheres, since it simulates the basic conditions with considerable

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acceleration. When this method is used for research, it may prove advantageous to operate with a different solution composition or concentration or temperature or at a different UV-intensity. Material specifications should always be written in terms of the standard requirements of the appropriate salt-spray method, thereby making it possible to test a variety of materials from different sources in the same equipment.

5.4 Analysis of Test Data

In the past two decades, however, the advancement in environmental chamber design as well as a better understanding of fundamentals in corrosion and weathering process has enabled us to attempt correlation studies, at least in a qualitative sense, between laboratory tests using a variety of accelerated environmental chambers and natural outdoor exposures. The objective of such studies is primarily to determine the relative merits of materials. In this study, the assumption was made that rankings established in a severe environment will prevail in more moderate weathering conditions as in all other accelerated laboratory testing.

Unless otherwise specified in the specification covering the material or product being tested, the test shall be continuous for the duration of the entire test period. Continuous operation implies that the chamber be closed and the dry and wet cycles operating continuously except for the short daily interruptions necessary to inspect the specimens, and collect the data, such as temperature within the exposure zone of the chamber, latest exposure time and percent of panel area corroded. In this study, as mentioned earlier, ASTM photographic standards were used to evaluate the degree of corrosion on test samples. Whenever the chamber was stopped for

data collection purposes, the percentage of specimen area rusted, based on ASTM photographic standards (Figure 13), was recorded along with respective exposure time. It was almost impossible to establish the percentage of panel area corroded precisely, since visual observation is not a reliable means of measurement. In this study, the objective was to identify the best coating system on relative grounds rather than to establish the exact rust grades or to predict the life of a system in natural environment. Exposure time in hours and percent of corrosion were plotted on horizontal and vertical axes respectively. Curve fitting was performed on data obtained. Various higher order polynomials were tried but a third order polynomial seems to fit the data more closely. Tables rendering the information about empirical equations, constants, coefficients of correlation, etc., and figures representing the outcome of testing are included in the Appendix A.

As shown in the Appendix A, coating systems, widely used in several states, namely Alabama, Florida, Georgia, Louisiana, Tennessee and Texas, along with other prominent brands, such as, Amershield, Amerlock 400, supplied by Ameron Paint Manufacturing Company, were tested and relative rankings were made. Texas Department of Transportation System, as shown in Figure 26, topped the ratings. The Florida Highway Department system, as shown in Figure 19 through 21, was at second place. These sytems with a dry film thickness (D.F.T.) in the neighborhood of 6.0 mils performed even better than the other systems of up to 8.0 mils. It is important to note that the difference in dry film thicknesses is due to the variability in viscosity of coatings and not because of the number of coats applied. For comparative analysis it is necessary that the number of coats should be the

same for all the systems. In this research, all the coatings being tested and compared were of identical number of coats. Alabama Highway Department system (Figures 17, 18, and 28) along with Tennessee system (Figure 22) were tied at third place. Louisiana system (Figure 25) was at fourth position which was followed by Georgia system (Figures 23 and 24). Although making such rankings was possible based on the test results, it should be noted that the maximum differential of the corroded area in the unscored specimens (except Georgia system) was only 3%.

As all these products were tested under accelerated coastal environment, it is possible that the ratings may not represent the true behavior pattern in the prevailing weather conditions away from the coast line. By behavior pattern, it is meant that the rust and failure patterns may vary but the relative standings which are based on protective characteristics are expected to remain unchanged in a much less harsh natural environment. As far as the testing of specimens, supplied by paint companies, the aliphatic polyurethane system has shown greater resistance against corrosion than inorganic zinc, vinyl chloride copolymer, epoxy zinc etc. The former took about 175 hours for the rust to cover 50% of the paint testing panel area, while the later reached the same state in about 150-160 hours. Fifty percent of specimen area corrosion was considered a failure criterion in this study, hence once rust reached the 50% mark the testing was stopped. The ratings established here, represents test results of unscored specimens rather than of a scored one, since it is difficult to judge the protective properties of a coating in scored specimens where metal surface is exposed to the severe environment.

VI. RESULTS: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From this study, the following conclusions are drawn.

1. An environmental chamber of fairly simple construction, as modified for this research, demonstrated a useful capability for accelerated simulation of the effects of corrosion on painted panels of a sea coast environment. The chamber exhibited high precision of test results within runs.

2. During testing, information concerning percent of panel area corroded and corresponding exposure time were recorded on the basis of ASTM D610-68 specification and curves were plotted. These curves and tables are shown in the Appendix A. These plots can be used in determining the correct order of coating systems, since they are based on replicate testing results. These curves reflect that the rate of corrosion is a non-linear function of time.

3. It was perceived that corrosion, like other chemical reactions, is markedly affected by temperature. Somewhat higher rate of corrosion was observed in specimens which were tested with cabinet temperature of 104^0F, as compared to temperature of 95^0.

4. The proposed experimental technique is found to be particularly applicable to research studies of the effect of altering parameters and for the evaluation of the quality of the product. This is so because of the normal duration of test, which runs for 175-200 hours or more, giving ample opportunity for observations at practical intervals of the effects of minor parameter changes.

5. Irrespective of the values of parameters and coating system type, some initial time is required for the rust to initiate, implying that the parameters start affecting the surfaces of coated specimens after some time due to the resistance of the system. This elapsed time period ranges between 20-40 hours, and is directly proportional to the dry film thickness.

6. The maximization in UV-intensity did not affect the corrosion rate markedly. However, somewhat greater effect was observed in scored samples. Also, some discoloration or dullness was noticed in the color of darker coatings.

7. It was noticed that when the data were collected with large intervals of time (10-12 hours), the observed rate of corrosion was more than the case when data were collected with lesser time intervals (6-8 hours).

8. In most of the instances, it was seen that the corrosion starts from the perimeter and corners of panels and from the brink of scored surfaces.

9. Rate of degradation was found to be higher in scored samples, particularly after the elapsed time of 40 hours or so.

10. It was marked that, once rust was initiated (i.e., after the breakdown of paint film thickness), the corrosion rate increased sharply.

11. The life of a coating system was directly proportional to the total dry film thickness (DFT). Consequently three-coat systems were found out to be better than two-coat systems, as also shown in Ref. (23).

12. It was virtually impossible to predict the effects of test variables individually, since degradation was a function of combined effects of these parameters. However, it was noticed that the increment in temperature from $98\,^{0}F$ to $104\,^{0}F$, while keeping other factors constant, shortened the elapsed time before the initiation of corrosion to some extent.

13. The fog collected in the collectors was tested and no loss of pH and sodium chloride concentration was found in the atomization process. The measurement of pH was done electrometrically.

14. In this research work several corrosion factors were intensified so that the degradation takes place expeditiously. It is usually rather difficult on the basis of such accelerated short-term tests, to make any prediction regarding the life of a coating system in any naturally occurring, less stringent environment.

6.2 Recommendations

On the basis of the previous conclusions, the following recommendations are made.

1. Temperature must be maintained uniform throughout the testing in order to get the reproducible results. One should also bear in mind that the comparison of two samples being tested under different cabinet temperatures may yield erroneous information even if the other variables were kept identical.

2. In this study, a coastal environment was simulated in the chamber, so only those coating systems were tested. Testing of a system designed for an environment other than the sea coast environment (for example, an industrial environment), is not justified under this particular simulation.

3. Misleading results can be obtained if tests are carried out on substrates markedly different from those that will arise in actual situations. Similarity should be maintained, not only in surface profiles, but in fact in every respect such as viscosity of paint, method of application of coating system in the field and in the laboratory, curing conditions, etc.

4. Frequent rinsing of test panels due to data collection with lesser interval of time may allow the rust spots to lift off and be rinsed away, so it is recommended that the data should be collected with an interval of 10-12 hours. This approach will yield a rather conservative estimation of rust. However, it may also be of significance that during the later part of the testing (i.e., after an exposure time of 70-80 hours), when the rate of degradation is high, smaller intervals for data collection should be employed. This is in order to get the better insight of coating failure pattern in the zone where the slope of the performance curve increases sharply.

5. Test panels must not have air bubbles on the surfaces to be tested. Air pocket may cause a premature failure of coating, thus yielding unreliable information. To avoid air bubbles, the top coat should be applied when the base coat is fully cured.

6. Care should be exercised in the interpretation of the data, since different metallic coatings react differently with the various constituents of a natural environment. No single synthetic environment can be made to match these constituents and at the same time accelerate their reactivity in the right order.

7. On test panels, the dry film thickness (DFT) must be maintained uniform. Keeping in mind that the DFT is a measure of resistance of paint, it is impossible to assess the full worth of a good coating system having non-uniform DFT.

8. It is strongly recommended that in the short-term laboratory testing, the corrosive medium in terms of its qualitative chemical composition should essentially be the same as that in the corresponding actual environment.

9. Environmental chamber should be placed away from other metallic installation, since purging of corrosive fog, at the time of evaluation, may corrode other metallic objects in the vicinity of the chamber.

10. Extreme care should be exercised concerning exposure of any part of body to UV-light. During evaluation, it is recommended that mercury light bulb, emitting UV-radiation, must be shut off. Also when purge control valve is open and allowing air to force purge the fog mist from cabinet, one should not stand close to the chamber. The inhalation of acidic fumes may prove dangerous.

11. Final decisions should be made regarding selection of coating system type on the basis of results of at least two to three testings.

6.3 Further Research

Efforts should be directed in developing a correlation between the less severe natural exposure and accelerated laboratory environment in order to predict the life of a coating system, on the basis of short-term evaluation in ambient conditions. Recently, statistical methods have come

to be widely used in the treatment of corrosion data. These methods provide information as to the degree of confidence that can be placed in the accuracy of the result or conclusion. To develop such a correlation and to formulate a comprehensive physical theory of the performance of anti-corrosive systems, research on measuring and minimizing the variability in outdoor exposure is essential. Attention is directed here to a demonstrated fact that weather variability (year-to-year as well as day-to-day) is a significant variable in field tests, just as run-to-run variability is important in the environmental chamber.

Some protective systems are chemically complex and even close monitoring of such coatings may not yield reliable information regarding their performance, failure pattern, etc. Conceivably these systems could be linearized by rendering the laboratory test less aggressive, thereby extending the test period. But this may not be the sensible choice, because an important feature of laboratory tests is the reduction of testing time to a minimum. So it is recommended that standard performance curves should be developed, for the systems, in both laboratory and field conditions.

The relationship between runs and replications must be established, and the significant difference, if any, should be eliminated. This means that if the run-to-run variability is large then the laboratory-to-field correlation must be subjected to very large variation. Additional research to uncover the source of this variability would be of value.

VII. REFERENCES

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APPENDIX A

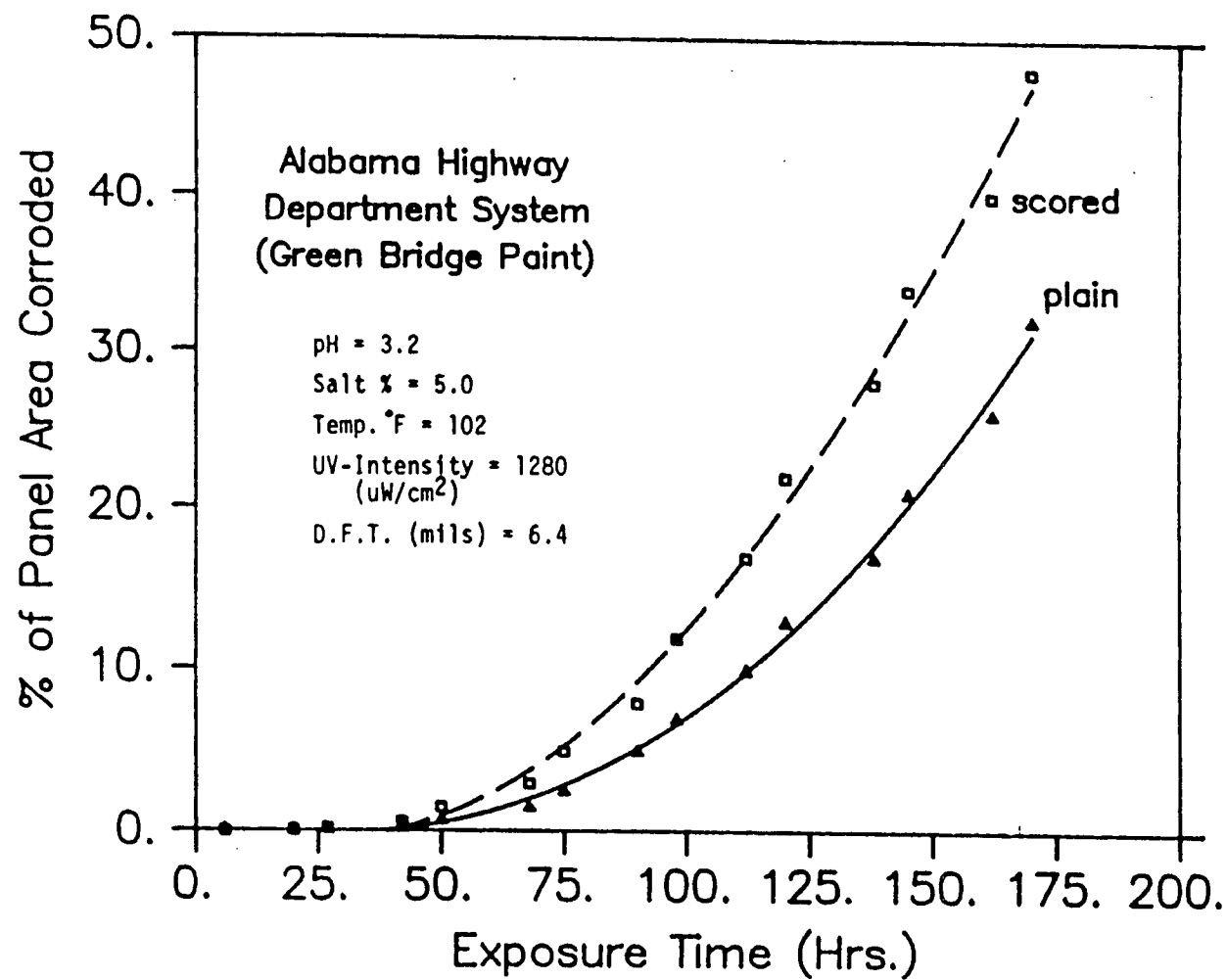TESTING RESULTS FOR VARIOUS SYSTEMS ON THE BASIS

OF ASTM STANDARDS

Figure 17. Alabama Highway Department System (Green Bridge Paint)
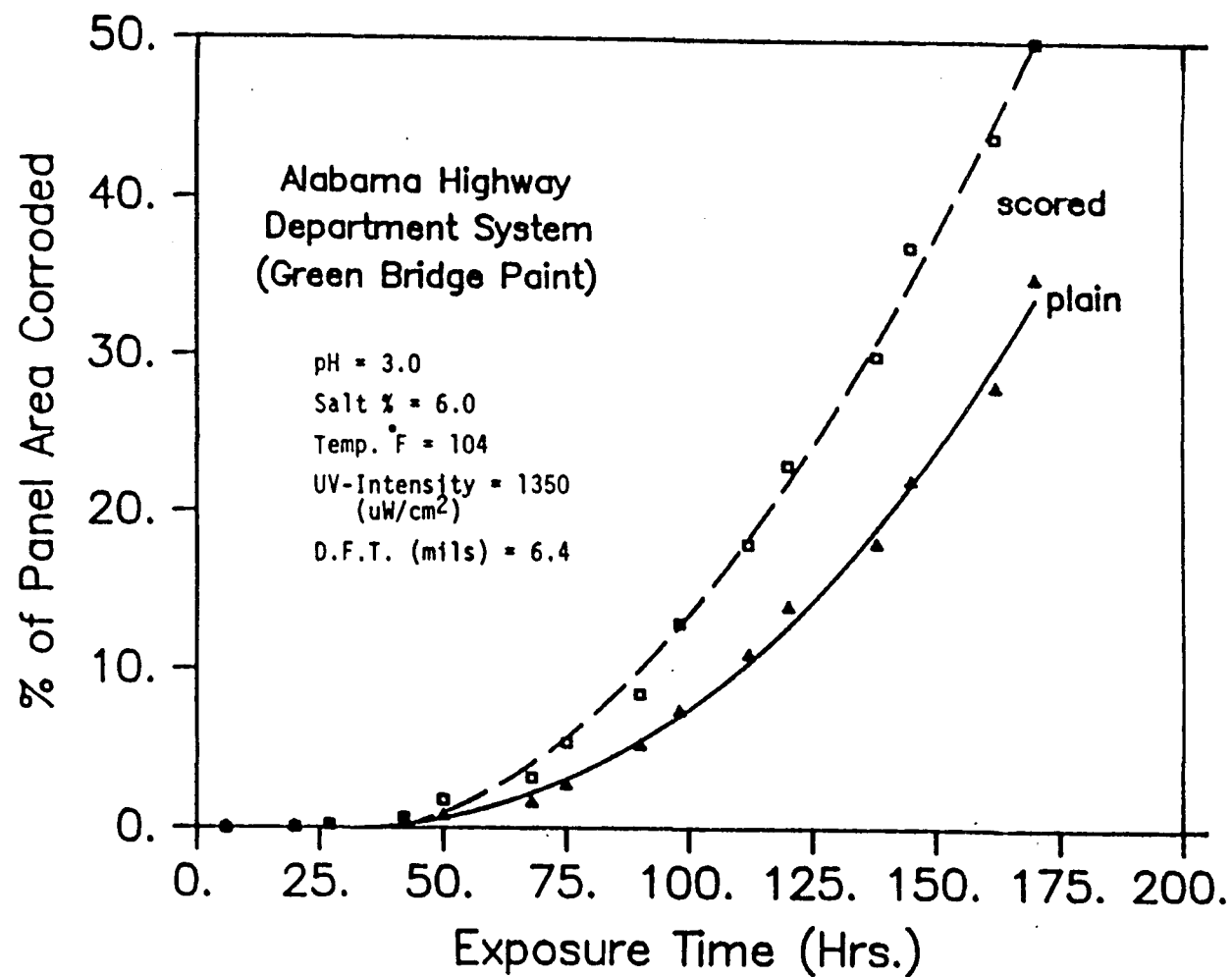
Figure 18. Alabama Highway Department System (Green Bridge Paint)

The chart shows "% of Panel Area Corroded" on the y-axis (0. to 50.) versus "Exposure Time (Hrs.)" on the x-axis (0. to 200.).

Florida Highway
Department System.

pH = 3.2
Salt % = 5
Temp. °F = 102
UV-Intensity = 1280
   (uW/cm²)
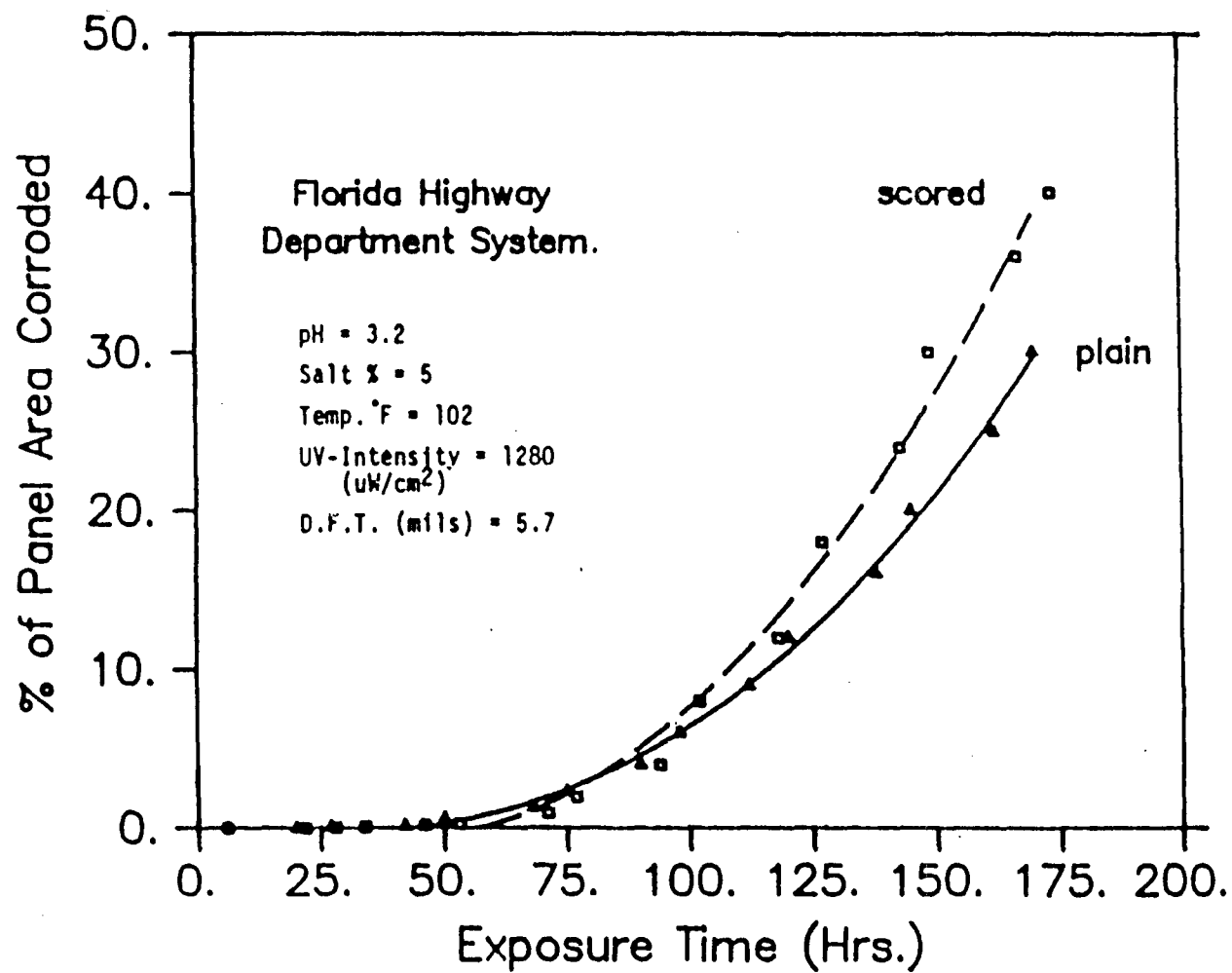D.F.T. (mils) = 5.7

scored

plain

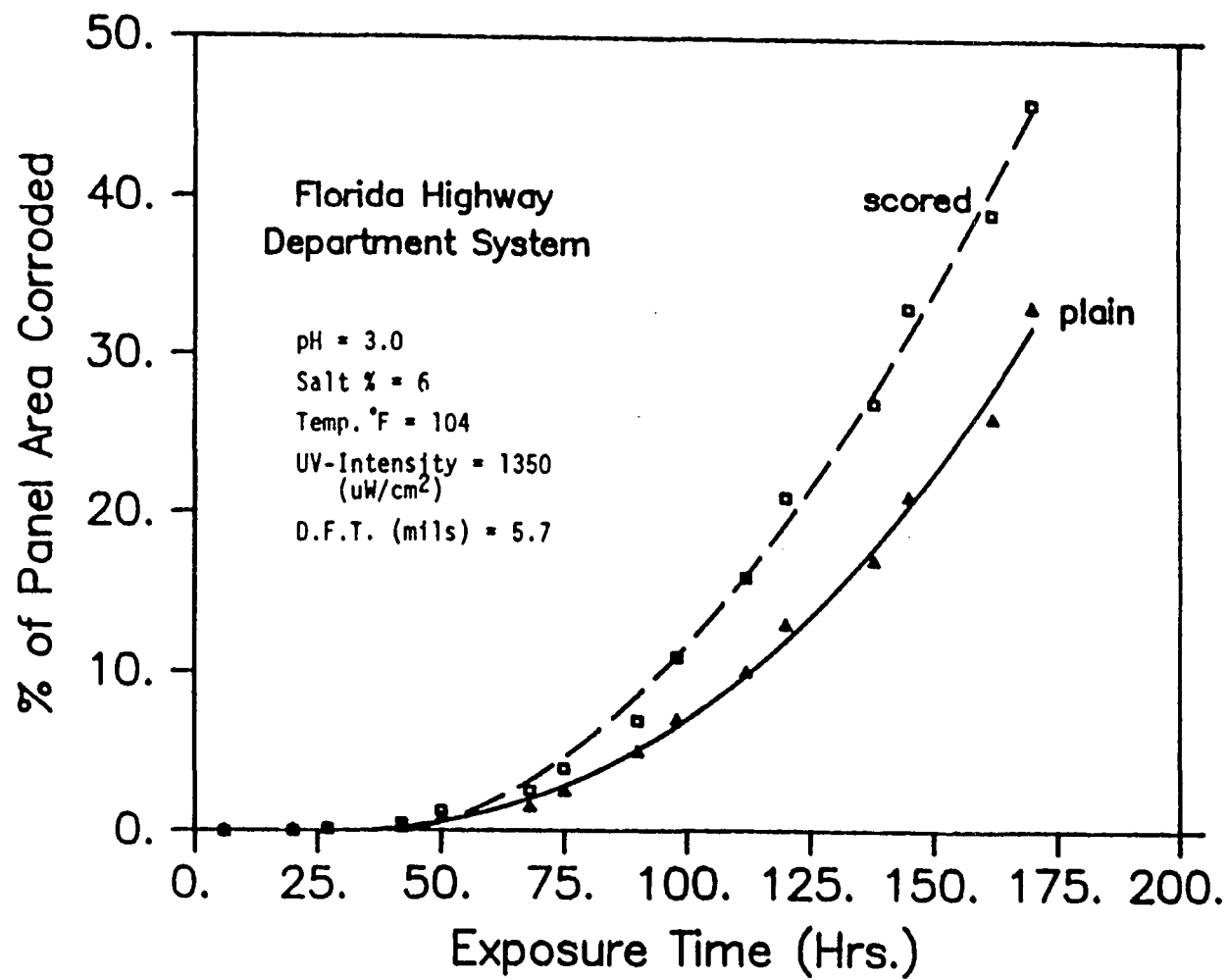Figure 19. Testing Results: Florida Highway Department System.
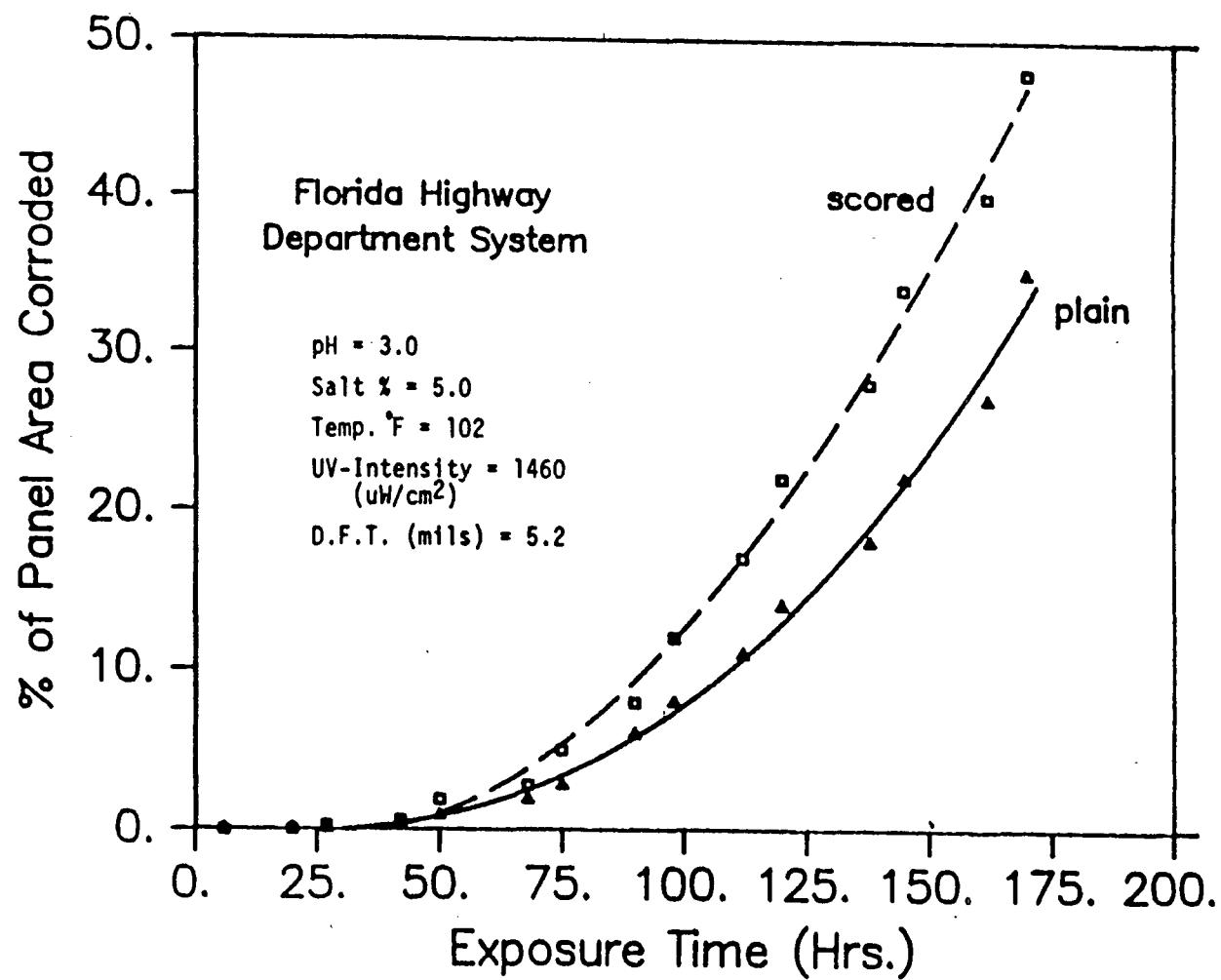
Figure 20. Florida Highway Department System.

Figure 21. Florida Highway Department System.

Table 3

Constants and Standard Deviations of Cubic Polynomial
for Figures 17 Through 21

| $Y = A + BX + CX^2 + DX^3$; where X = Exp. Time (Hrs.), Y = % Corrosion					
Figure Number	Specimen Type	Constants				Coefficient of Correlation, R
		A	$B(10^{-2})$	$C(10^{-4})$	$D(10^{-6})$	
17	Plain	0.561	− 5.58	9.76	2.41	0.998
	Scored	1.43	−13.8	26.4	− 1.49	0.998
18	Plain	0.42	− 4.36	7.77	3.73	0.998
	Scored	1.72	−15.9	30.0	− 2.28	0.998
19	Plain	0.642	− 5.75	8.86	2.67	0.999
	Scored	2.16	−15.6	20.1	0.964	0.996
20	Plain	0.381	− 4.07	7.21	3.55	0.998
	Scored	1.72	−15.5	37.4	− 1.81	0.99
21	Plain	0.232	− 3.36	7.47	3.49	0.997
	Scored	1.42	−13.4	25.8	− 1.24	0.998
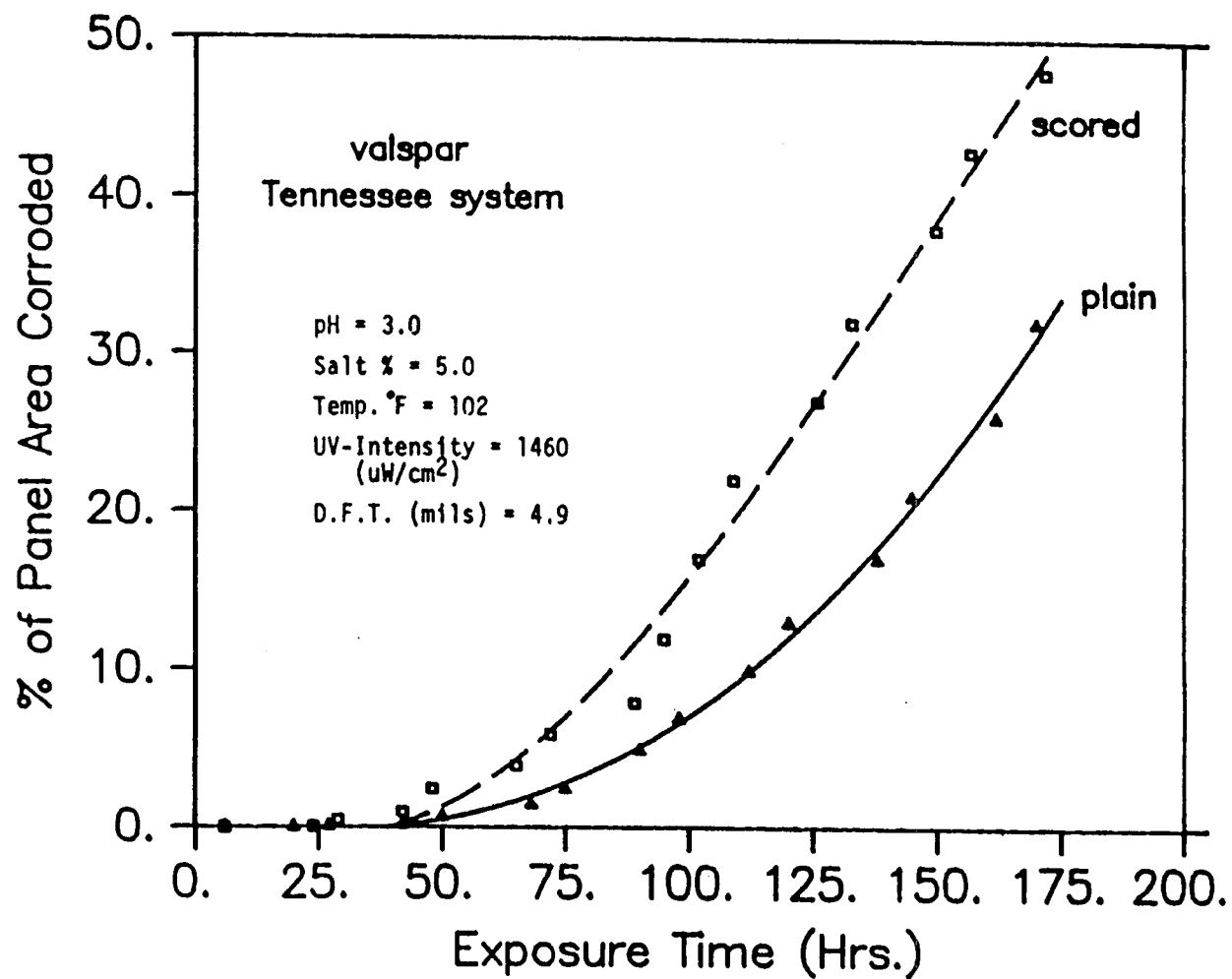
Figure 22. Valspar, Tennessee System.
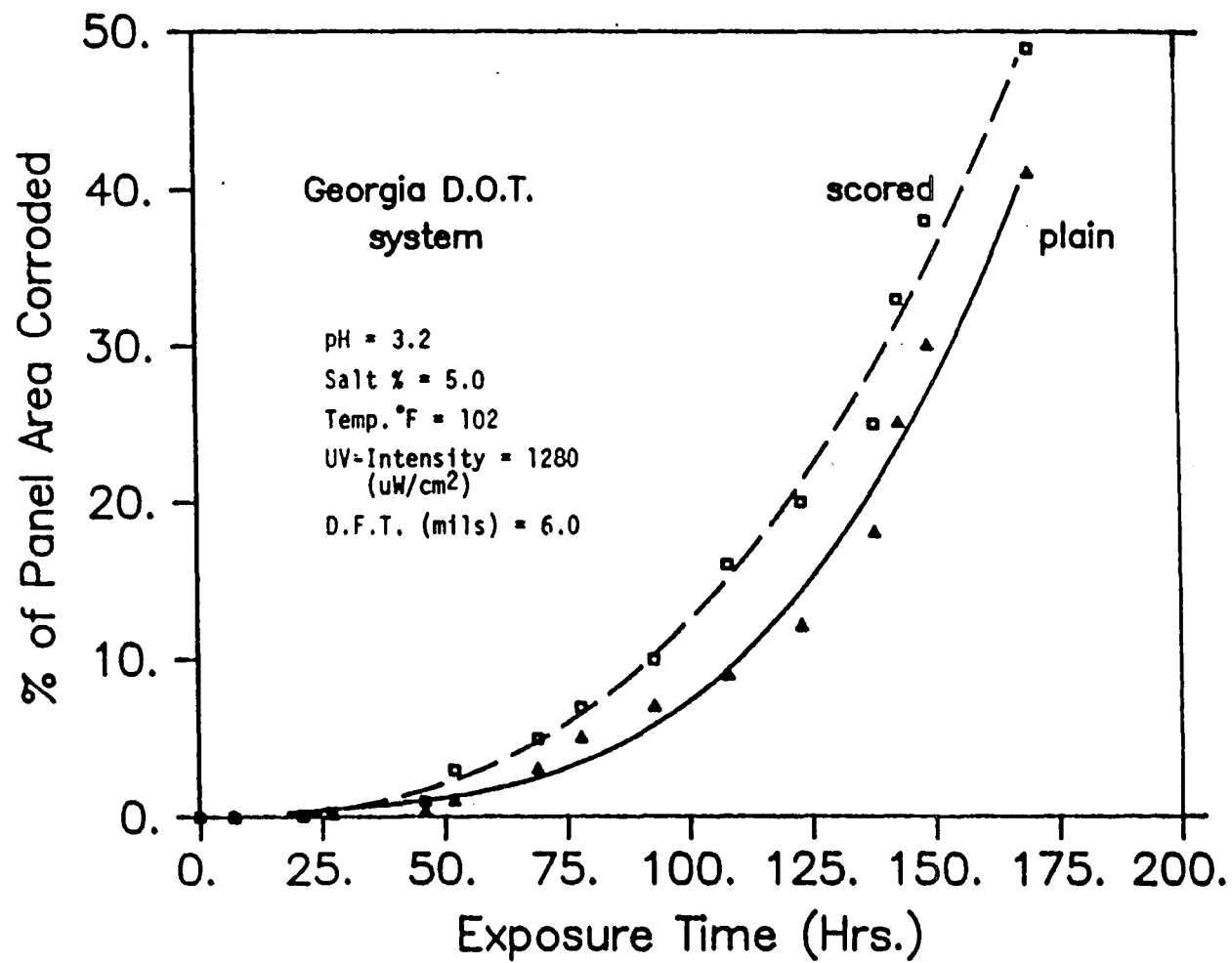
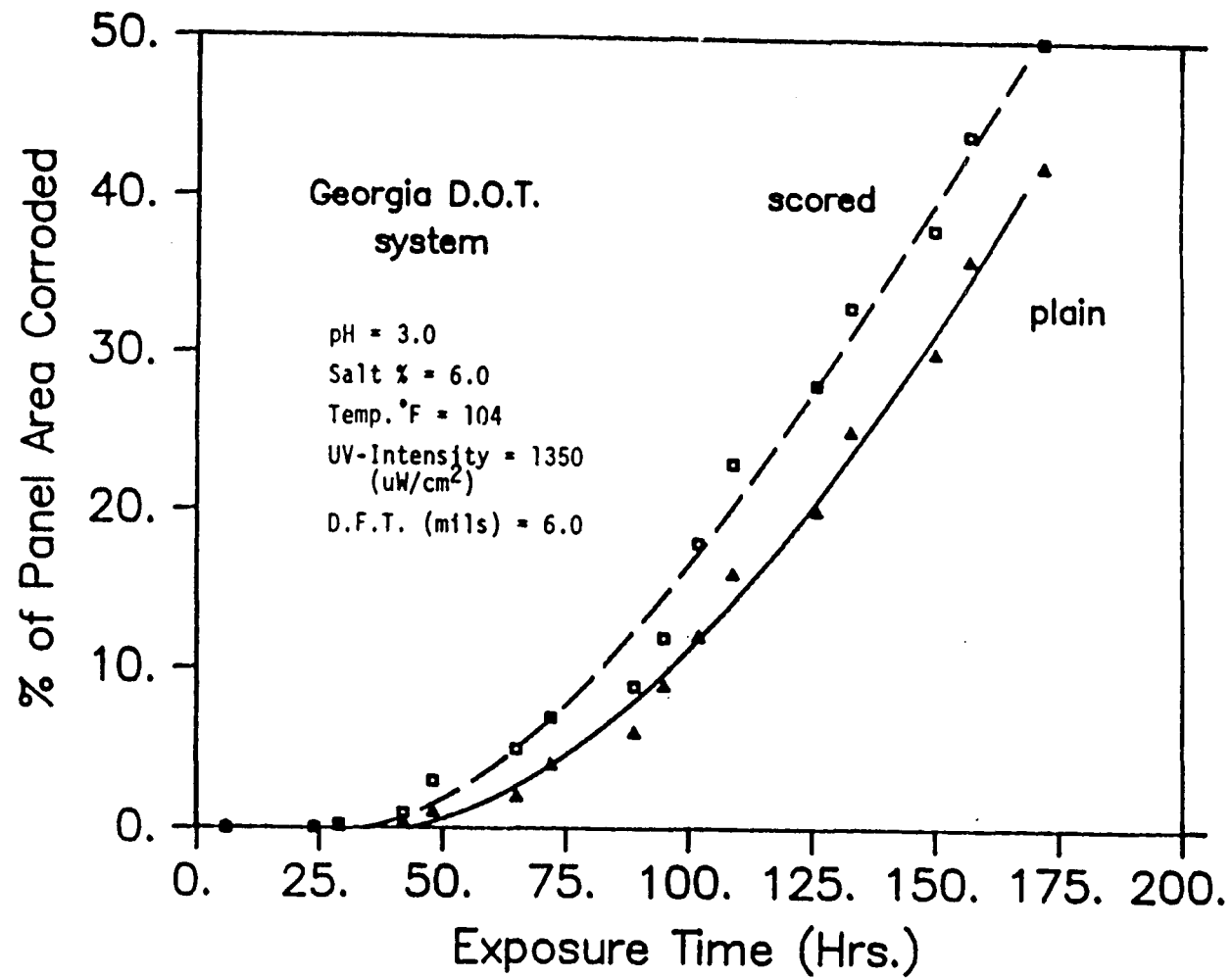Figure 23. Georgia D.O.T. System.

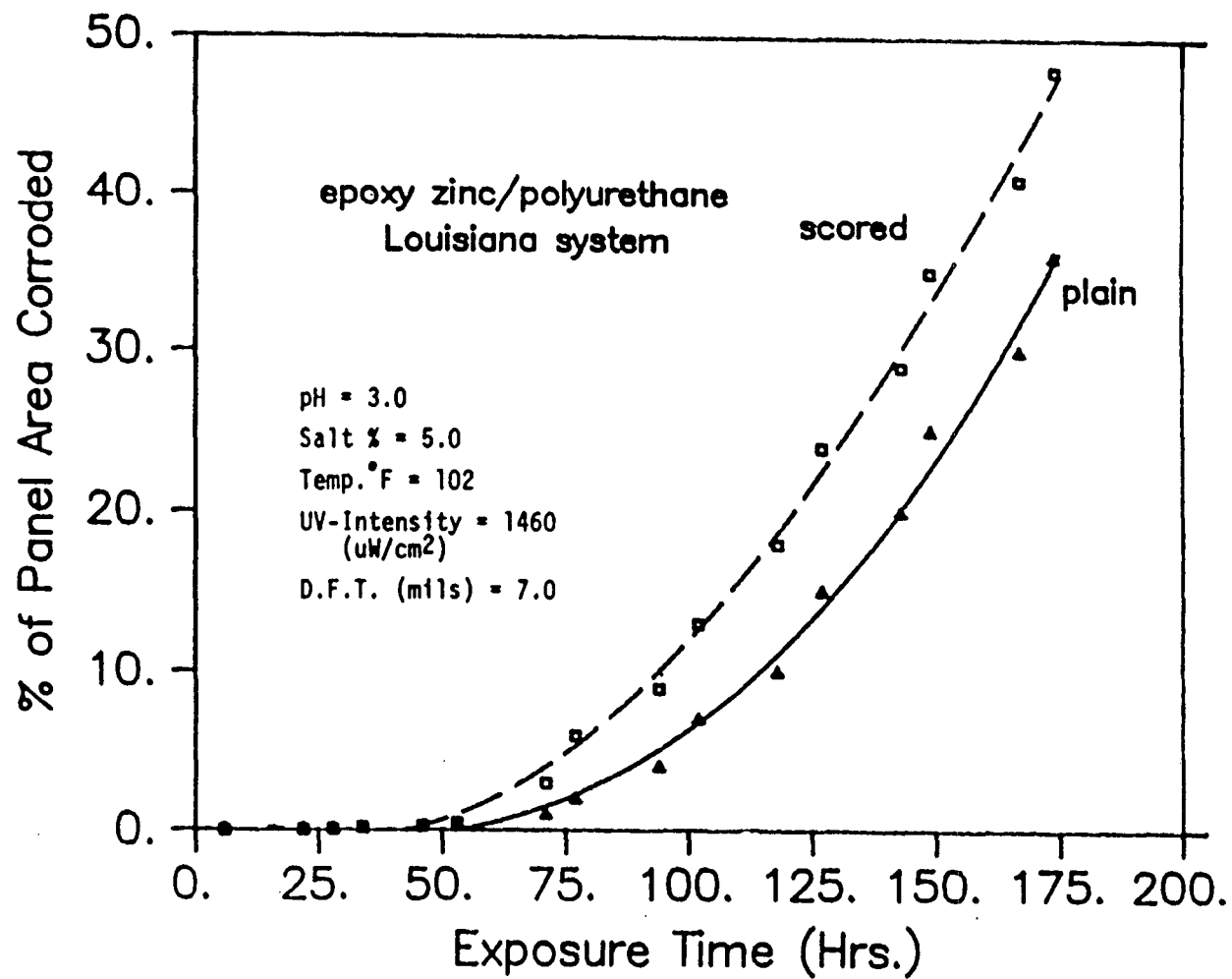Figure 24.   Georgia D.O.T. System.

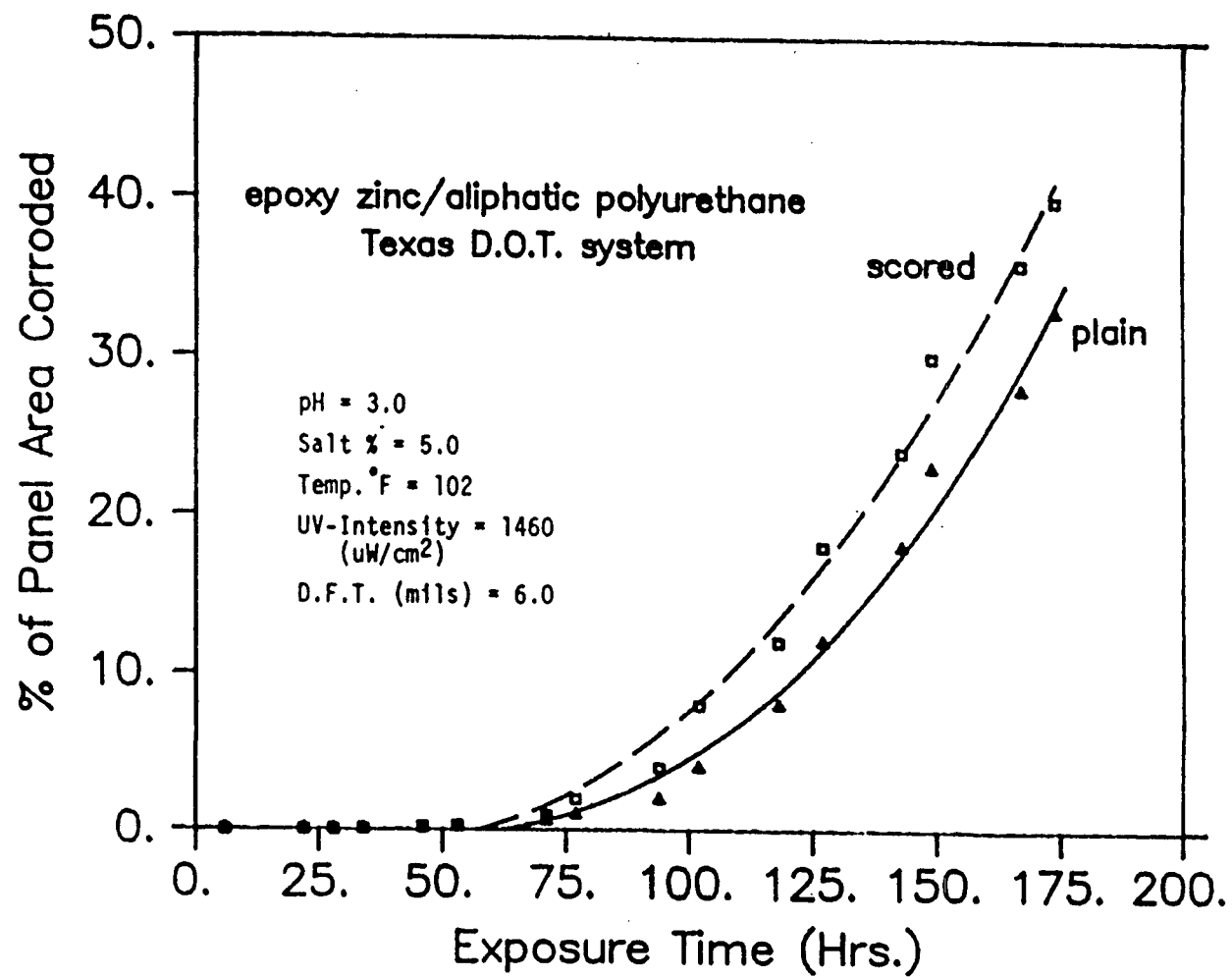Figure 25. Epoxy Zinc/Polyurethane, Louisiana System.

Figure 26. Epoxy Zinc/Aliphatic Polyurethane, Texas D.O.T. System.

Table 4

Constants and Standard Deviations of Cubic Polynomial
for Figures 22 Through 26

| $Y = A + BX + CX^2 + DX^3$; where X = Exp. Time (Hrs.), Y = % Corrosion					
Figure Number	Specimen Type	Constants				Coefficient of Correlation, R
		A	$B(10^{-2})$	$C(10^{-4})$	$D(10^{-6})$	
22	Plain	0.561	− 5.58	9.76	2.41	0.998
	Scored	2.85	−25.5	50.4	−11.6	0.996
23	Plain	−0.708	5.77	−10.3	12.7	0.995
	Scored	0.045	−14.7	8.01	5.96	0.997
24	Plain	1.62	−15.1	27.7	2.95	0.997
	Scored	1.97	−19.4	42.7	− 8.74	0.996
25	Plain	1.20	− 8.73	10.5	3.38	0.997
	Scored	1.64	−15.6	28.6	− 2.64	0.998
26	Plain	1.18	− 6.99	4.55	5.82	0.996
	Scored	2.16	−15.6	20.1	0.964	0.996
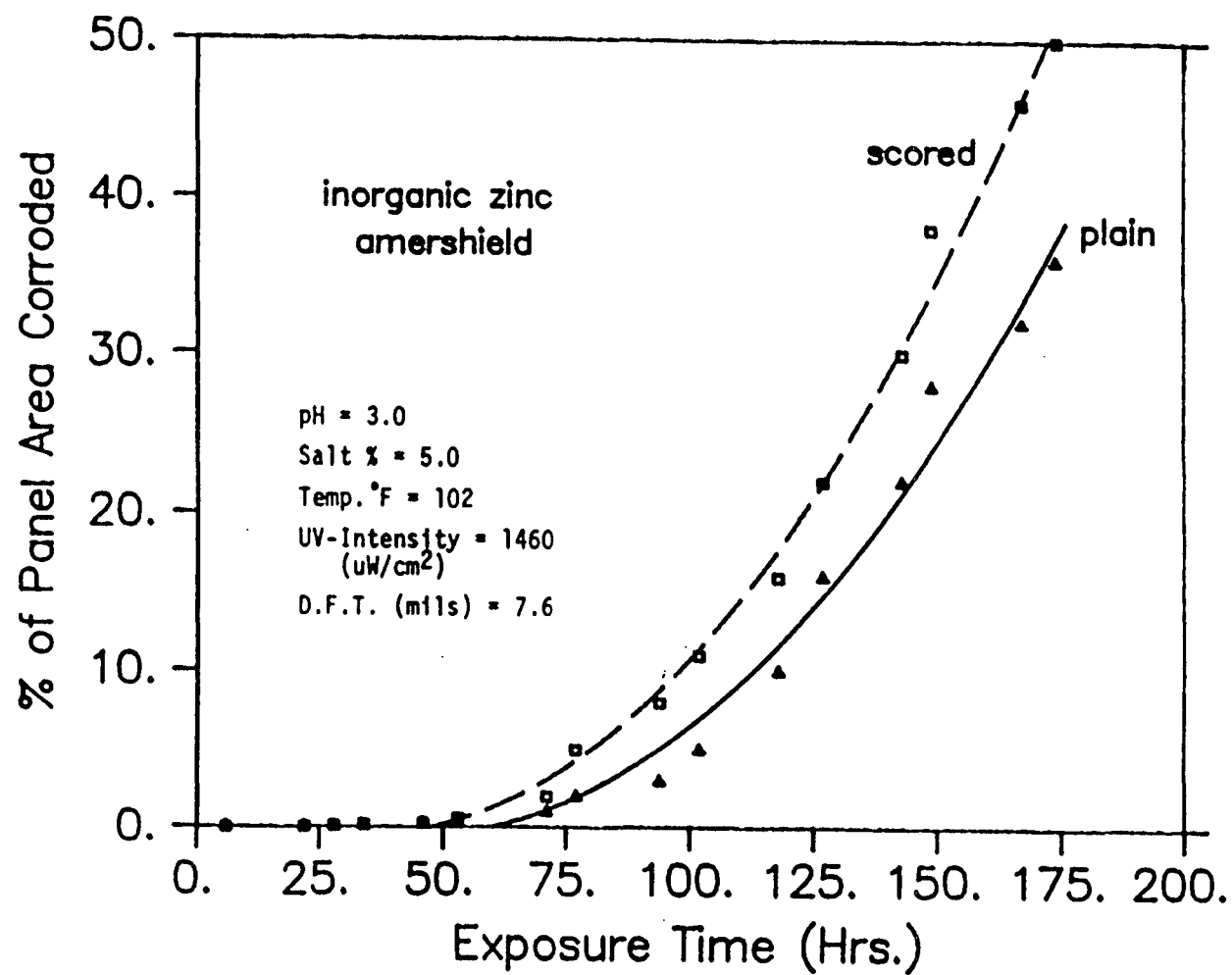
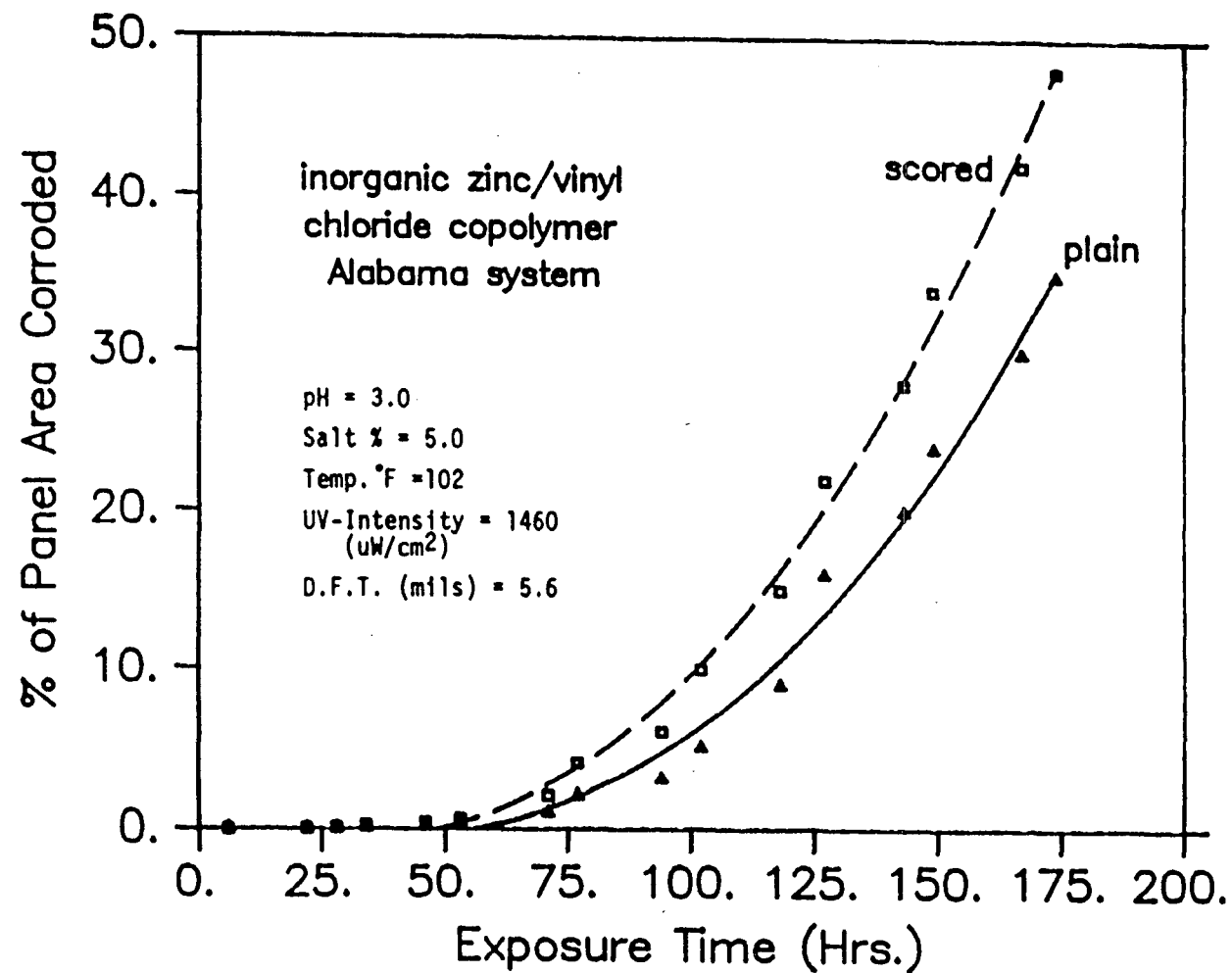Figure 27. Inorganic Zinc/Amershield.

Figure 28.   Inorganic Zinc/Vinyl Chloride Copolymer, Alabama System.
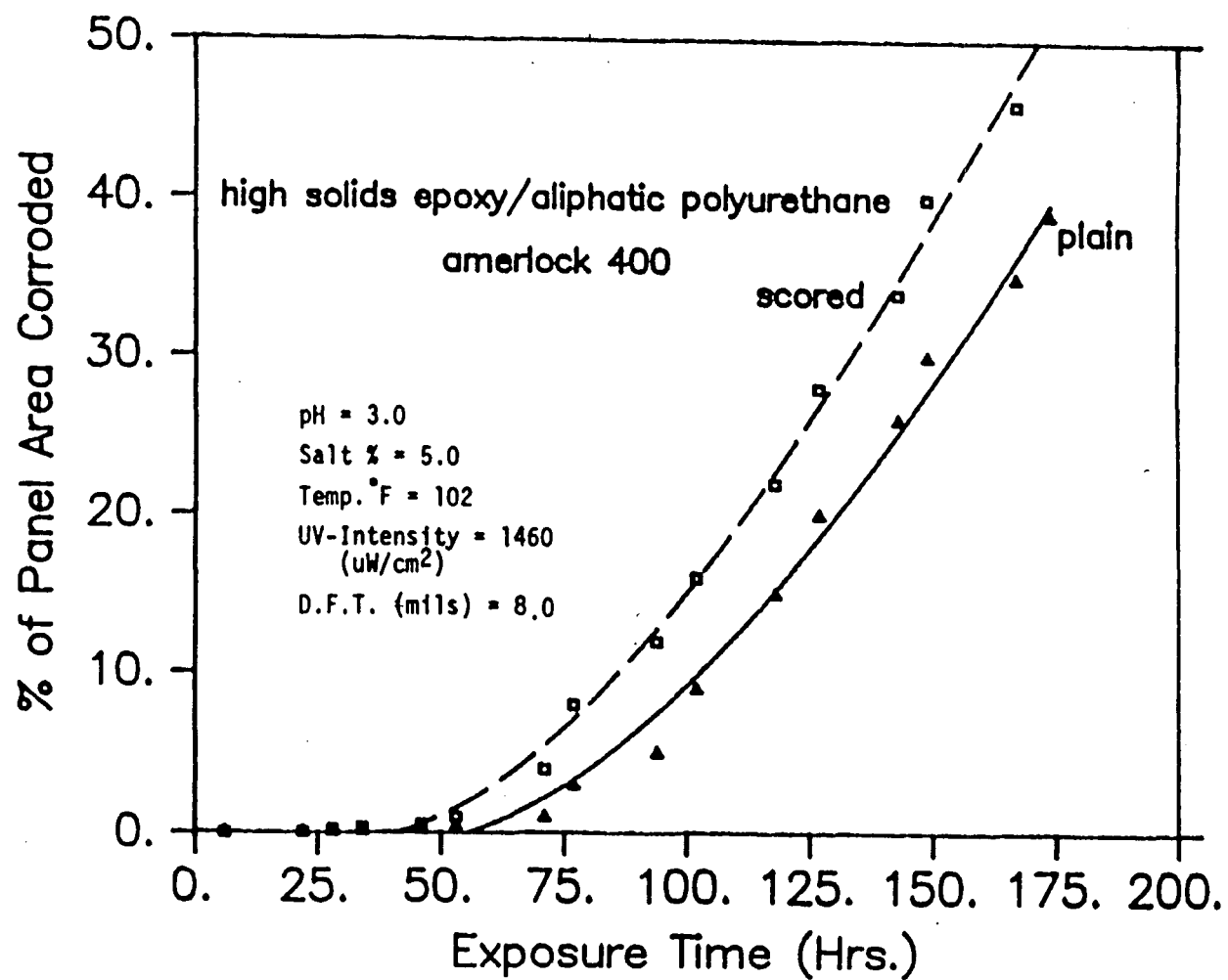
Figure 29. High Solids Epoxy/Aliphatic Polyurethane, Amerlock 400.
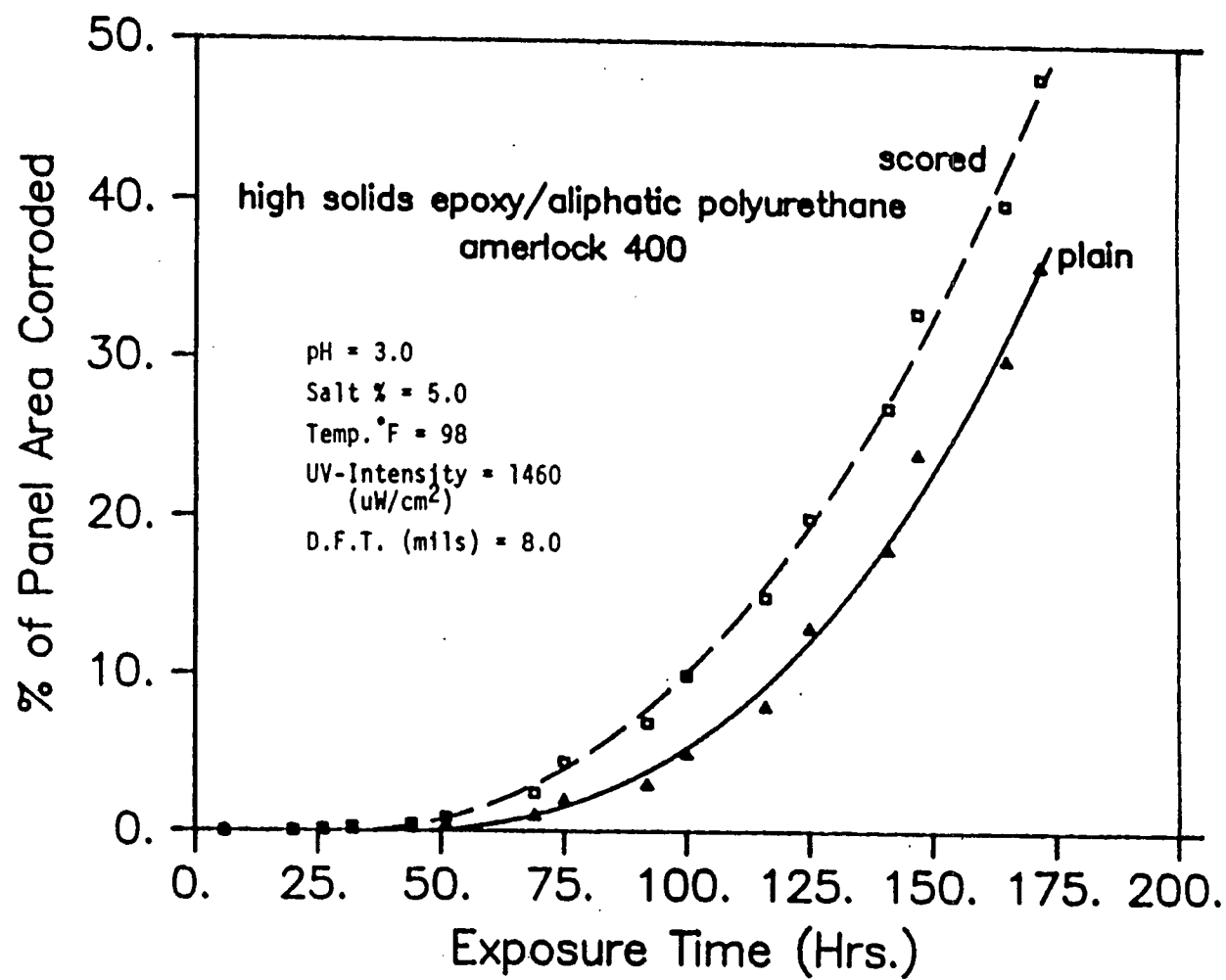
Figure 30. High Solids Epoxy/Aliphatic Polyurethane, Amerlock 400.
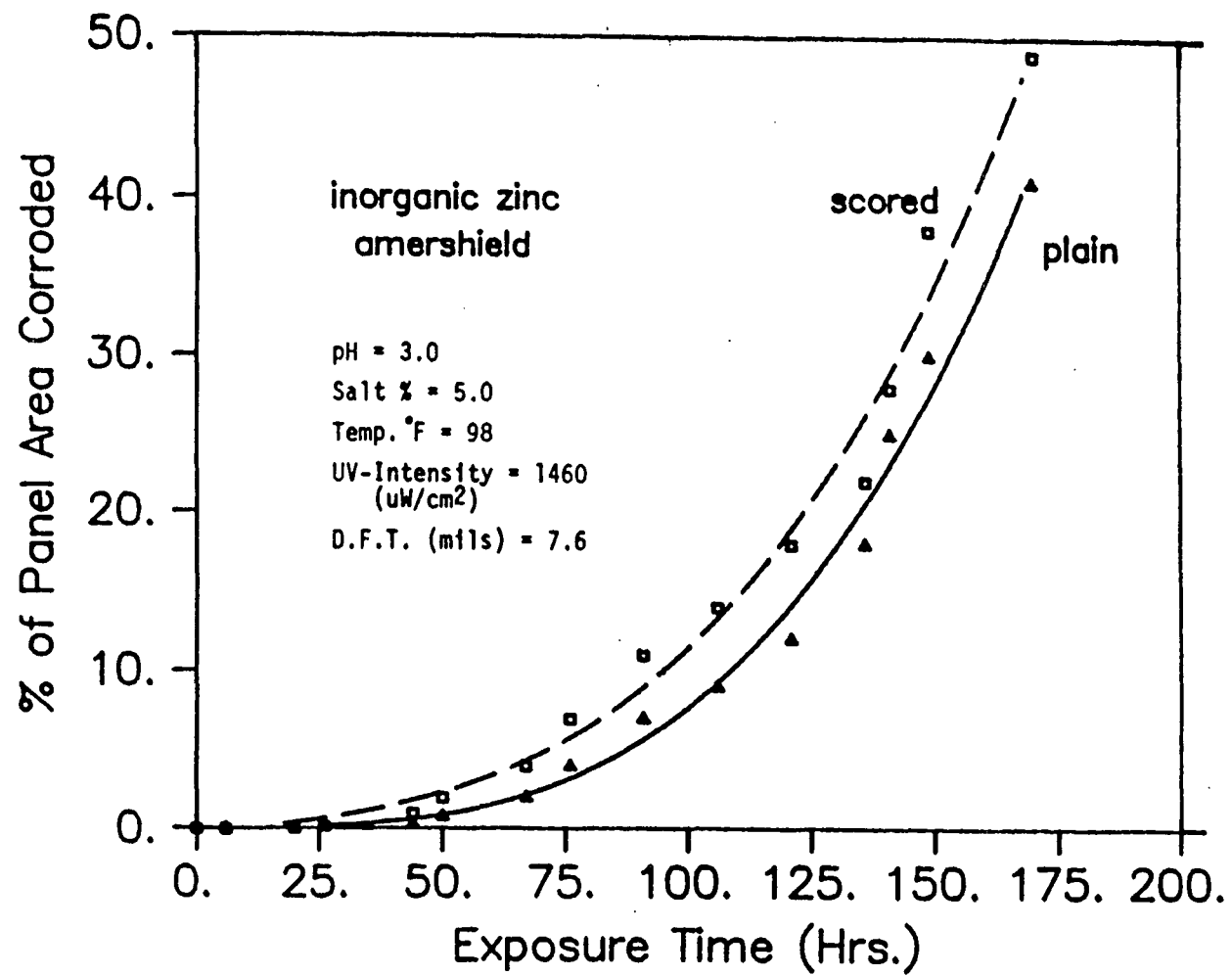
Figure 31. Inorganic Zinc, Amershield.

Table 5

Constants and Standard Deviations of Cubic Polynomial
for Figures 27 Through 31

$Y = A + BX + CX^2 + DX^3$; where X = Exp. Time (Hrs.), Y = % Corrosion					
Figure Number	Specimen Type	Constants				Coefficient of Correlation, R
		A	$B(10^{-2})$	$C(10^{-4})$	$D(10^{-6})$	
27	Plain	−0.574	4.82	− 8.51	12.0	0.995
	Scored	−1.24	8.56	− 6.61	11.2	0.992
28	Plain	1.41	− 9.45	10.3	3.61	0.995
	Scored	1.72	−13.2	18.8	2.41	0.998
29	Plain	2.83	−22.1	33.4	− 4.92	0.996
	Scored	2.09	−20.6	40.9	− 7.33	0.998
30	Plain	0.504	− 2.47	− 1.07	8.43	0.997
	Scored	0.928	− 7.66	12.4	4.49	0.998
31	Plain	−0.231	2.08	− 4.89	10.7	0.995
	Scored	−1.05	6.99	− 5.70	11.2	0.993

APPENDIX B

CHAMBER INSTALLATION AND OPERATION

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B.1 Chamber Installation

The cabinet should be located in an evenly heated area which is free of hot or cold draughts and with an ambient temperature in the range of 65^0F to 95^0F. The selected area should be readily accessible for compressed air, running water, electrical power, and floor drain. Once the cabinet is set in place, it must be leveled by means of four leveling screws.

B.1.1 Electrical Wiring:

Only a qualified electrician should be permitted to make the electrical circuits. Appropriate wiring diagrams, shown in ref. (43) should be consulted. One should not attempt to test electrical circuits until water jackets and humidifying tower have at least 12" of water in them.

B.1.2 Air and Water Connections:

The cabinet is supplied with a combination of air regulator and oil/water extractor mounted at the bottom of humidifying tower. At this point an air connection by means of a 1/4" pipe should be made. The air pressure within the system should be within the specified limits suggested in the operation manual (43), because the valves, pipe joints, pressure caps etc. are designed for a certain pressure level.

A water supply is needed at the cabinet site to facilitate filling of cabinet water jackets, washing of chamber interior and cleaning of test specimens. Installation of a 1/2" copper water line with a shut-off valve and hose connector is recommended.

B.1.3 Drains:

Two drains are provided in the chamber and both are located on the bottom side of cabinet. One is the water jacket drain and the other is the drain for the inside chamber. For water jacket drain a

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metallic pipe may be used, but for inner chamber drain all the pipe fittings must be PVC or a suitable noncorrosive material.

B.1.4 <u>Exhaust</u>: The cabinet is supplied with an exhaust system which is located in the end wall opposite the control end. All the piping in the exhaust line must be of PVC. The exhaust piping does not have any traps or sags in it because even a slight trap will cause back pressure in line and cause the cainet cover to lift. Additionally, it could create adverse conditions within the chamber which could affect the testing.

B.2 <u>Initial Start-up and System Check</u>

Once the cabinet and accessories are completely installed, the following step by step start-up procedure should be followed:

* Make certain that both water jacket and inner chamber drain valves are closed.

* With the aid of a funnel, pour rust inhibitor into water jacket and fill connection. Attach water hose and fill water jackets to within 1" of the top of the sight gauge glass. Disconnect the water hose and fill the water seal around the perimeter of the top of cabinet. Close cabinet cover.

* Set chamber temperature control [1] to 95 ^{0}F. Turn on cabinet heater switch and check electrical circuit to be certain that both cabinet heaters are heating. The pilot light marked Cabinet Heaters "ON" should be lit. Allow 3-4 hours for cabinet to heat up, at which time the cabinet heaters should kick off and the pilot lights go out. At this time, check the thermometer mounted on cabinet cover to be sure it is reading the same temperature as set on cabinet control. If not, adjust the knob on the chamber

Numerals in the square brackets denote the numbers shown in figures 5 and 6.

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temperature control. If system is functioning properly, turn off
cabinet tower switch.

* Fill humidifying tower [3] and the humidifying tower control
reservoir [2] with distilled or deionized water with pH of 7.

(a) Remove filler plug [10].

(b) Open valves [13], [14], [15], and [17].

(c) Close humidifying tower drain valve [9].

(d) Start filling level control reservoir [2] through opening of
filler plug [10] and as it is filling water will be flowing
down the humidifying tower water line [16] into humidifying
tower [3]. Continue filling until water level in [3] reaches
the bottom of the air control pipe [19]. Then close valve
[15] and continue filling reservoir [2] until full. Then
insert filler plug [10] and seal it closed, and close valves
[13], [14], and [17]. Now that the system is filled, turn on
the bubble tower heater switch and check the electrical
circuit to be certain that heater is heating properly. The
humidifying tower temperature control [4] is factory set at
118^0F and if the system is functioning properly, the bubble
tower heater pilot should be lit. Turn on the humidifying
tower air valve [6] gradually, and adjust pressure regulator
until 15 psi is indicated on the pressure guage [5]. Open
valves [14], [15], and [17] which will put level control
reservoir [2] in operation. If level control is functioning
properly, the water level in the humidifying tower will
remain at the bottom section of air control pipe [19]. If

the unit is not working well, it could be because of an air

leak in the connections or fluctuation in air supply.

If the system appears to be functioning properly, allow humidifying

tower [3] to continue operating until the 118^{0}F temperature is reached and

the pilot light goes out and heater cuts off. To adjust the temperature

use the temperature control screw [4]. If the unit does not function

properly close air valve [6] and valves [14], [15], and [17]. Open "WITH

CAUTION" pressure release valve [13] and bleed off built-up pressure.

Check and retighten all fittings and recheck water fill plug [10] to be

sure it is sealed. Reclose pressure release valve [13] and open valves

[14], [15], and [17], and air supply valve [6]. Once the unit is

functioning properly and the humidifying tower temperature is controlling

at right temperature, shut off air supply valve [6] and valve [15], and

turn off tower heater switch.

Open cabinet cover and install specimen support racks and bars

supplied with cabinet. Chamber is now installed and is ready for testing.

APPENDIX C

CHAMBER OPERATION AND TESTING

C.1 Operating Cabinet for Salt Spray (Fog) Tests

Once the salt solution is made up, fill level control reservoir [18] through filler plug opening [21]. Open salt solution control valve [23] and allow external and internal reservoirs [11] and [24] to fill to within 2" of the top of both. Then, close valve [23] and continue filling level control reservoir until full. Close and seal filler plug [21].

Now that all necessary solution reservoirs have been filled with salt solution and the humidifying tower and reservoir filled, proceed as follows:

(i) Turn on cabinet heater and bubble tower heater switches to start initial heat up.

(ii) Open cabinet cover and place test specimens in their proper positions in the chamber.

(iii) Place a minimum of two condensate collection funnels (80 cm^2) and graduates (100 ml.) in the cabinet at the same level as test specimens. One as close to the tower as possible and the other as far away from the tower as possible, as indicated in specifications (43).

(iv) Before closing cabinet cover, it is always a good idea to check if the atomizing nozzle is functioning correctly or not. At this stage open air supply valve [6] and observe if a fog mist is being generated. If so, close valve [6]. If not, check atomizing nozzle for obstruction and clean if necessary. For cleaning of nozzle refer to the maintenance manual (43).

(v) Rotate vertical tube of Uni-Fog dispersion tower until the four holes at the base of tube are fully open and adjust dispersion cone at the top of vertical tower tube so that the bottom tip of cone is even with the top edge of vertical tube.

(vi) Close cabinet cover and check to see if the water seal is full of water.

(vii) Once cabinet and humidifying tower are heated up and stabilized at correct operating temperatures, check to be sure that inner chamber drain valve is closed and the air purge control valve [26] is closed, turn on air control valve [6] and open humidifying tower water control valve [15].

(viii) Cabinet is now in full operation and the test has started. After 24 hours of test, or as outlined in the specifications, one should check the condensate collectors to make sure that the collecting rate is uniform.

C.2 To Stop Testing Operation

(i) Shut off air supply valve [6] and close humidifying tower water control valve [15].

(ii) Open purge control valve [26] and allow air to force purge the fog mist from cabinet. Observe this purging operation through the plexiglas port entry window and once inner cabinety is clear of fog, shut off purge control valve.

(iii) Remove condensate collection funnels and record collection rates. Also check the pH of the collected salt solution in accordance with the specifications.

C.3 Adjustments in Collection Rates

   If the collection rates are not within the specifications, then refer

to the following cases and adjust accordingly. As it will become clear

that many available adjustments are built into the Uni-Fog Tower System,

the cabinet can be precisely fine tuned to where any desired uniform

collection rate can be achieved and maintained.

   C.3.1 Collection rates are even but slightly high:

   * Rotate vertical tube of Uni-Fog tower to where four holes at

      base are partially closed. This will restrict and cut down the

      amount of fog flow from the tube.

   * Or lower air pressure slightly at humidifying tower. But in doing

      so, one must also lower the temperature of humidifying tower by

      approximately 0.5^0 to 1.0^0F for every pound of pressure drop.

   * Or lower solution level in both external and internal reservoirs

      [11] and [24].

   C.3.2 Collection rates are even but slightly low:

   * Increase air pressure at humidifying tower slightly and again,

      readjust the temperature of humidifying tower by increasing it by

      0.5^0 to 1.0^0F for every pound of pressure increased.

   * Or raise solution level in both external and internal reservoirs.

   C.3.3 Collections low near tower but high away from tower:

   * Raise dispersion cone on top of certical tube of Uni-Fog tower.

      The raising of this cone will increase the discharge opening and

      thus reduce the velocity and outward flow of the fog which will

      allow more fog to concentrate near tower.

C.3.4 Collections high near tower but low away from tower:

* Lower dispersion cone on top of vertical tube of Uni-Fog tower.
  The lowering of this cone will decrease the discharge opening and
  thus increase the velocity and outward flow of the fog which will
  allow more fog to concentrate away from tower.

C.4 To Restart Testing Operation

* Turn the top cap of jet exhaust unit so that slot is closed.

* Turn on air supply valve [6] and open humidifying tower water
  control value [15].

* Now the unit is back in operation.

* Recheck collection rates after 24 hours of test and readjust if
  needed.

* Always open and close cabinet cover very gently as a very rapid
  opening or closing will splash water from the water seal and this
  water could go into the collecting funnels and distort the
  collections drastically.

* In order to refill salt solution level control reservoir [18],
  close salt solution control valve [23] and remove filler plug
  [21]. Fill reservoir with salt solution until full, replace
  filler plug, close and seal. Open salt solution control valve
  [23] and now the unit is filled and back in operation. This
  refilling operation can be done, even when a test is in process
  and there is no need to shut down the chamber for refilling.

* In order to refill humidifying tower level control reservoir [2],
close air control valve [17] and humidifying tower water control
valve [14]. Open pressure release valve [13] very carefully and
bleed off built-up pressure in reservoir. Once pressure has been
released, remove filler plug [10] and fill reservoir with
distilled water until full. Replace filler plug, close pressure
release valve and reopen air control valve and humidifying tower
water control valve. The chamber is now filled and back in
operation. The solution reservoirs are designed with enough
capacity to last from 48-72 hours between fillings.

APPENDIX D

PROGRAM LISTING AND SAMPLE DATA

```
C
C          THIS IS A PROGRAM TO FIND A NTH ORDER POLYNOMIAL TO FIT
C          THE RAW DATA PROVIDED.
C          TITLE=ALPHANUMERIC CHARACTER STRING OF UP TO 80.
C          N=NUMBER OF RAW DATA IN A SET
C          K=AN ORDER OF POLYNOMIAL DESIRED
C          THERE IS NO LIMIT ON THE ORDER OF THE POLYNOMIAL DESIRED
C          AS LONG AS THE BLANK COMMON ARRAY IS SUFFICIENT.
C
           IMPLICIT REAL*8(A-H,O-Z)
           REAL TITLE(20),AA(5000)
           DIMENSION A(2500),LKI(5000)
           COMMON AA
           COMMON/SET/K,N,KP1,K2,IN,IO
           EQUIVALENCE (AA(1),LKI(1)),(AA(1),A(1))
           IN=5
           IO=6
   99 READ(IN,500,END=98) (TITLE(I),I=1,20)
  500 FORMAT(20A4)
           WRITE(IO,601) (TITLE(I), I=1,20)
  601 FORMAT(1H1,20A4)
           READ(IN, *) N,K
           K2=K*2
           KP1=K+1
           L2=1+KP1*KP1
           L3=L2+KP1
           L4=L3+N
           L5=L4+N
           L6=L5+N
           L7=L6+K2
           L8=(L7+KP1)*2+1
           NSIZE=L8+N*2
           IF(NSIZE.GT.5000) GO TO 97
           WRITE(IO,600) NSIZE
  600 FORMAT(/' ','BLANK COMMON=',I5/)
           CALL STAT(A(1),A(L2),A(L3),A(L4),A(L5),A(L6),A(L7),
      1 LKI(L8),TITLE)
           GO TO 99
   97 WRITE(IO,600) NSIZE
   98 STOP
           END
           SUBROUTINE STAT(A,RI,XI,YI,YHAT,SXI,RII,INDEX,TITLE)
           IMPLICIT REAL*8(A-H,O-Z)
           REAL TITLE(20)
           DIMENSION A(KP1,KP1),RI(KP1),RII(KP1),XI(N),YI(N),YHAT(N),
      1 SXI(K2),INDEX(KP1,2)
           COMMON/SET/K,N,KP1,K2,IN,IO
           DO 20 I=1,N
   20 READ(IN, *) XI(I),YI(I)
           DO 1 I=1,K2
    1 SXI(I)=0.0
           DO 2 I=1,K2
           DO 2 J=1,N
    2 SXI(I)=SXI(I)+XI(J)**I
```

```
      DO 3 I=1,KP1
    3 RI(I)=0.0
      DO 4 I=1,KP1
      DO 4 J=1,N
    4 RI(I)=RI(I)+XI(J)**(I-1)*YI(J)
      DO 5 I=1,KP1
      DO 5 J=2,KP1
    5 A(I,J)=SXI(I+J-2)
      DO 6 I=2,KP1
    6 A(I,1)=SXI(I-1)
      A(1,1)=N
      MSING=1
      CALL SIMULE(A,RI,RII,INDEX,KP1,MSING)
      IF(MSING.EQ.1) GO TO 25
      WRITE(IO,605)
  605 FORMAT(//' ','SINGULARITY IN COEFFICIENT MATRIX'//)
      GO TO 26
   25 DO 22 I=1,KP1
   22 RII(I)=0.0
      DO 21 I=1,KP1
      DO 21 J=1,KP1
   21 RII(I)=RII(I)+RI(J)*A(I,J)
      DO 7 I=1,N
      YHAT(I)=0.0
      DO 7 J=1,KP1
    7 YHAT(I)=YHAT(I)+RII(J)*XI(I)**(J-1)
      SYI=0.0
      DO 8 I=1,N
    8 SYI=SYI+YI(I)
      YMEAN=SYI/N
      SST=0.0
      DO 9 I=1,N
    9 SST=SST+(YI(I)-YMEAN)**2
      SSE=0.0
      DO 10 I=1,N
   10 SSE=SSE+(YI(I)-YHAT(I))**2
      RSQ=1.0-SSE/SST
      R=DSQRT(RSQ)
      WRITE(IO,601)
  601 FORMAT(' ',5X,'XI',8X,'YI',8X,'FIT')
      DO 11 I=1,N
   11 WRITE(IO,602) XI(I),YI(I),YHAT(I)
  602 FORMAT(3F10.3)
      WRITE(IO,606)
  606 FORMAT(/' ','COEFFICIENTS OF POLYNOMIAL'/
     1 ' ','FIT=B(1)+B(2)*XI+B(3)*XI**2+....+B(N)*XI**(N-1)'/)
      WRITE(IO,603) (I,RII(I), I=1,KP1)
  603 FORMAT(' ','B(',I2,')=',E10.3)
      WRITE(IO,604) R
  604 FORMAT(/' ','COEFFICIENT OF CORRELATION, R:',F7.4)
   26 RETURN
      END
      SUBROUTINE SIMULE(A,B,Q,INDEX,N,MSING)
    C
```

```
C     THIS IS A MATRIX INVERSION ROUTINE
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(N,N),B(N),Q(N),INDEX(N,2)
      DO 100 I=1,N
  100 INDEX(I,1)=0
      II=0
  109 AMAX=-1.
      DO 110 I=1,N
      IF(INDEX(I,1))110,111,110
  111 DO 112 J=1,N
      IF(INDEX(J,1))112,113,112
  113 TEMP=DABS(A(I,J))
      IF(TEMP-AMAX)112,112,114
  114 IROW=I
      ICOL=J
      AMAX=TEMP
  112 CONTINUE
  110 CONTINUE
      IF(AMAX)225,115,116
  116 INDEX(ICOL,1)=IROW
      IF(IROW-ICOL)119,118,119
  119 DO 120 J=1,N
      TEMP=A(IROW,J)
      A(IROW,J)=A(ICOL,J)
  120 A(ICOL,J)=TEMP
      II=II+1
      INDEX(II,2)=ICOL
  118 PIVOT=A(ICOL,ICOL)
      A(ICOL,ICOL)=1.0
      PIVOT=1.0/PIVOT
      DO 121 J=1,N
  121 A(ICOL,J)=A(ICOL,J)*PIVOT
      DO 122 I=1,N
      IF(I-ICOL)123,122,123
  123 TEMP=A(I,ICOL)
      A(I,ICOL)=0.0
      DO 124 J=1,N
  124 A(I,J)=A(I,J)-A(ICOL,J)*TEMP
  122 CONTINUE
      GO TO 109
  125 ICOL=INDEX(II,2)
      IROW=INDEX(ICOL,1)
      DO 126 I=1,N
      TEMP=A(I,IROW)
      A(I,IROW)=A(I,ICOL)
  126 A(I,ICOL)=TEMP
      II=II-1
  225 IF(II)125,127,125
  127 GO TO 130
  115 MSING=0
  130 RETURN
      END
```

SAMPLE INPUT

    FIG 14 TEST I PL
    15,3,
    7.,0.,
    21.,.03,
    27.,.1,
    46.,.3,
    52.,1.,
    69.,3.,
    78.,5.,
    93.,7.,
    108.,9.,
    123.,12.,
    138.,18.,
    143.,25.,
    149.,30.,
    153.,40.,
    174.,47.,

    SAMPLE OUTPUT

FIG 14 TEST I PL

BLANK COMMON= 183

XI	YI	FIT
7.000	0.000	-0.258
21.000	0.030	0.237
27.000	0.100	0.390
46.000	0.300	0.918
52.000	1.000	1.168
69.000	3.000	2.345
78.000	5.000	3.360
93.000	7.000	5.877
108.000	9.000	9.692
123.000	12.000	15.110
138.000	18.000	22.435
143.000	25.000	25.354
149.000	30.000	29.197
153.000	40.000	31.975
174.000	47.000	49.630

COEFFICIENTS OF POLYNOMIAL
FIT=B(1)+B(2)*XI+B(3)*XI**2+....+B(N)*XI**(N-1)

B(1)=-0.638E+00
B(2)= 0.629E-01
B(3)=-0.133E-02
B(4)= 0.151E-04

COEFFICIENT OF CORRELATION, R: 0.9840