BRIDGE DECK SURFACE DURABILITY SURVEY

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16. Abstract

Bridge deck deterioration including cracking, scaling and spalling, is a serious problem for transportation departments. The Arkansas Highway and Transportation Department selected 45 bridges to be included in a survey of bridge deck deterioration. Samples were taken from the decks and data, like deck finish and construction details, were recorded. The samples were tested for chloride content, density, and strength. Findings of the survey were compared with an evaluation of the deck condition.

Chlorides at the level of reinforcement steel is the primary cause of bridge deck deterioration. The use of deicing salt on bridge decks is the primary source of chlorides.

The depth of concrete cover over reinforcement steel is the most important factor which prevents chlorides from reaching the reinforcement steel. Age of the bridge deck, the amount of traffic, and strength of the concrete are also factors which determine the condition of bridge decks in the study.

Data from the survey is insufficient to prove that a tined deck finish vs. a smooth finish contributes to deck deterioration.

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BRIDGE DECK SURFACE DURABILITY SURVEY

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Implementation

Two equations, equations 5 and 6 of this report, were developed which can be used to predict bridge deck rating to factors which include depth of concrete cover over reinforcement steel, traffic, age, and strength. The equations are a statistical evaluation of a limited data base and indicate only general effects of the factors relevant to deck design.

Gains-Findings-Conculsions

1. Chloride application, for snow and ice removal from bridges, has accelerated the deterioration of bridge decks.
2. The depth of concrete cover over steel reinforcement is the most important factor in prolonging deck life.
3. Deck deterioration in Arkansas is not as high as the national average.

SUMMARY

Bridge deck deterioration including cracking, scaling and spalling, is a serious problem for transportation departments. The Arkansas Highway and Transportation Department selected 45 bridges to be included in a survey of bridge deck deterioration. Samples were taken from the decks and data, like deck finish and construction details, were recorded. The samples were tested for chloride content, density, and strength. Findings of the survey were compared with an evaluation of the deck condition.

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Chapter One

INTRODUCTION

Bridge decks are among the most severly exposed and loaded of concrete structures. They are typically horizontal surfaces subject to alternate wetting and drying, freezing and thawing. They experience large temperature gradients and intense live-load stresses accompanied by fatigue and impact. Concrete covers of at least 3 inches have long been recommended in marine environments to prevent steel corrosion by salt water. Yet the specified cover on many bridge decks remained 1.5 inches until recently despite the six-fold national increase in the use of deicing salts between 1961 and 1975 alone (NCHRP Synthesis #57).

Construction difficulties in consolidation, finishing, and curing and problems caused by steel congestion can also weaken the deck, especially at its surface where it is subject to traffic abrasion.

As a result, bridge deck deterioration continues to be a serious problem facing highway engineers. In 1979, a National Cooperative Highway Research Program Synthesis of Highway Practice (NCHRP Synthesis #57) estimated that over 100,000 of the nation's bridges were in need of replacement or repair. The cost was estimated conservatively at 23 billion dollars (Hillenbrand, 1977).

Bridge deck deterioration appears in three common phenomena: cracking, scaling, and spalling. Cracking and scaling affect the riding surface of the deck, and lead to further deterioration.

Damage from spalling is more serious because repairs are difficult and expensive. The appearance of spalling at a deck surface indicates more extensive deterioration below the surface.

"Cracking (Figure 1.1) is characteristic of concrete because of concrete's low tensile strength and the relatively large volume changes in response to changes in humidity and temperature" (NCHRP Synthesis #57). The effect of cracking upon the durability of a deck depends upon the origin of the crack. Cracks due to shrinkage or settlement of the falsework are usually fine and do not adversely affect the durability of a deck, while map or pattern cracking due to reactive aggregrates can result in the complete disintegration of the deck (NCHRP Synthesis #57).

Scaling (Figure 1.2) is the flaking of the surface mortar. The top one-quarter to one-half inch of the concrete flakes away, leaving a rough area. Scaling is caused by the frost deterioration of the concrete and is increased by the use of deicing salts (NCHRP Synthesis #57). Air entrainment is effective in reducing or preventing scaling. But improper curing and finishing will reduce the dispersion of air in the concrete, making the air entrainment inadequate.

Spalling (Figure 1.3) is the result of the corrosion of the reinforcing steel below the deck surface. Basically, spalling is the disintegration of a section of the concrete above the reinforcing steel as expansive steel corrosion causes the concrete cover to separate from the concrete below the steel level. Under traffic small pieces will be knocked about, leaving a hole or

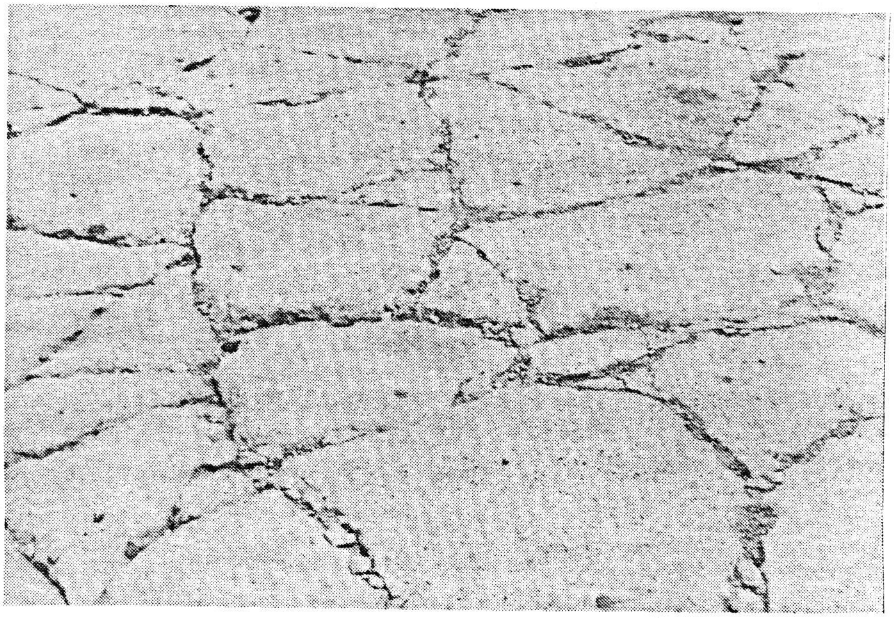


Figure 1.1 Cracking

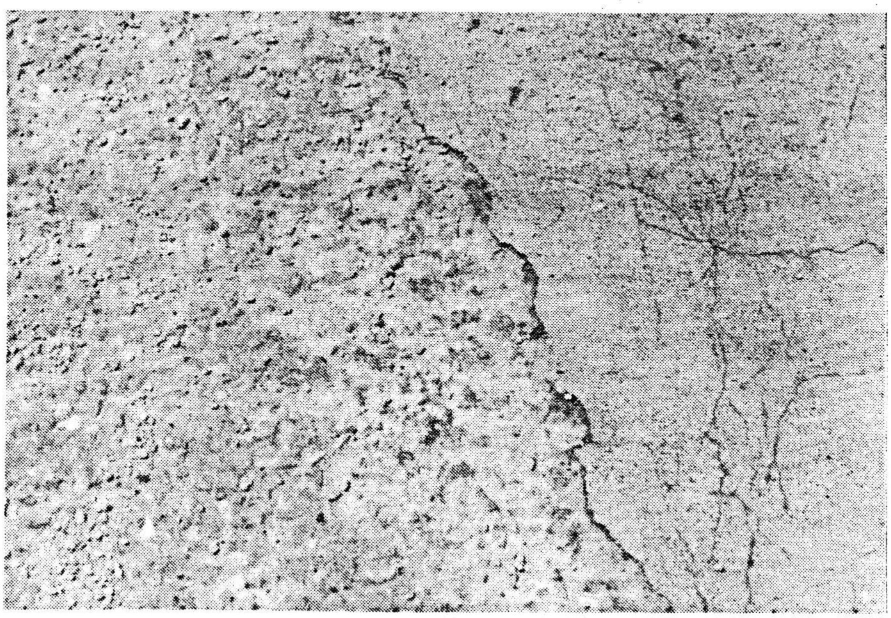


Figure 1.2 Scaling (on left)

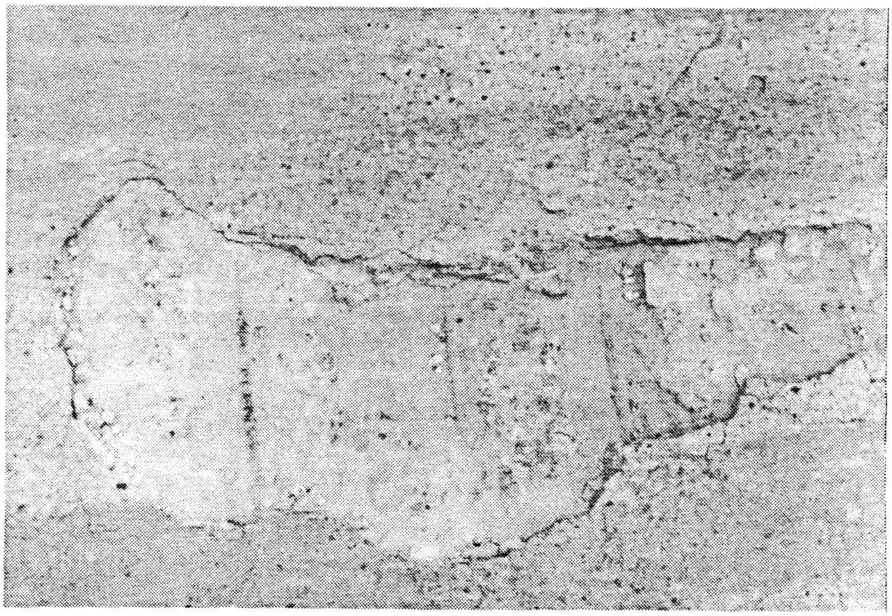


Figure 1.3 Spalling

spall, and exposing the top layers of reinforcing steel. The area of bridge deck affected can be up to several square feet. If not repaired, the affected area will grow in size.

Spalling can endanger the structural integrity of a bridge deck. The best method of repair is to completely remove and replace all concrete to a depth of three or four inches where the concrete has cracked to the level of the reinforcing steel. Replacing the concrete may not stop the spalling process. If the spalling process is not stopped, the new surface will deteriorate rapidly.

In order to identify the factors contributing to bridge deck deterioration, the Arkansas Highway and Transportation Department (AHTD) selected forty-five bridges of varying age and surface finish for review and testing. The review examined construction records for information relating to age, "mix designs, suppliers, contractors, sources, and any unusual aspects of the specific bridge decks" (project proposal). Also included was "an evaluation of maintenance costs by structure type as far as practical." Testing included core and chloride samples taken from the selected bridges by the AHTD and tested by the University of Arkansas for "density, compressive strength, total chloride ion content, degradation, observed segregation," wear, and delamination, and "surface hardness with depth."

Chapter Two

LITERATURE REVIEW

CORROSION PROCESS

Corrosion is an electro-chemical process which requires three elements to be present: an anode, a cathode, and an electrolyte (NCHRP Synthesis #57). The anode, where corrosion takes place, is the source for electrons. The cathode does not corrode but maintains the ionic balance by receiving electrons from the anode. The electrolyte is the solution which is capable of conducting electric current by ionic flow. In the bridge deck, water acts as the electrolyte and the reinforcing steel acts as both the anode and the cathode. If the steel is exposed, the anodes appear as dark or rusted areas.

A corrosion cell exists in concrete because electrical potential differences are present. Iron, being high in the electromotive force series, tends to enter into solution, thus freeing electrons at the anode.

$$\text{Anodic Reaction: } Fe \rightarrow Fe(++) + 2e(-)$$

To maintain equilibrium, the free electrons are consumed at the cathode. If hydrogen and oxygen are present in sufficient quantities, hydroxyl ions are formed.

$$\text{Cathodic Reaction: } O_2 + 2\ H_2O + 4\ e(-) \rightarrow 4\ OH(-)$$

Ferrous hydroxide is deposited at the anodes.

$$2\ Fe + 2\ H_2O + O_2 \rightarrow 2\ Fe(OH)_2$$

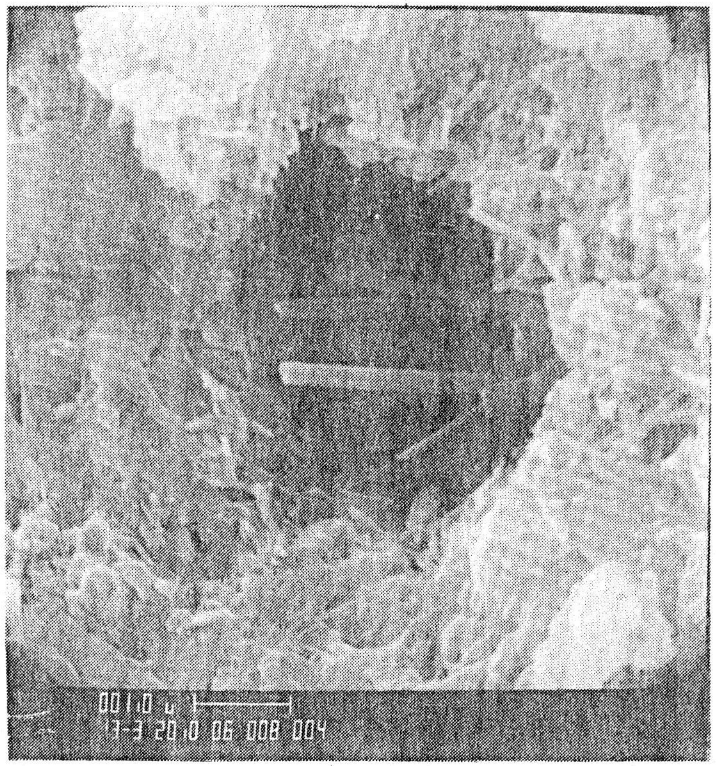
The ferrous hydroxide is converted to ferric hydroxide, commonly known as rust.

$$4\ Fe(OH)_2 + 2\ H_2O + O_2 \rightarrow 4\ Fe(OH)_3$$

As the corrosion process continues, the iron oxides that develop occupy up to 13 times the original volume of the steel and "can create expansion pressures of as much as 4,700 pounds per square inch," (Crumpton, 1985) many times the tensile strength of the concrete. Figure 2.1 shows photomicrographs of the growth of rust crystals within the concrete matrix. These pressures exist within the concrete deck when the rust crystal expansion is prevented. Thus, horizontal fracture planes begin to develop at the level of the reinforcing steel. The area affected is referred to as a delaminated area. The action of vehicular loading and ice formation breaks apart the concrete in this area and creates spalls, ('potholes').

EFFECT OF CHLORIDES

Normally, concrete possesses a resistance to corrosion because of a pH of approximately 11.4. Concrete's high pH results from the presence of calcium hydroxide and other alkalis which inhibit corrosion (NCHRP Synthesis #57). However, if enough chloride ions



Swordlike crystals of rust from a corroding reinforcing bar protruding into a concrete cavity.

Rust crystals found two inches from corroding reinforcing steel.

Figure 2.1 Rust Crystals in Portland Cement Concrete (Crumpton, 1985) courtesy Kansas DOT exist in the concrete, the resistance to corrosion is neutralized. Deicing chemicals, which contain chlorides, are the primary cause of increased bridge deterioration. During the 60's, when most states adopted a 'bare pavement' policy of removing all ice and snow on roads, the use of deicing chemicals increased by about 400 percent (Carrier & Cady, 1975).

As chlorides are applied to the wearing surface, the soluble chlorides penetrate the deck. The natural resistance to corrosion, supplied by the concrete, is neutralized whenever the percent chlorides reaches a specific concentration (Clear, 1976). The concentration of chlorides necessary to induce corrosion is known as the "corrosion threshold." The corrosion threshold is dependent upon cement content, but is approximately 0.2 percent Cl- per gram of cement (Table 2.1).

Table 2.1 Total Chloride Corrosion Threshold
(Clear, 1976)

Cement Factor 94 lb bags/cu.yd	Cement Content lbs/cu.yd	Total Cl Corrosion threshold, lbs Cl/cu.yd
6.0	564	1.13
6.75	634.5	1.27
7.0	658	1.32
8.0	752	1.5
8.75	822.5	1.65

AHTD "Standard Specifications for Highway Construction" called for a cement factor of 6.0 bags per yard for structural concrete (Class S and S(AE)) until 1972 when the requirement was raised to 6.5 bags per yard for which the threshold is 1.22 lbs Cl/cu.yd.

Unsalted concrete may contain 0.2 to 0.4 lbs. Cl/cu.yd. If water and oxygen are present and the corrosion threshold is exceeded at the level of reinforcing steel, corrosion will normally begin.

CONCRETE FACTORS AFFECTING DURABILITY

To increase the durability of the concrete and reduce spalling, the penetration of chlorides into the deck must be retarded. The rate of penetration for the same amount of chloride ion concentration is dependant upon the permeability of the concrete. The permeability of the concrete depends on the: water/cement ratio, concrete-aggregrate ratio, air entrainment, degree of consolidation, and curing. Low permeability reduces the penetration of chlorides and increases the life of the bridge. The resistance of the bridge deck to corrosion is primarily determined by the following factors (Clear, 1976):

1. Depth of clear cover over steel
2. Concrete water/cement ratio
3. Degree of consolidation

Clear Cover:

The clear cover is the thickness of concrete above the top reinforcing bars. Depth of cover is probably the most important factor that determines the resistance to corrosion. For good concrete, the time required for corrosion to begin varies with the square of the depth of concrete cover over the steel (NCHRP Synthesis #57). For example, twice the cover requires four times as long. Therefore, each additional inch of cover significantly increases the time before corrosion begins (Table 2.2).

Water/Cement Ratio:

Water/cement ratio is another major factor in determining corrosion resistance. The lower the water content, the less porous the concrete. Lower porosity reduces the penetration speed of the chlorides (Figure 2.2). Almost twice as much cover is necessary to protect concrete with a 0.6 w/c ratio than is required to protect a 0.4 w/c ratio concrete for an equal length of time (Clear, 1976). The time to corrosion is drastically decreased by higher water/cement ratios (Table 2.2).

Table 2.2 Effect of Depth of Cover and Water/Cement Ratio on Time to Corrosion (Clear, 1976)

Depth of cover (inches)	Estimated Time to Corrosion, Days w/c=0.4 concrete	w/c=0.5 concrete	w/c=0.6 concrete
1.0	120	7 to 28	7
2.0	1000	140	75
3.0	$\gg$1000	925	375

Consolidation:

Effective consolidation produces dense concrete that impedes chloride penetration. During construction, effective consolidation can be routinely achieved by using internal vibration and experienced personnel if the slump of the concrete is more than about three inches (Clear, 1976).

However, in low-slump concretes, good construction practices do not guarantee adequate consolidation (Clear, 1976). Clear's test specimens were compacted and screeded to the proper elevation

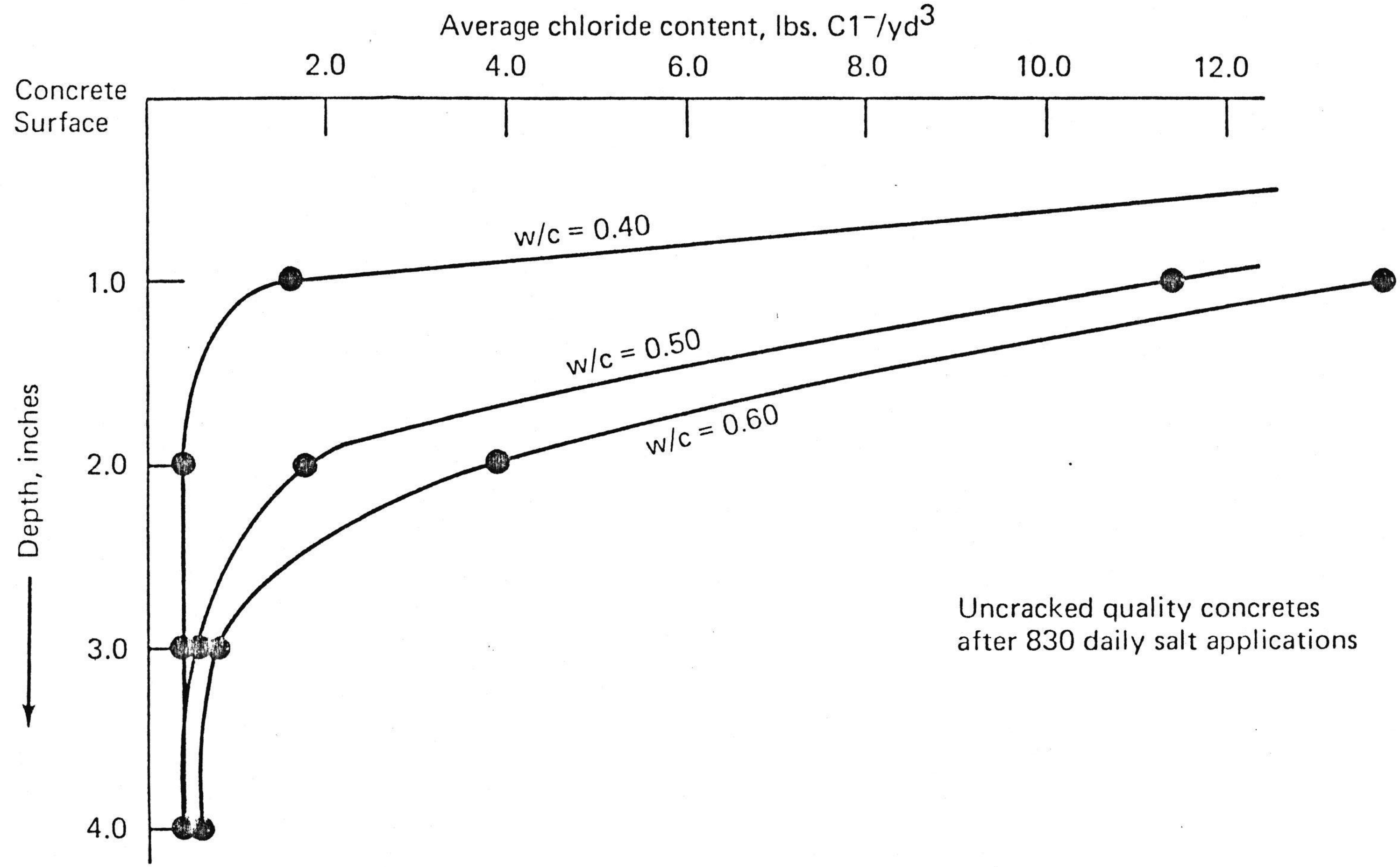


Figure 2.2 Effect of Water/Cement Ratio on Permeability (Clear, 1976)

by a finishing machine specially designed for use with low slump concrete. The degree of consolidation was checked with a nuclear density guage. The random "improperly consolidated" concrete exhibited a 4 to 6 percent reduction in density compared with the equally random "properly consolidated" concrete when it occurred. The resulting higher porosity in the "improperly consolidated" concrete required a 3.4 inch cover to provide the same amount of protection provided by a 1.4 inch cover for the "properly consolidated" slabs. The difference is shown in the chloride profiles for the low water/cement ratio "Iowa" mix concrete in Figure 2.3. Thus the attempt to achieve a dense impervious concrete by means of low-slump can be offset by difficulty in getting adequate consolidation.

CONCRETE FACTORS NOT AFFECTING DURABILITY

The following factors were found to have little or no effect on resistance to corrosion (Clear, 1976):

1. Cement factor -- the number of bags of cement per cubic yard of concrete.
2. Allowing the concrete to "age" one year before salting.

Even though the corrosion threshold varies with the cement content (Table 2.1), chloride induced corrosion cannot be significantly reduced by changing cement content (Clear, 1976). The average chloride penetrations (Figure 2.4) for all three cement contents are practically identical except at the one inch depth.

Allowing the deck to "age" one year before its first salting will not increase its resistance to chloride penetration. On a

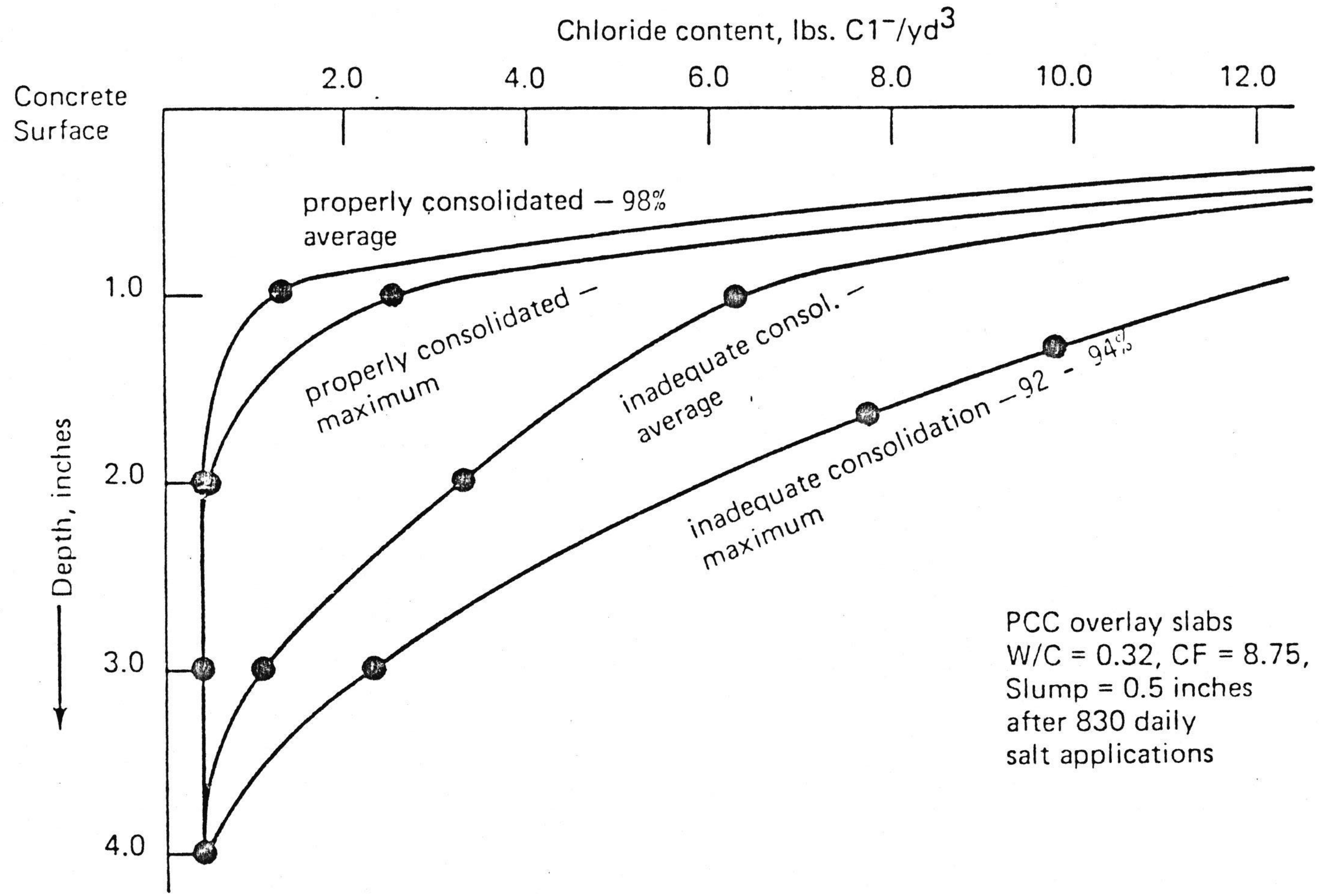


Figure 2.3 Effect of Consolidation Upon Permeability (Clear, 1976)

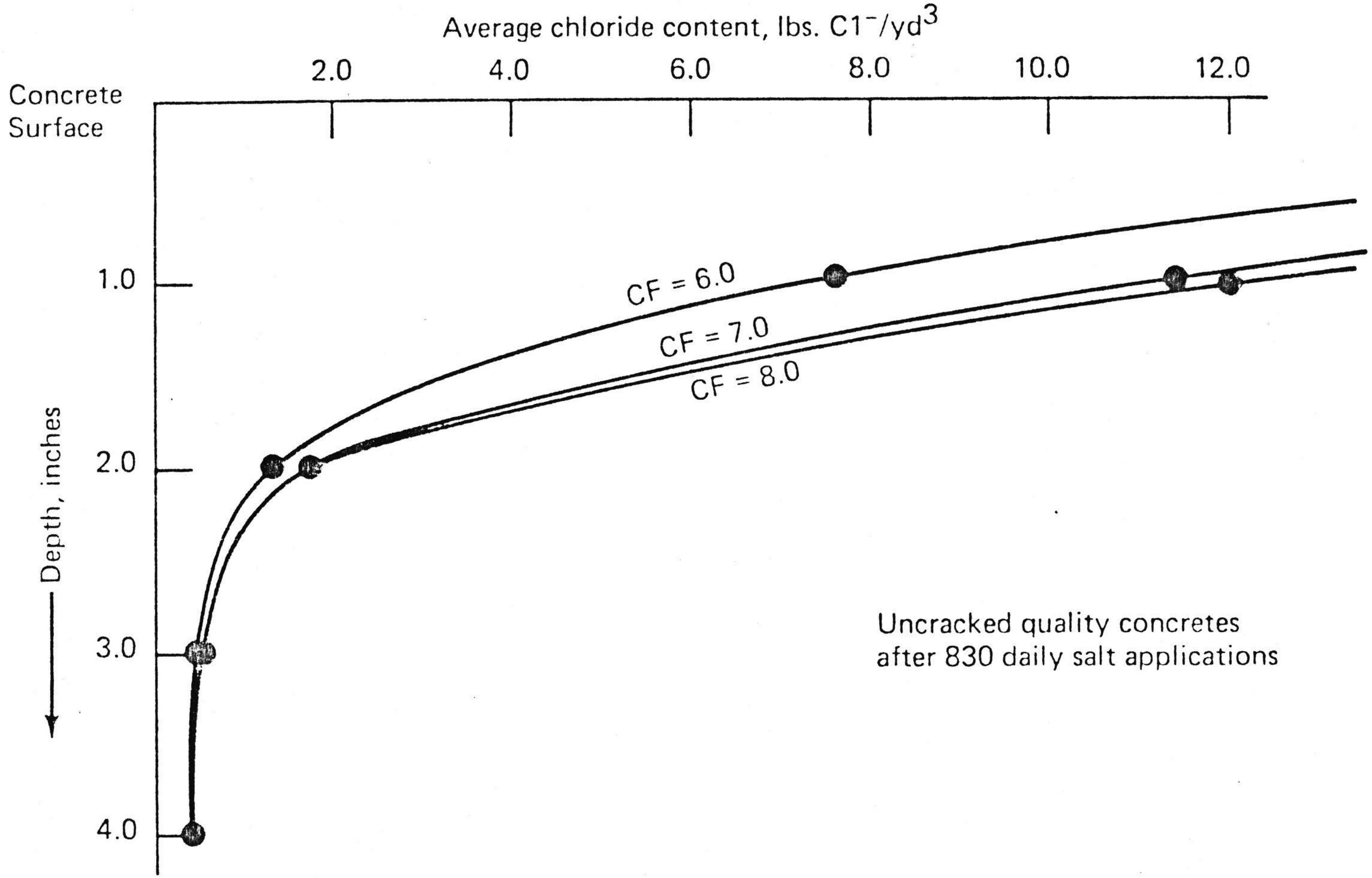


Figure 2.4 Effect of Cement Content Upon Permeability (Clear, 1976)

test slab that was aged one year, rust stains were seen ten months after the initiation of daily salting (Clear, 1976). The chloride profiles of aged concrete were not significantly different from those of freshly salted concrete.

NEW CONSTRUCTION TECHNIQUES

New construction techniques are possible solutions to the durability problem. New construction techniques are those techniques which are not commonly used, most of which are still in the research stage. The techniques reduce spalling by either inhibiting the corrosion process, stopping the corrosion process, or reducing the chloride penetration in the deck.

Inhibiting Corrosion:

Non-Corrosive Reinforcement

Reinforcing steel's susceptibility to corrosion is not significantly affected by the type of steel used or the level of stress to which the steel is subjected (NCHRP Synthesis #57). All natural weathering steels corrode in concrete containing moisture and chlorides (NCHRP Synthesis #57). Stainless steel bars are being produced in South Africa and England. They do resist corrosion but are used in special applications only. The use of stainless steel bars in bridge decks is currently not economical.

Stainless steel clad bars are being tested as a lower cost alternative to solid stainless steel bars. The bars are coated with a layer of stainless steel approximately 0.5 mm thick. After twenty months of daily salt applications, red rust stains and corrosion induced cracks appeared in test slabs using stainless steel clad bars. The amount of corrosion was less for the stainless steel clad bars than for the black steel control bars. It was undetermined at that time whether "corrosion of the clad bars was confined to black steel corrosion at defects in the coating or whether corrosion of the cladding occurred" (NCHRP Synthesis #57).

The strength, stiffness, and bond behavior of fiberglass reinforcing bars are being tested at the University of Arkansas (Pleimann, 1985). Fiberglass reinforcement does not corrode and should perform well in an hostile environment, such as in a chloride contaminated deck. Results of the study are encouraging and should be available in late 1986.

Coated Reinforcing Steel

Another attractive alternative to non-corrosive reinforcing bars is to apply a coating to conventional reinforcing bars. The coating would isolate the steel from chlorides and moisture thus preventing corrosion. Powder epoxy coatings perform satisfactorily and may be economically feasible. In 1977, the additional in-place cost was reported as $0.15 per pound (NCHRP Synthesis #57). The price would drop as more epoxy-coated steel is used. The epoxy must be applied to the steel when it is at a temperature of 400-450 degrees F, ruling out field application. The bars must be bent before application since bending will crack the coating.

The main problem in using epoxy coated bars is that the coating is easily damaged during transportation and handling. Small cracks can be repaired in the field using an epoxy-resin compound. Small defects are not patched unless damage exceeds 2% in straight areas and 5% in bent areas.

Metallic coatings are of two types: sacrificial or non-sacrificial. Sacrificial coatings are those that are higher than iron in the electromotive series. When the coating is damaged and the steel is exposed, the sacrificial coating becomes the cathode and the steel becomes the electrode. The sacrificial coating loses electrons and corrodes instead of the steel. Zinc is a commonly used coating. Once the sacrificial metal has completely corroded, the reinforcing steel may begin to corrode.

Non-sacrificial metals only protect the steel if the coating is unbroken. If exposed, the steel may corrode rapidly. The corrosion of the steel is what should theoretically happen, but in the highly alkaline environment of the concrete, the activity of metals may not be determined by the metal's position in the electromotive series (NCHRP Synthesis #57). Because of the uncertain effectiveness of galvanized bars, the Federal Highway Administration limits installations using galvanized steel to three bridge decks per state (NCHRP Synthesis #57).

Corrosion Inhibitors

Corrosion inhibitors may be added to concrete to reduce the speed of the corrosion process. Compound groups, primarily chromates, phosphates, hypophosphites, alkalines, and fluorides are being studied (NCHRP Synthesis #57). Some reduce corrosion but have negative side effects such as reduced compressive strength. Others give conflicting results. The mechanism is complex and there is not a general theory that applies to all situations. The appeal of inhibitors is that they would be simple to use and to incorporate into design and construction practices.

Stopping the Corrosion Process:

Cathodic Protection

Cathodic protection has been used for 30 years in protecting pipelines, but only recently has it been applied to bridge decks (NCHRP Synthesis #57). The theory behind cathodic protection for steel in concrete is to apply sufficient direct current to the steel such that corroding anodes on the steel are prevented from discharging ions. The current discharging anodes become current receiving cathodes, thus the name "cathodic protection".

The two methods of cathodic protection are galvanic anodes and impressed current. The galvanic anode system uses a metal higher in electromotive series than the metal to be protected and connects it to the protected metal. The protected metal acts as a cathode and the protecting metal acts as the anode. The protecting metal corrodes and must be replaced after being consumed. The disadvantage of this system is that the current voltages are low and numerous anodes are required. The advantage is that overprotection is not possible. Zinc and magnesium are the most suitable anodes for the protection of steel reinforcing bars.

The impressed current system depends on a battery or a direct current (DC) rectifier operating on an alternating current (AC) line voltage for power. The top mat of reinforcing steel must be electrically continuous. Also, the anodes placed in the deck must be in an electrically conductive layer (Figure 2.5). The layer is usually a mixture of asphalt and coke. Coke is the residue of coal after distillation.

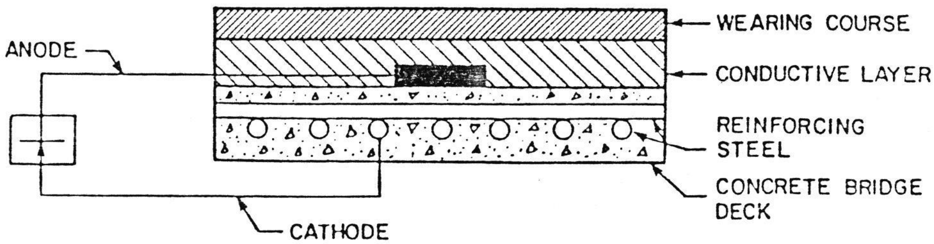


Figure 2.5 Cathodic Protection Installation (Clear, 1976)

Overprotection occurs when too much current is applied to the deck. When too much current is applied, hydrogen bubbles form at the reinforcing steel. The bubbles reduce the bond between the concrete and reinforcing bars.

The impressed current system requires expertise in design, construction, inspection, and maintenance that doesn't exist in many highway departments. The value of cathodic protection is that it will stop active corrosion without the necessity of removing all chloride contaminated concrete.

Electroshock Therapy

Another process which is similiar to cathodic protection is electroshock therapy. Electroshock therapy involves a direct current applied to the deck but does not have to be continous. The unwanted chloride solution in a bridge deck was assumed to act as a conductor of electricity (Spellman & Aames, 1967). The top surface was covered with a copper screen to form a positive electrode. The reinforcing steel was used as the negative electrode. Chloride ions, being negative are drawn to the positive electrode, i.e., the top of the deck. Chloride ions, according to the tests, were removed from the deck (Spellman & Aames, 1967).

However, when the ions were removed, voids were left behind. An attempt to fill these voids with a polymer sealent was unsuccessful. The polymer consisted of a liquid possessing positive ions. The polymer liquid was applied to the top of the deck and was drawn to the negative electrodes, the reinforcing bars. Heat created in the concrete by the passage of the liquid caused the polymer to become a hard plastic-like material. While the polymer did move to the level of the reinforcing steel, it did not fill all of the voids and seal the bridge deck against further chloride penetration.

Preventing Chloride Penetration:

Another approach in improving durability is to prevent the penetration of chlorides into the deck by using sealants, impregnants, overlays, or membranes. The absence of chlorides will allow the concrete to protect the reinforcing steel from corrosion.

Sealants

Sealants are mixtures that are applied to the concrete deck and penetrate to a depth of about one-quarter of an inch (NCHRP Synthesis #57). Sealants do not prevent the penetration of chlorides but do retard penetration. Many materials have been tried including: linseed oil, resins, epoxys, emulsions, and rubber (Snyder, 1965). Linseed oil is presently used by many highway departments. Based on economy and performance, none of the other materials are as good as linseed oil (Snyder, 1965). Linseed oil provides excellent protection against scaling especially in decks that are improperly air entrained (Snyder, 1965). The problem with sealants is that they do not last long and they provide little protection against spalling.

Impregnants

An impregnant is similiar to a sealant but the penetration is increased. Deeper penetration increases the life of the treatment by filling the pores of the concrete. Most impregnants are some type of polymer but linseed oil has also been tried. The process is to cast the deck using normal procedures, allow the deck to dry, vacuum soak the deck with a monomer, and polymerize the monomer in the voids of the concrete.

Polymerization is the joining of the molecules of the monomer to form a large-molecule plastic. The monomer is polymerized by gamma radiation (X-rays) or chemical initiators. The problem with polymerization is that the monomers are expensive and volatile, and the procedures involved are lengthy. The process, however is successful in reducing deterioration.

Overlays

An overlay is an additional thickness of wearing surface added to an existing deck. Overlays have been constructed of polymer concrete, low-slump Portland cement concrete, polymer or latex modified concrete, and internally sealed Portland cement concrete.

Polymer overlays use a polymer concrete mortar applied to the deck in a one-half inch layer. The advantage of polymer overlays is that few materials are used. Disadvantages are rapid wear, lack of flexibility at low temperatures, differential thermal expansion, and shrinkage. The coefficient of thermal expansion for epoxy mortar may be as much as five times greater than that of conventional concrete (Rooney, 1968).

Concrete overlays may be classified as low-slump concrete, polymer modified concrete, or internally sealed concrete. Low slump concrete consists of a very low water/cement ratio, dense Portland cement concrete. The water/cement ratio is usually around 0.32 (NCHRP Synthesis #57). The maximum slump is about one inch (NCHRP Synthesis #57). Consolidation must be checked with a nuclear density guage and water must be added to hydrate the concrete. The materials used are inexpensive but the procedure is labor intensive and requires the use of specialized equipment (NCHRP Synthesis #57).

Polymer modified concrete or latex modified concrete is more expensive than low slump concrete but requires less manpower and can be placed by conventional equipment (NCHRP Synthesis #57). In polymer or latex modified concrete, polymers are mixed with the concrete. Twenty-four states have used polymer modified concrete and "performance has generally been satisfactory though extensive cracking and some debonding have been reported, especially in overlays, 3/4's of an inch thick" (NCHRP Synthesis #57).

Internally sealed concrete uses fusible polymeric particles mixed with the concrete. The particles are fused together with heat after the concrete has cured. A mixture of montan and parafin wax has been the most promising (NCHRP Synthesis #57). Montan is a brittle, mineral wax. The disadvantages of internally sealed concrete are that the heating process is slow and causes cracking (NCHRP Synthesis #57).

Waterproof Membranes

Waterproof membranes prevent water and chlorides from penetrating to the level of the reinforcing steel. The membranes lie underneath an asphalt wearing course. The asphalt wearing course is necessary because most membranes are not durable enough to withstand the wear of traffic. Most membranes are roofing felt or asphalt impregnated protection boards. There are many problems with membranes including leakage, blistering, and insufficient bonding. The bonding problem is such that membranes are not recommended on grades greater than 4 percent or areas subject to rapid acceleration or turning by traffic (NCHRP Synthesis #57).

RECENT LITERATURE

The general nature of concrete bridge deck deterioration is sufficiently understood that the American Concrete Institute has recently published a report, "Corrosion of Metals in Concrete" (ACI Committee 222, 1985). Much of the report is concerned with the same analysis of causes and methods of prevention that are found in the bulk of this chapter, but it does bring the discussion up-to-date. All the questions about the "corrosion of metals in concrete" are not yet answered. An entire recent issue of Concrete International is dedicated to the subject of "chlorides in concrete" (ACI, 1985). Several ideas from the two ACI publications are important for inclusion here.

The Committee 222 report re-emphasizes chloride ions as "the major cause of premature corrosion of steel reinforcement," although it also recognizes that "corrosion can occur in some circumstances in the absence of chloride ions, however. For example, carbonation of concrete results in reduction of its alkalinity, thereby permitting corrosion of embedded steel" (ACI Committee 222, 1985). The report recognizes that "chloride ions are common in nature and small amounts are unintentionally contained in the mix ingrediants in concrete." It also notes that "chloride ions ... may be intentionally added, most often as a constituent of accelerating admixtures."

The background chloride content provided by these sources is normally distributed uniformly thoughout the concrete volume. Not only the chlorides but also "both oxygen and moisture must be present if electrochemical corrosion is to occur." The report emphasizes that "reinforced concrete with significant gradients in chloride ion content is vulnerable to macrocell corrosion, especially if subjected to cycles of wetting and drying" (ACI Committee 222, 1985).

The sources of the differential chloride concentrations which drive the corrosion process are external, i.e., "when chloride permeates from the surface of the hardened concrete, uniform chloride contents will not exist around the steel because of differences in the concentration of chlorides on the concrete surface (resulting from poor drainage, for example), local differences in permeability, and variations in the depth of cover to the steel" (ACI Committee 222, 1985).

The model described in Chapter Four by which the test data was analyzed is a one-dimensional one. It emphasizes the variation of chloride content in the vertical direction (particularly at the level of the highest deck reinforcing steel) and not the lateral variation in Cl- content that drives the corrosion process.

Future refinement of the modeling of corrosion deterioration will need to distinguish between the initial background chloride concentration and that which contributes to the corrosion process. There is some indication that a test to "differentiate between the different sorts of chloride ions and ... determine only those which are responsible for the corrosion process" (Hope, ACI, 1985) will be available in the future.

Chapter Three

INVESTIGATION

PRELIMINARY PROCEDURES

Forty-five bridges were selected for the deck durability survey in Arkansas (Figure 3.1). The bridges were constructed between 1958 and 1980. Specific locations of the bridges are given in Table 3.1, "Masterlist of Bridge Decks."

Each bridge deck was rated (Table 3.1) by the AHTD according to a Federal Highway Administration (FHWA) system. According to the system, each deck is given a category and rating. For example, a deck may be assigned category #2 (Moderate Deterioration) with a rating of 5 which means that spalls will cover less than 5% of the deck area and deck delamination will be between 20 and 40% of the deck area. Details of the FHWA system are given in Table 3.2.

SAMPLING AND TESTING PROCEDURES

Chloride and core samples were taken from the bridges during the period of August to October, 1984. Samples were tested for chloride content at the laboratories of the Civil Engineering Department of the University of Arkansas in Fayetteville. Core samples were visually examined for type of surface, cover, and general condition. They were then tested for compressive strength, density, and surface hardness.

Bridge #8 (Structure #A5142) was across the state line in Texas, and, therefore, unavailable for testing. A contractor was

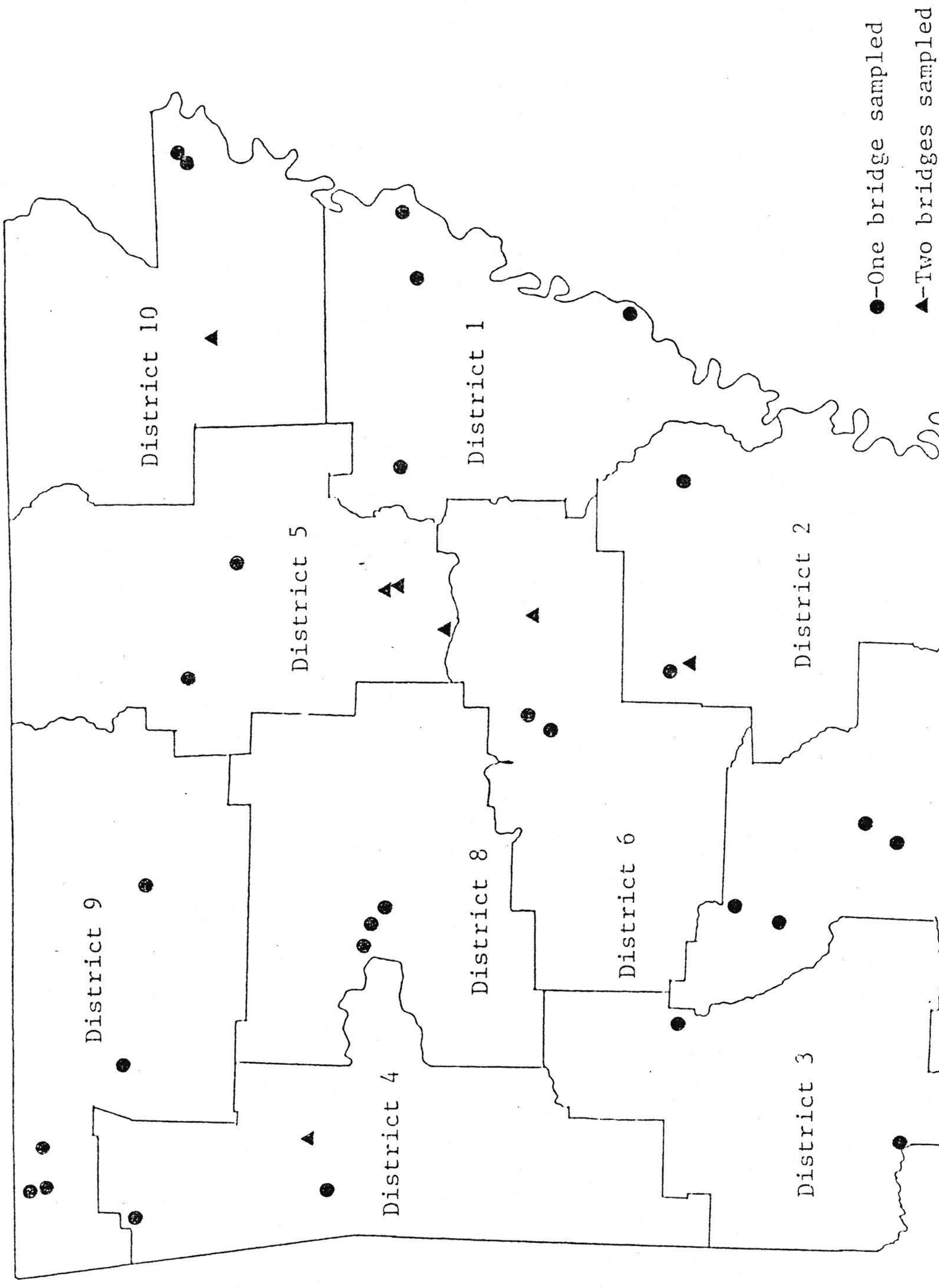


Figure 3.1
Location of Bridges

Table 3.1

MASTERLIST OF BRIDGE DECKS

ID	DIST	COUNTY NO	COUNTY NAME	RTE	SEC	LOGMILE	STRUC	JOB #	YEAR	DECK RATING	COND. CAT
1	1	68	St Francis	40	51	259.75	B3900	11668	1965	7	3
2	1	18	Crittenden	40	52	276.05	B3114	11593	1958	5	2
3	1	74	Woodruff	64	13	7.31	3823	11699	1964	6	2
4	2	1	Arkansas	1	5	2.96	3386	2599	1961	6	2
5	2	35	Jefferson	65	14	12.70	A5611	2783	1974	8	3
6	2	35	Jefferson	65	14	16.60	A5500	2782	1973	6	2
7	2	35	Jefferson	65	14	16.60	B5500	2782	1973	8	3
8	3	46	Miller	71	3	2.90	A5142	3601	1967	4	1
9	3	46	Miller	71	3	2.90	B5142	3601	1967	4	1
10	3	55	Pike	70	5	8.74	3089	3575	1961	6	2
11	3	41	Little Riv	71	4	0.00	5817	3824	1980	9	3
12	4	17	Crawford	40	11	12.56	A3807	4483	1965	6	2
13	4	17	Crawford	40	11	24.49	A5109	4527	1967	7	3
14	4	17	Crawford	40	11	24.49	B5109	4527	1967	8	3
15	4	72	Washington	16	2	3.93	5464	9437	1972	8	3
16	5	32	Independen	167	17	16.48	5644	5681	1977	7	3
17	5	69	Stone	14	6	13.99	5466	5623	1972	8	3
18	5	73	White	67	12	0.21	A5088	1348	1966	8	3
19	5	73	White	67	12	0.20	B5088	1348	1966	8	3
20	5	73	White	67	12	20.65	A5535	5635	1975	8	3
21	5	73	White	67	12	20.65	B5535	5635	1975	8	3
22	5	73	White	67	13	0.59	A5536	5635	1976	8	3
23	5	73	White	67	13	0.59	B5536	5635	1976	8	3
24	6	43	Lonoke	40	4	174.00	A3227	6680	1961	6	2
25	6	43	Lonoke	40	4	174.00	B3227	6680	1961	6	2
26	6	60	Pulaski	10	8	14.44	A1538	6678	1961	7	3
27	6	60	Pulaski	430	21	0.88	A5307	6848	1972	8	3
28	7	10	Clark	30	14	61.96	B3888	7612	1965	6	2
29	7	10	Clark	51	2	0.32	1412	7547	1960	6	2
30	7	52	Ouachita	79	4	2.15	5348	8574	1973	8	3
31	7	52	Ouachita	79	4	10.06	3612	7563	1962	7	3
32	7	52	Ouachita	79	4	10.06	A3612	7793	1978	9	3
33	8	58	Pope	40	22	80.30	A3587	8476	1962	6	2
34	8	58	Pope	40	22	73.97	B3316	8461	1962	7	3
35	8	58	Pope	40	22	85.80	B3967	8488	1966	8	3
36	9	44	Madison	23	9	4.08	3583	9466	1962	5	2
37	9	51	Newton	65	3	1.20	3735	9435	1964	6	2
38	9	4	Benton	62	2	7.11	3974	9433	1966	7	3
39	9	4	Benton	71	19	5.66	2157	9579	1976	8	3
40	9	4	Benton	71	19	7.84	5614	9579	1977	8	3
41	10	16	Craighead	63	7	2.26	A5203	10743	1967	7	3
42	10	16	Craighead	63	7	2.26	B5203	10743	1967		
43	10	47	Mississippi	55	12	63.28	B3162	10616	1959	6	2
44	10	47	Mississippi	55	12	66.75	B3166	10616	1959	7	3
45	10	54	Phillips	49	11	0.56	2899	11631	1961	3	1

Table 3.2

ARKANSAS STATE HIGHWAY AND TRANSPORTATION DEPARTMENT

CONCRETE DECK EVALUATION - CONDITION RATING ITEM 58

Category Classification	Adjectival Rating	Rating	Condition Indicator (% Deck Area) Spalls	Deck Delamination Or Deterioration
Category #3 Light Deterioration	New	9	None	None
	Good	8	None	None
		7	None	Less 2%
Category #2 Moderate Deterioration	Fair	6	Less 2%	Less 20%
		5	Less 5%	20 to 40%
Category #1 Extensive Deterioration	Marginal	4	Greater 5%	40 to 60%
	Poor	3	Greater 5%	Greater 60%
Structurally Inadequate Deck	Critical	2	Deck structural capacity grossly inadequate	
		1	Deck has failed completely Repairable by replacement only	
		0	Holes in deck - danger of other sections of deck failing	

NOTE: The specialized table can be used as a guide for evaluating deck conditions using different condition indicators.

For further information regarding Electrical Potential or Chloride Content Indicator, see FHWA RECORDING AND CODING GUIDE, 1979.

busy with repair work on Bridge #14 (Structure #B5109); later samples were not taken from this bridge. Neither of the two bridges were included in the statistical analysis of data.

Chloride Sampling and Testing:

The bridges were sampled for chlorides at three different locations, usually the gutter, outside wheel path, and between the wheel paths. Using a rotary drill to pulverize the concrete (Figure 3.2), samples were taken at half-inch increments to a depth of three inches (Figure 3.3).

The chloride samples were tested for total content of acid-soluble chloride ions according to AASHTO T-260-82. However, physical difficulties with the "poisoning" of the chloride-sensitive electrode available required that the actual evaluation of the chloride content be done by a titration procedure using mercuric nitrate as found in Standard Methods for Examination of Water and Wastewater. Detailed steps and illustrations of the procedure are found in Appendix A.

Core Sampling and Testing:

Using a coring truck (Figure 3.4), two core samples were taken from each bridge. The cores are approximately four inches in diameter and six to ten inches in height (Figure 3.5). The cores were usually taken from both ends of the bridge. On long bridges, the samples were taken approximately 100 feet apart. The samples usually came from the inside wheel path. The cores were visually examined in the laboratory for cover, type of surface, consolida-

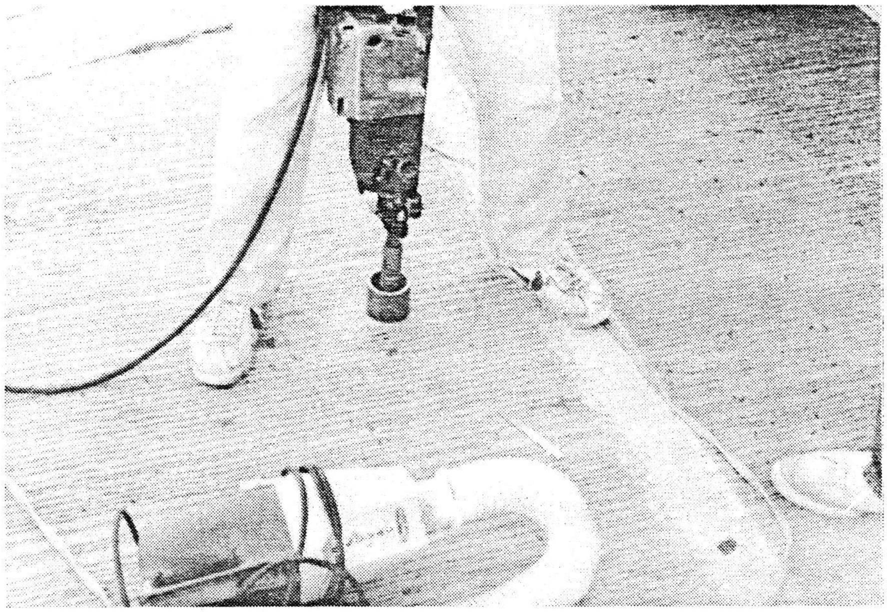


Figure 3.2 Pulverizing Concrete

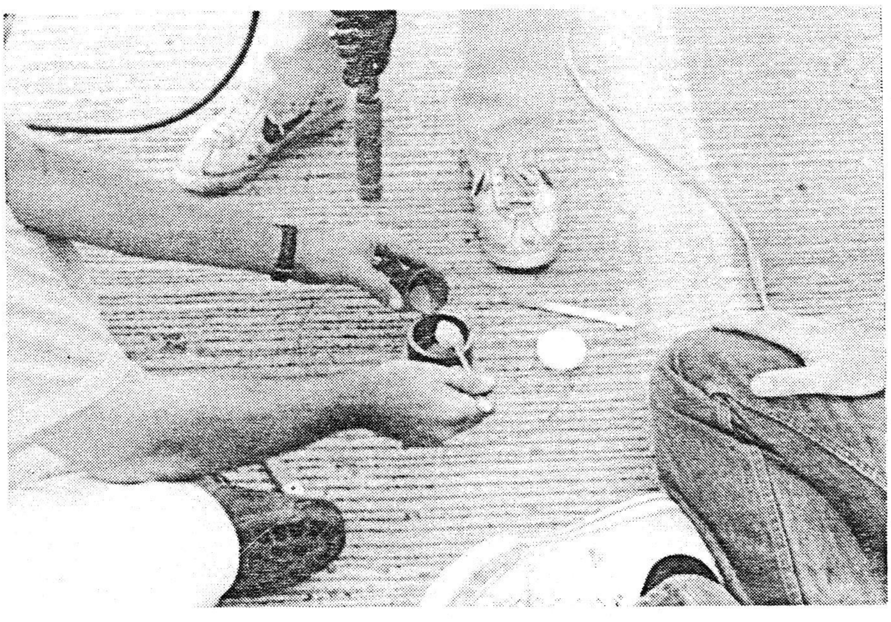


Figure 3.3 Collecting Sample

Figure 3.4 Coring Truck

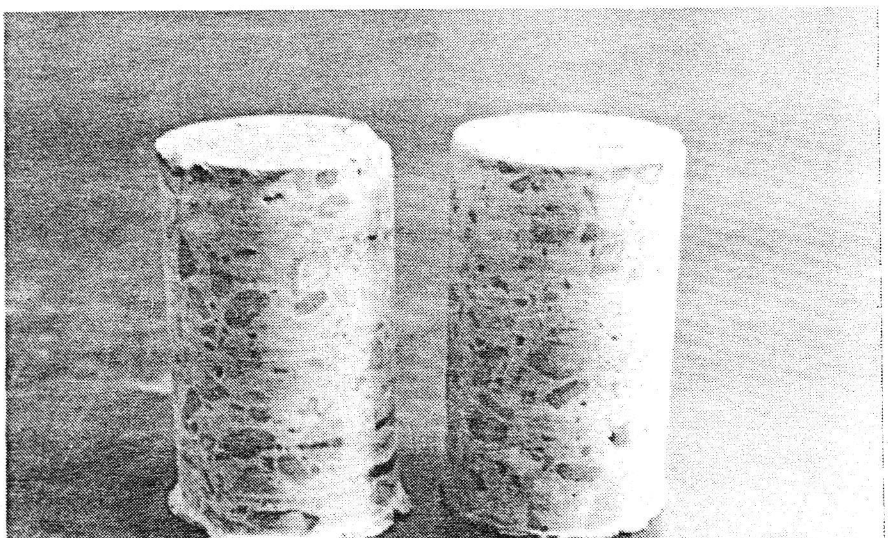


Figure 3.5 Core Samples

tion, and general condition. One core from each pair was tested for density. The core was sawn into disks approximately two inches thick. Cores containing reinforcing steel were sawn into smaller segments of cylinders if possible.

The density of each concrete disk was measured using ASTM D1188-83, Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens. Each disk was of known thickness and depth. The densities were plotted at the center of each disk providing a variation of density with depth. (Appendix C.) The density at a level corresponding to half the clear cover of the deck was evaluated for use in the statistical analysis. The average density of the core was also calculated because there was little variation of density with depth in most decks.

A literature search was made of possible methods of evaluating the strength of concrete by some form of hardness testing. The Schmidt rebound hammer was the best and most practical test available. The compressive strength tests were per ASTM C39-83b, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, except for minor changes which are described in Appendix A. The tests for surface hardness were per ASTM C805-79, Standard Test Method for Rebound Number of Hardened Concrete, except for minor changes which are described in Appendix A.

Chapter Four

TEST RESULTS AND EVALUATION

ANALYSIS MODEL:

The model assumes that concentration of chloride ions is the major contributing factor to the spalling of bridge decks. Viewed from the "vertical dimension" the model of deck deterioration is a simple one. Chloride ions are deposited on the surface of the bridge deck (Figure 4.1). The concrete cover hinders the chloride ions reaching the steel reinforcement below. Hindrance is provided by both the length of the path through which the chloride ions must flow, and the resistance to flow provided by that path, the "permeability."

Once the concentration of chloride ions at the first layer of steel reaches the "corrosion threshold," the corrosion begins and subsequently produces the delamination that finally results in spalling (Figure 4.2).

From the time that the bridge is cast, and especially from the time that it is subjected to traffic, the chloride content increases. However, it is only as the chloride content at the level of the top layer of steel (i.e., at the clear cover level) increases to the "corrosion threshold" concentration that corrosion and resulting deck distress begins.

Thus, one part of the analysis of the data is to estimate the time necessary to reach the "corrosion threshold" at the depth of cover. The resulting "threshold age" would then be included among the other variables to be included in the final analysis.

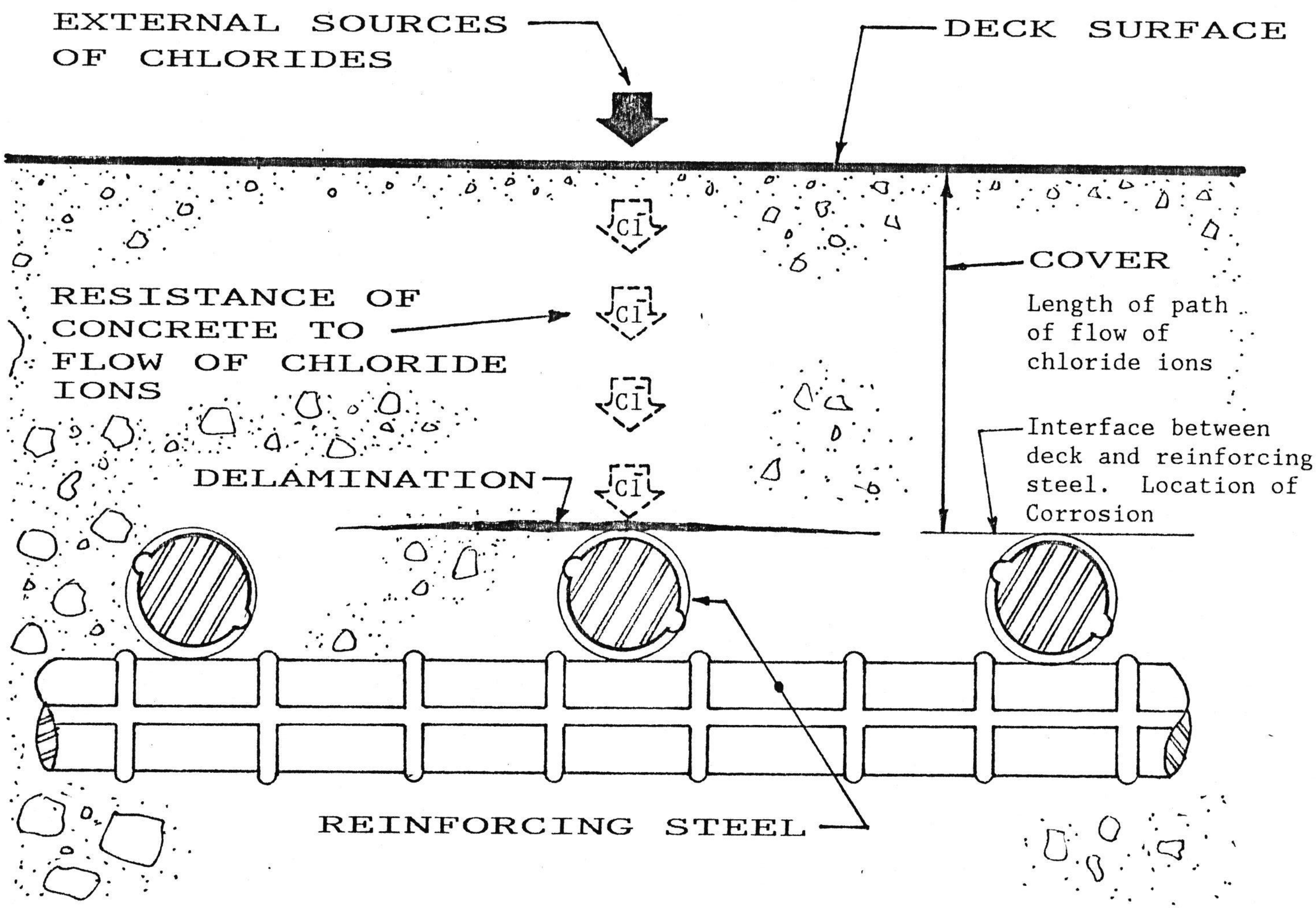


Figure 4.1 Simple Vertical Model of Deck Deterioration

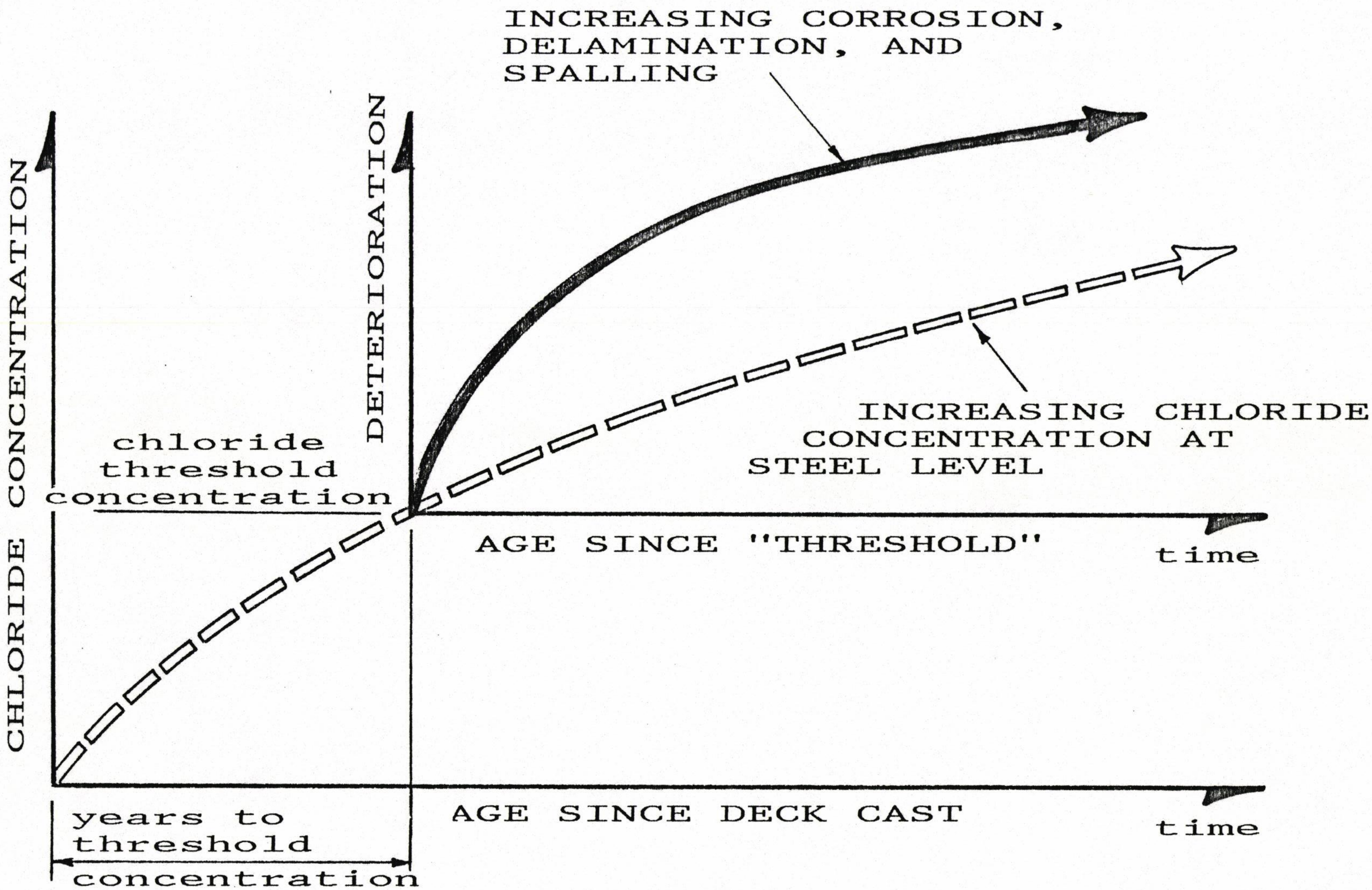


Figure 4.2 Time Schema for Deck Deterioration for "Simple Vertical" Dimension Model

No attempt was made to model the factors influencing the lateral variation of chloride content which drives the deterorattion process. The range of data required for such a task was outside the scope of this project. Also, the understanding of those factors is a subject of current discussion (ACI, 1985).

DATA AND TEST RESULTS:

The bridge's location, deck rating, and the year when the project was begun were given in Table 3.1. Table 4.1 contains the bridge deck's surface finish (tined or non-tined), the clear cover to the top of the first steel layer, the water/cement ratio, slump, curing method, and range of temperatures on the day the deck was cast as received from the construction diaries. Table 4.2 contains the results of the chloride tests. The three parts of Table 4.2 give the results for up to three samples for the same deck. The values are given in lbs.Cl-/cu.yd. of concrete at one-half inch intervals down to three inches below the surface.

Table 4.3 contains data about the dates the bridges were cast and open to traffic. It also contains the values from the tests performed that were used in the statistical analysis. "Agecast" is the length of time in years between the average casting date for the spans sampled and the date when the chloride samples were taken. "Ageopen" is the length of time between the date when the project was opened to traffic and the date when the chloride samples were taken. For some eight of the decks the opening date was unavailable. However, the averages of the "Agecast" and "Ageopen" values were one year apart. So a value of "Agecast" -

Table 4.1
DECK DATA FROM CONSTRUCTION DIARIES

Id	Bridge	Surface	Cover Ins.	W/C Ratio	Slump Ins.	Cure Method	Cure Temps.@
1	B3900	Smooth	1.5	-	-	-	64-90
2	B3114	Smooth	2.25	-	-	-	60-70
3	3823	Smooth	2.5	-	-	-	-
4	3386	Smooth	2.4	-	-	-	20-50
5	A5611	Tined	2.4	0.44	2.5	Burlap	70-90
6	A5500	Tined	1.9	0.49	1.5	Comp.	60-90
7	B5500	Tined	1.9	-	-	-	-
8	A5142	Smooth	2.5	-	-	-	-
9	B5142	Smooth	2.5	-	-	-	-
10	3089	Smooth	3.0	-	-	-	40-70
11	5817	Tined	2.8	0.42	2.75	Cot.Mat	50-90
12	A3807	Smooth	1.75	-	-	-	-
13	A5109	Smooth	1.875	-	-	-	50-90
14	B5109	Smooth	-	-	-	-	-
15	5464	Smooth	3.0	-	-	-	-
16	5644	Tined	-	0.4	3.0	Comp.	20-70
17	5466	Tined	3.0	-	-	-	50-90
18	A5088	Smooth	2.0	-	-	-	70-90
19	B5088	Smooth	1.5	-	-	-	50-80
20	A5535	Tined	3.25	0.50	1.75	Comp.	20-60
21	B5535	Tined	3.25	-	-	-	20-60
22	A5536	Tined	3.25	0.46	-	-	20-60
23	B5536	Tined	3.0	0.46	-	-	20-60
24	A3227	Smooth	2.4	0.44	2.0	Burlap	60-90
25	B3227	Smooth	2.4	0.44	2.0	Burlap	60-90
26	A1538	Smooth	2.25	0.44	3.0	Burlap	60 80
27	A5307	Tined	3.0	0.44	2.75	Burlap	30-50
28	B3888	Smooth	2.5	-	-	-	70-90
29	1412	Smooth	2.0	-	-	-	-
30	5348	Tined	2.64	-	-	-	60-80
31	3612	Smooth*	1.2	0.5	-	Burlap	50-80
32	A3612	Tined	2.25	0.44	2.75	Retard.	40-70
33	A3587	Smooth	1.2	0.50	3.0	-	-
34	B3316	Smooth	1.75	-	-	-	70-100
35	B3967	Smooth	1.8	-	-	-	40-80
36	3583	Smooth	2.0	-	-	-	50-80
37	3735	Smooth	1.875	-	-	-	70-90
38	3974	Smooth	1.875	-	-	-	-
39	2157	Tined	1.9	-	-	-	-
40	5614	Tined	-	-	-	-	-
41	A5203	Smooth	2.88	0.50	2.75	Burlap	60-90
42	B5203	Smooth	3.0	0.50	2.75	Burlap	60-90
43	3162	Smooth	2.0	-	-	-	-
44	B3166	Smooth	1.8	-	-	-	-
45	2899	Smooth	1.25	0.55	2.50	-	

@-Temperatures are the low's and high's when deck was cast.
*-Asphalt overlay, reported cover is thickness of concrete.

Table 4.2

CHLORIDE CONCENTRATIONS (lbs./cu.yd.)

Id	Bridge	Sample A Pos.*	Depth (ins.) 0.5	1.0	1.5	2.0	2.5	3.0
1	B3900	-	-	-	-	-	-	-
2	B3114	G	3.8	1.8	1.4	1.2	0.7	0.5
3	3823	G	10.6	6.9	4.1	7.2	4.3	2.6
4	3386	G	18.7	14.2	13.8	9.5	7.2	HS
5	A5611	G	4.9	2.2	1.9	1.9	1.9	HS
6	A5500	G	5.9	6.0	3.5	3.6	-	-
7	B5500	G	6.0	4.8	3.1	1.7	-	-
8	A5142	-	-	-	-	-	-	-
9	B5142	G	7.0	1.1	0.9	0.7	0.3	-
10	3089	G	50.4	22.9	16.8	13.5	8.5	-
11	5817	O	2.7	1.6	1.2	0.7	0.4	0.5
12	A3807	G	2.6	1.4	1.4	0.9	0.9	0.8
13	A5109	G	2.7	1.6	1.2	0.5	0.4	0.3
14	B5109	S	2.9	1.6	0.9	0.6	0.2	0.5
15	5464	I	9.1	3.6	1.9	1.3	1.1	0.7
16	5644	G	3.6	1.9	1.1	0.6	0.4	0.2
17	5466	G	4.4	1.4	0.8	0.5	0.2	0.2
18	A5088	I	6.3	12.8	10.6	8.6	10.8	-
19	B5088	G	6.8	4.8	HS	-	-	-
20	A5535	O	3.0	1.6	0.6	0.5	0.5	0.5
21	B5535	O	3.0	1.6	0.6	0.5	0.5	0.5
22	A5536	G	5.1	0.9	0.7	0.4	0.4	0.4
23	B5536	-	-	-	-	-	-	-
24	A3227	-	5.7	5.5	3.4	2.2	1.0	1.0
25	B3227	-	8.0	5.9	4.3	3.3	2.0	1.9
26	A1538	G	7.0	4.5	2.6	2.5	1.9	4.3
27	A5307	O	7.6	4.1	5.0	4.5	4.1	2.9
28	B3888	G	8.6	4.9	4.4	3.0	2.7	2.8
29	1412	-	14.0	8.2	9.0	8.2	7.3	7.0
30	5348	G	3.4	1.5	0.1	0.0	0.0	0.0
31	3612	G	7.8	4.6	2.6	1.2	0.8	0.7
32	A3612	G	0.7	0	0	0	0	0
33	A3587	G	14.1	9.6	5.5	5.8	5.3	HS
34	B3316	O	10.5	5.5	4.3	3.3	3.3	2.7
35	B3967	O	4.0	1.7	1.4	1.4	1.3	1.2
36	3583	G	16.8	15.7	12.8	9.2	7.0	5.5
37	3735	-	8.6	6.6	4.7	3.0	3.1	2.0
38	3974	-	-	-	-	-	-	-
39	2157	-	-	-	-	-	-	-
40	5614	-	-	-	-	-	-	-
41	A5203	G	1.9	0.6	0.9	0.5	0.3	0.3
42	B5203	S	7.5	3.6	2.5	1.5	1.4	1.4
43	B3162	-	13.5	11.4	10.0	7.6	6.7	5.8
44	B3166	S	1					
45	2899	S	8.9	10.0	14.0	9.2	-	-

* S-Shoulder G-Gutter O-Outside wheel path I-Inside wheel path B-Between the wheel paths HS-hit steel

Table 4.2 (Cont.)

CHLORIDE CONCENTRATIONS (lbs./cu.yd.)

Id	Bridge	Sample B Pos.*	Depth (ins.) 0.5	1.0	1.5	2.0	2.5	3.0
1	B3900	-	-	-	-	-	-	-
2	B3114	-	-	-	-	-	-	-
3	3823	O	10.8	4.5	4.4	3.3	2.6	2.6
4	3386	O	10.5	9.1	9.4	9.4	6.8	4.2
5	A5611	O	6.9	6.6	2.6	2.0	2.0	0.4
6	A5500	O	2.6	3.4	-	2.4	-	-
7	B5500	O	1.7	1.0	1.1	1.2	-	-
8	A5142	-	-	-	-	-	-	-
9	B5142	O	12.3	6.3	5.9	0.3	1.3	-
10	3089	O	9.2	8.0	6.7	5.6	HS	-
11	5817	O	3.4	3.4	1.5	1.4	1.4	HS
12	A3807	O	1.5	1.3	-	0.6	0.5	0.3
13	A5109	O	2.5	0.9	0.8	0.7	0.8	0.9
14	B5109	O	0.9	0.9	0.7	0.3	0.5	0.5
15	5464	B	6.3	19.4	13.4	10.4	8.4	5.2
16	5644	O	5.6	2.6	0.7	0.2	0.3	0.3
17	5466	O	7.6	3.7	1.7	1.5	1.2	1.2
18	A5088	O	5.5	4.6	3.5	3.5	1.5	2.4
19	B5088	O	13.3	5.9	HS	-	-	-
20	A5535	G	1.8	0.6	0.2	0.1	0.1	0.0
21	B5535	O	3.5	3.4	1.5	1.3	1.3	1.2
22	A5536	O	7.4	2.8	1.4	0.8	0.7	1.2
23	B5536	G	8.9	4.0	1.6	0.5	0.2	0.2
24	A3227	-	9.4	3.2	2.5	1.8	1.5	1.0
25	B3227	-	11.7	8.0	6.8	6.0	4.4	4.3
26	A1538	O	14.8	8.7	5.6	4.1	4.0	10.1
27	A5307	G	3.8	5.6	3.9	1.8	1.8	HS
28	B3888	B	4.3	2.6	1.6	0.6	0.5	0.2
29	1412	O	4.7	4.5	3.6	-	0.8	-
30	5348	O	3.7	0.5	1.3	0.2	0.5	0.5
31	3612	O	2.4	1.4	1.6	1.4	1.4	0.8
32	A3612	O	5.6	1.4	0.7	0.5	1.5	0.7
33	A3587	-	5.2	2.4	2.1	1.6	1.2	0.7
34	B3316	-	-	-	-	-	-	-
35	B3967	O	4.4	2.0	0.5	0.9	0.7	0.3
36	3583	O	14.8	19.4	5.8	2.3	2.2	1.9
37	3735	O	7.7	9.8	16.4	6.8	5.2	4.7
38	3974	-	-	-	-	-	-	-
39	2157	-	-	-	-	-	-	-
40	5614	-	-	-	-	-	-	-
41	A5203	O	3.6	0.6	0.5	1.1	1.0	0.8
42	B5203	O	8.9	4.0	2.3	1.2	1.1	1.1
43	B3162	O	14.6	15.8	11.7	9.1	7.4	
44	B3166	O	12.7	9.3	5.2	2.3	1.5	0.5
45	2899	O	14.6	9.2	5.3	3.5	-	-

* S-Shoulder G-Gutter O-Outside wheel path I-Inside wheel path
B-Between the wheel paths HS-hit steel

Table 4.2 (Cont.)

CHLORIDE CONCENTRATIONS (lbs./cu.yd.)

Id	Bridge	Sample C Pos.*	Depth (ins.) 0.5	1.0	1.5	2.0	2.5	3.0
1	B3900	-	-	-	-	-	-	-
2	B3114	-	-	-	-	-	-	-
3	3823	B	10.2	4.0	3.0	2.7	HS	-
4	3386	B	16.2	12.8	11.7	9.6	-	-
5	A5611	O	5.2	2.3	1.9	3.0	2.2	2.9
6	A5500	B	4.1	1.9	2.8	1.9	-	-
7	B5500	B	3.2	2.0	1.2	1.1	-	-
8	A5142	-	-	-	-	-	-	-
9	B5142	B	10.6	6.5	5.7	HS	-	-
10	3089	B	7.5	2.8	2.7	2.1	1.3	0.9
11	5817	B	0.9	0.8	0.7	0.7	0.7	0.7
12	A3807	B	1.6	1.1	1.0	0.9	0.8	0.5
13	A5109	B	3.4	0.9	0.6	0.6	0.7	0.3
14	B5109	I	2.0	0.9	0.6	0.9	0.7	0.7
15	5464	G	5.9	3.1	2.8	1.3	1.5	2.0
16	5644	B	3.8	0.7	0.0	0.1	0.1	0.1
17	5466	-	-	-	-	-	-	-
18	A5088	G	1.6	1.5	1.4	1.1	HS	-
19	B5088	I	14.8	9.8	7.8	6.8	4.1	HS
20	A5535	O	9.1	2.6	0.9	0.9	0.3	0.3
21	B5535	-	6.3	3.4	2.1	1.2	0.6	0.6
22	A5536	I	8.0	3.5	1.2	0.7	0.2	0.0
23	B5536	O	3.6	1.8	1.5	1.5	1.5	1.5
24	A3227	B	5.8	4.0	1.6	1.4	1.1	0.5
25	B3227	B	6.4	2.6	2.4	1.3	0.9	0.5
26	A1538	I	11.3	9.6	7.4	5.9	7.7	3.7
27	A5307	I	9.6	7.7	6.3	5.3	4.3	2.3
28	B3888	O	6.5	2.4	2.4	2.2	1.4	0.8
29	1412	G	30.1	14.3	13.0	11.5	HS	-
30	5348	-	2.8	1.7	2.1	2.1	2.1	1.7
31	3612	B	5.5	2.2	1.1	0.8	0.6	0.6
32	A3612	B	2.5	0.7	0.4	0.4	0.4	0.4
33	A3587	-	-	-	-	-	-	-
34	B3316	S	7.1	3.7	3.0	2.3	1.7	HS
35	B3967	S	7.1	3.7	3.0	2.3	1.7	HS
36	3583	G	17.3	11.7	6.6	5.1	2.6	1.6
37	3735	B	9.4	8.6	6.0	5.1	3.3	3.7
38	3974	-	-	-	-	-	-	-
39	2157	-	-	-	-	-	-	-
40	5614	-	-	-	-	-	-	-
41	A5203	B	0.8	0.4	0.4	0.3	0.3	0.3
42	B5203	B	9.6	2.8	1.6	1.0	0.6	0.1
43	B3162	-	12.9	10.7	6.6	6.5	4.9	0.5
44	B3166	-	8.4	4				
45	2899	I	16.5	10.7	6.2	3.1	-	-

* S-Shoulder G-Gutter O-Outside wheel path I-Inside wheel path
B-Between the wheel paths HS-hit steel

Table 4.3
DATA FOR STATISTICAL ANALYSIS

ID	Bridge	Agecast years	Ageopen years	Chloride at 2 ins. lbs/cy	Chloride at Cover lbs/cy	Density lbs/cf	Rebound Number@ Cover	Average Rebound Number	Compressive Strength psi	Maintsum dollars	Trafsum $x10^{-3}$
1	B3900	18.18	17.04			139.0	44.0	41.95	4303	5,588.45	249.0
2	B3114	26.31	23.94	1.20	0.80	142.0	33.4	35.57	7463	1,678.55	300.4
3	3823	19.84	17.61	4.40	3.23	140.9	50.8	51.95	5603	1,919.88	54.0
4	3386	22.81	21.39	9.50	5.40	144.6	36.3	38.08	6692	2,789.96	33.1
5	A5611	10.24	9.24*	2.30	1.87	133.3	35.5	38.25	3761	0	61.4
6	A5500	7.85	6.46	2.64	2.72	144.2	36.8	37.30	4366	0	54.5
7	B5500			1.33	1.42	145.4	37.8	41.43	5495	597.76	§
8	A5142†	-----	-----	-----	-----	-----	-----	-----	-----	2,112.83	-----
9	B5142	21.34	20.34*	0.50	0.80	140.2	30.7	30.10	3630	8,314.07	374.6
10	3089	22.96	22.20	7.07	4.00	144.6	44.9	42.18	6507	21,825.39	56.2
11	5817	3.57	3.31	0.93	0.84	146.2	36.4	35.85	5954	0	29.4
12	A3807			0.81	0.95	139.8	42.4	41.70	4850	0	169.3
13	A5109	15.04	13.62	0.60	0.70	124.1	32.7	44.88	4663	0	134.3
14	B5109†	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
15	5464	11.94	11.30	4.33	2.63	152.5	35.2	34.38	5878	0	13.6
16	5644	7.97	6.97*	0.30	§	§	§	27.03	4825	0	109.4
17	5466	11.24	10.87	1.00	0.70	136.9	39.9	36.65	6691	0	8.4
18	A5088	15.98	14.78	4.40	4.40	140.6	30.2	34.38	4288	2,229.54	121.9
19	B5088	15.98	14.78	4.57	4.90	147.7	31.0	34.98	5016	2,846.40	121.9
20	A5535	9.57	8.07	0.50	0.27	138.5	33.9	32.00	6921	487.72	78.2
21	B5535	8.57	8.07	1.00	0.77	140.4	34.6	38.53	4028	161.16	78.2
22	A5536	9.57	8.07	0.63	0.53	133.4	19.8	19.05	5095	1,100.51	78.2
23	B5536	9.57	8.07	1.00	0.85	135.4	40.3	39.18	5895	1,325.81	78.2
24	A3227	22.20	20.82	1.80	1.32	144.0	46.3	43.28	6377	13,042.18	310.5
25	B3227	22.17	20.82	3.53	2.74	141.1	41.6	41.47	4463	1,302.68	310.5

* calculated "Ageopen" by "Agecast" - 1.00
† deck omitted from testing and analysis
§ data available but date or cover value lacking to calculate this value

Table 4.3 (cont.)
DATA FOR STATISTICAL ANALYSIS

ID	Bridge	Agecast years	Ageopen years	Chloride at 2 ins. lbs/cy	Chloride at Cover lbs/cy	Density lbs/cf	Rebound Number@ Cover	Average Rebound Number	Compressive Strength psi	Maintsum dollars	Trafsum $x10^{-3}$
26	A1538	23.06	22.09	4.17	4.33	144.2	23.8	23.60	5380	24,787.02	494.8
27	A5307	9.48	9.23	3.87	2.33	139.2	45.7	46.58	5636	0	175.7
28	B3888	19.15	18.81	1.93	1.53	143.7	25.0	22.13	4234	0	175.3
29	1412	24.39	24.05	7.30	7.30	142.2	35.3	36.88	5698	11,886.81	38.2
30	5348	9.32	8.32*	0.77	0.83	145.1	45.0	45.50	4746	6,038.21	59.0
31	3612	20.87	20.25	1.13	2.37	143.6	40.5	43.28	5819	0	67.7
32	A3612	4.65	3.65*	0.30	0.47	143.0	29.5	33.15	4401	0	14.5
33	A3587	20.74	20.05	3.70	5.18	143.5	40.3	44.80	5980	387.00	159.0
34	B3316	20.98	20.30	2.80	3.23	142.0	44.0	43.78	3957	762.21	164.1
35	B3967	17.82	17.70	1.53	1.60	145.3	30.7	25.13	7569	1,595.60	171.7
36	3583	22.03	21.37	5.53	5.53	146.0	41.2	43.78	5646	9,967.90	20.3
37	3735	19.26	17.33	4.97	6.70	134.3	36.3	40.63	4657	4,780.70	57.2
38	3974	17.43	16.99			149.3	44.8	44.35	5617	0	70.1
39	2157	8.16	7.16*			143.0	38.4	36.00	4900	0	67.3
40	5614	7.06	6.06*			§	§	42.95	6818	0	49.3
41	A5203	14.95	14.08	0.63	0.47	139.5	39.5	40.10	5643	0	117.6
42	B5203	14.95	14.08	1.23	0.87	142.7	43.6	44.98	5456	0	117.6
43	B3162			7.73	7.73	140.8	47.5	41.40	3648	1,326.28	§
44	B3166			4.27	4.83	140.2	43.1	43.35	4632	13,441.47	§
45	2899	24.04	23.04*	5.27	9.27	142.2	41.8	41.58	4767	52,143.52	46.3

* calculated "Ageopen" by "Agecast" - 1.00
§ data available but date or cover value lacking to calculate this value

1.00 was used for each of the missing eight values of "Ageopen." Those eight calculated values of "Ageopen" are indicated with an asterisk.

"Chloride at 2 ins." is the value of the chloride concentration at a uniform depth of 2.0 inches averaged among 1 to 3 samples. It was used in evaluating the growth of chloride concentration with time. The values of chloride concentration were plotted (Appendix C) and the values found at the depth of the clear cover. The average value at this depth for all samples for a given deck is the "Chloride at Cover" value from Table 4.3.

The values of density of the concrete at various levels were plotted (Appendix C). The value of density at the half-clear-cover level is the variable marked "Density" in Table 4.3.

The average rebound numbers for ten readings at each depth for each sample were also plotted (Appendix C). The variable "RN at Cover" is the value of the Rebound Number at the clear cover level. The value "RN Average" is the average of the Rebound Number averages from each of the four depths measured. The variable "Strength" is the compressive strength of the cores in psi corrected according to the height/diameter ratio of the specimen.

"Maintsum" is the total dollars that were spent on the particular deck in the last eight years. "Trafsum" is the summation of the Annual Average Daily Traffic Estimates for each deck for the period of years from the opening date for the bridge to 1984. The values were taken from the yearly Traffic Volume maps published by AHTD.

No records were available for the amounts of chloride delivered to each deck. However, it was thought that deck deicer chemicals delivered were in some way related to the "Trafsum" intensities especially since traffic evens out the distribution by carrying some salts between decks.

Rating:

AHTD evaluates each bridge in the state every few years. The rating given each bridge is an indication of the general condition of the bridge and is determined by the amount of delamination and spalling present in the bridge deck. The relationship between the extent of deterioration and rating is given in Table 3.2.

The rating, obtained for all forty-five bridges (Table 3.1), ranged from a 3, which is an extensively deteriorated bridge, to a value of 9 for a new bridge. The average rating is a 6.84. A rating of 6 means a bridge has undergone moderate deterioration with the area of spalls being less than two percent of the total area and the area of delaminations being less than twenty percent of the total area. A value of 7 means that no spalling is apparent and that less than two percent of the deck area is delaminated. Over sixty percent of the selected bridges exhibit "none" to "light" deterioration.

The "Rating" value is the only numerical measurement of deck deterioration available. It is the value with respect to which all the other values will be statistically compared. The rating value is, however, an arbitrarily arranged set of indicators whose values bear no continuous numerical relation to the physical process of deterioration. Plots of age vs. rating, and age vs. percent delamination illustrate this point (Figures 4.3 and 4.4).

In Figure 4.3 the ratings of the decks are plotted in reverse order (Rating decreases as deterioration increases) versus "Agecast." The progress of deterioration seems a steady linear pattern with some scatter. In Figure 4.4, however, the point for an individual deck is plotted on a scale of increasing percent delamination versus "Agecast." The rating numbers of 9, 8, 7, 6, 5, and 4 represent ranges of percent delamination of 0, 0, 2, 18, 20, and 20 respectively. The points have been plotted at the mid-height of the appropriate range. Thus location of the points might be anywhere within the indicated range. Even with this uncertainty of location the picture of the pattern of deterioration with time is quite different. Many more of the decks are now recognized as having only minimal deterioration. A lesser number now show the possibility of significant damage. The lack of a continuous relation between the rating number and the actual physical process of deterioration probably reduces the statistical correlation of the data.

Another potential problem is related to the measurement of the extent of deck deterioration. A drag chain is used to evaluate the percent of delamination on which the Rating number is partly based. The drag chain method is subjective and results may vary due to different operators. In turn, the statistical correlation may be reduced.

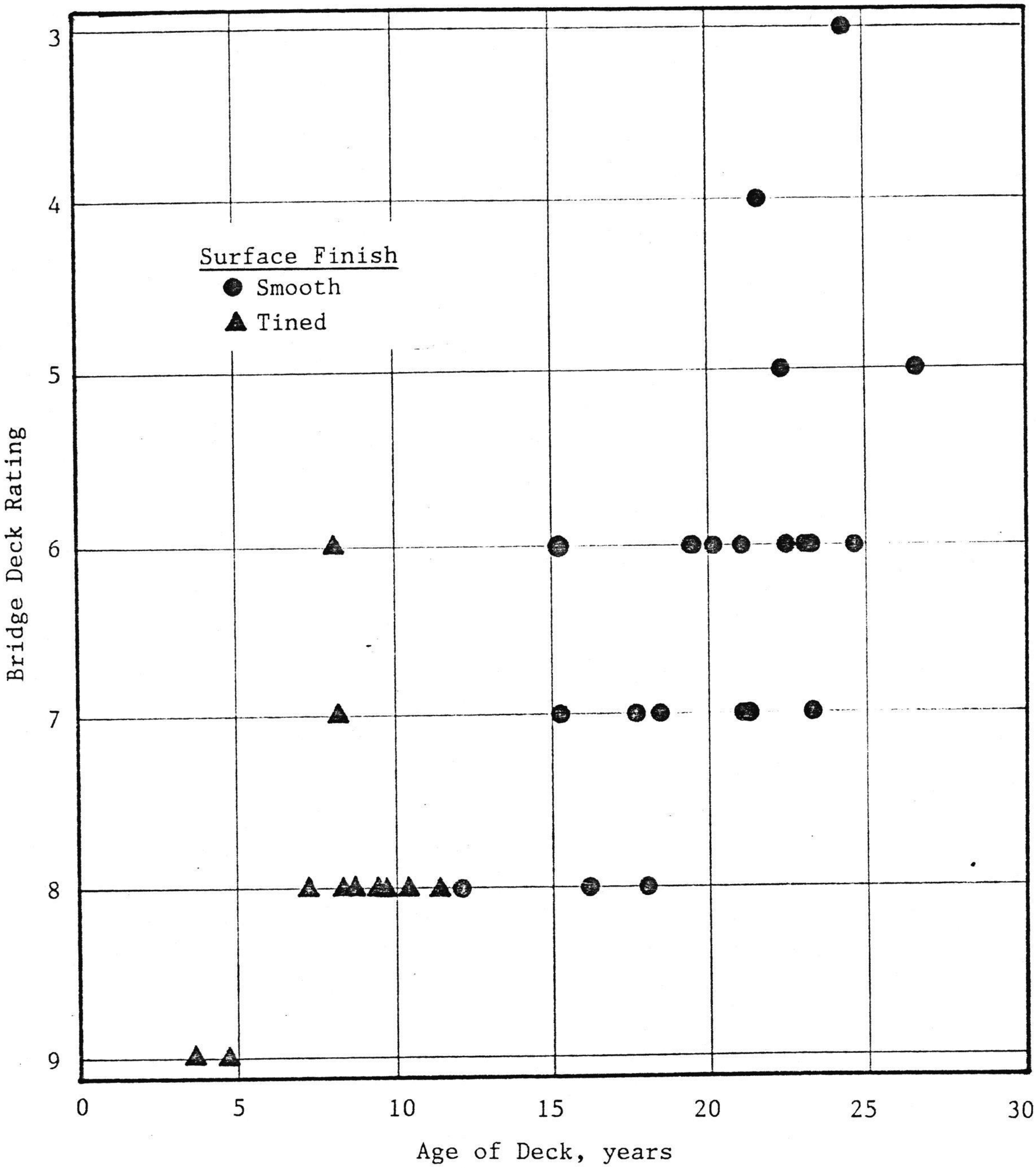


Figure 4.3 Bridge Deck Rating Vs. Age of Deck

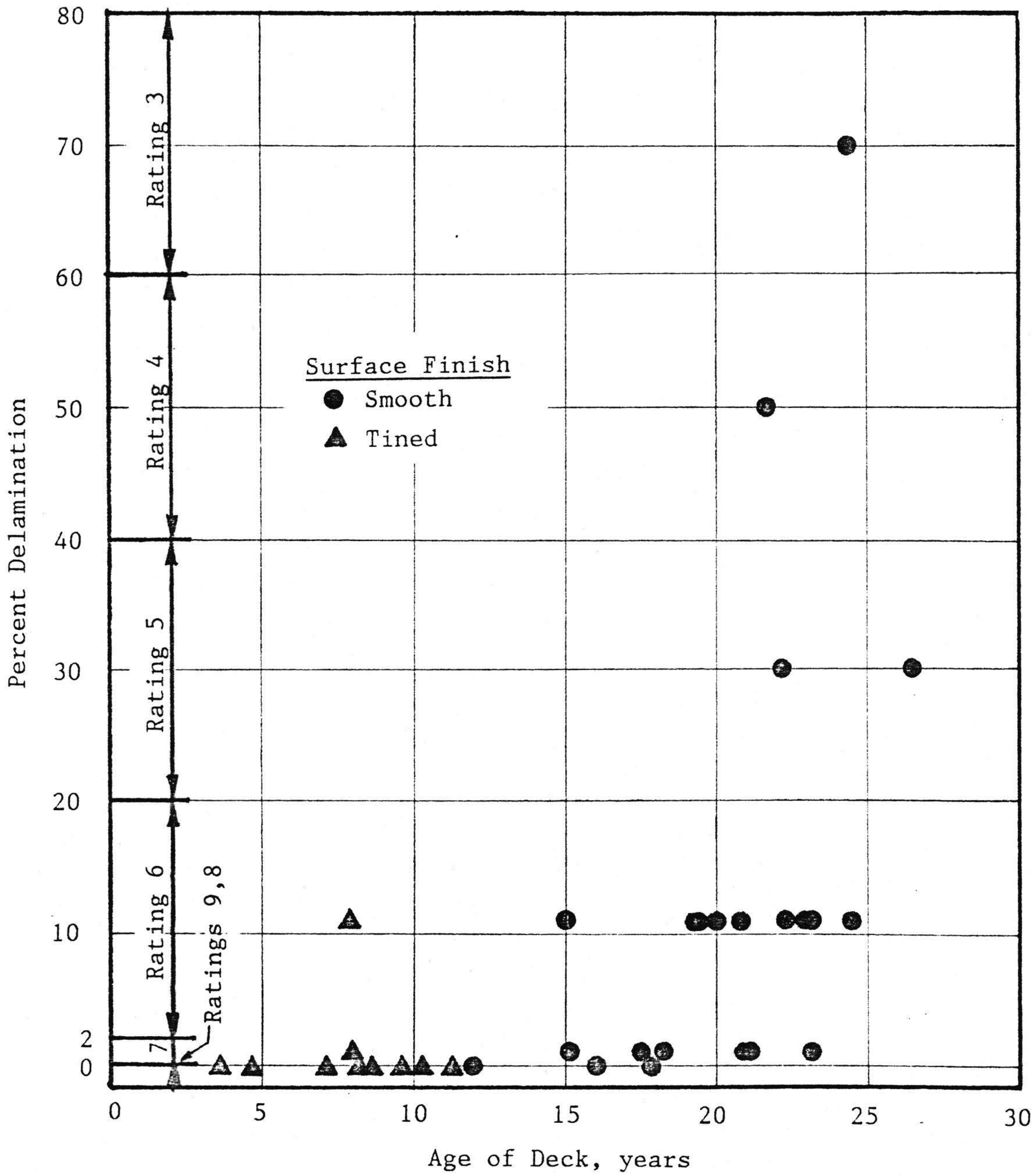


Figure 4.4 Percent Delamination Vs. Age of Deck

Surface:

Fourteen of the forty-three bridges had a tined finish. The tined finish consists of shallow transverse grooves pressed into the deck surface to improve skid resistance. The remaining twenty-nine had smooth finishes. The tined finish is relatively new. All of the test bridges built in 1973 and later have tined finishes. Bridges built before 1973 have smooth finishes. Grooves in tined surfaces may hold deicer salt concentrations on the bridge, possibly increasing salt concentration in the bridge deck. The cover is reduced by the depth of the groove. In addition, the finishing technique may disturb and lessen the near surface density of the bridge deck resulting in reduced durability.

Cover:

The cover was known for all but two of the forty-three bridges analyzed (Table 4.1). The cover reported is the minimum measured cover. Cover was measured in a spalled area, from the core, or whenever steel was found when sampling for chlorides. The remaining covers were found from measurements made at the time of the construction of the deck and contained in the project "Bridge Books" on file at AHTD. The average cover was 2.27 inches. The maximum cover was 3.25 inches and the minimum was 1.2 inches. Most actual covers were within a quarter inch of the specified cover. A plot of cover versus age of deck shows some trend to increase the deck cover in new bridges (Figure 4.5). The average cover for the more recent tined bridges is 2.66 inches, while that of the previous non-tined bridges is only 2.09 inches.

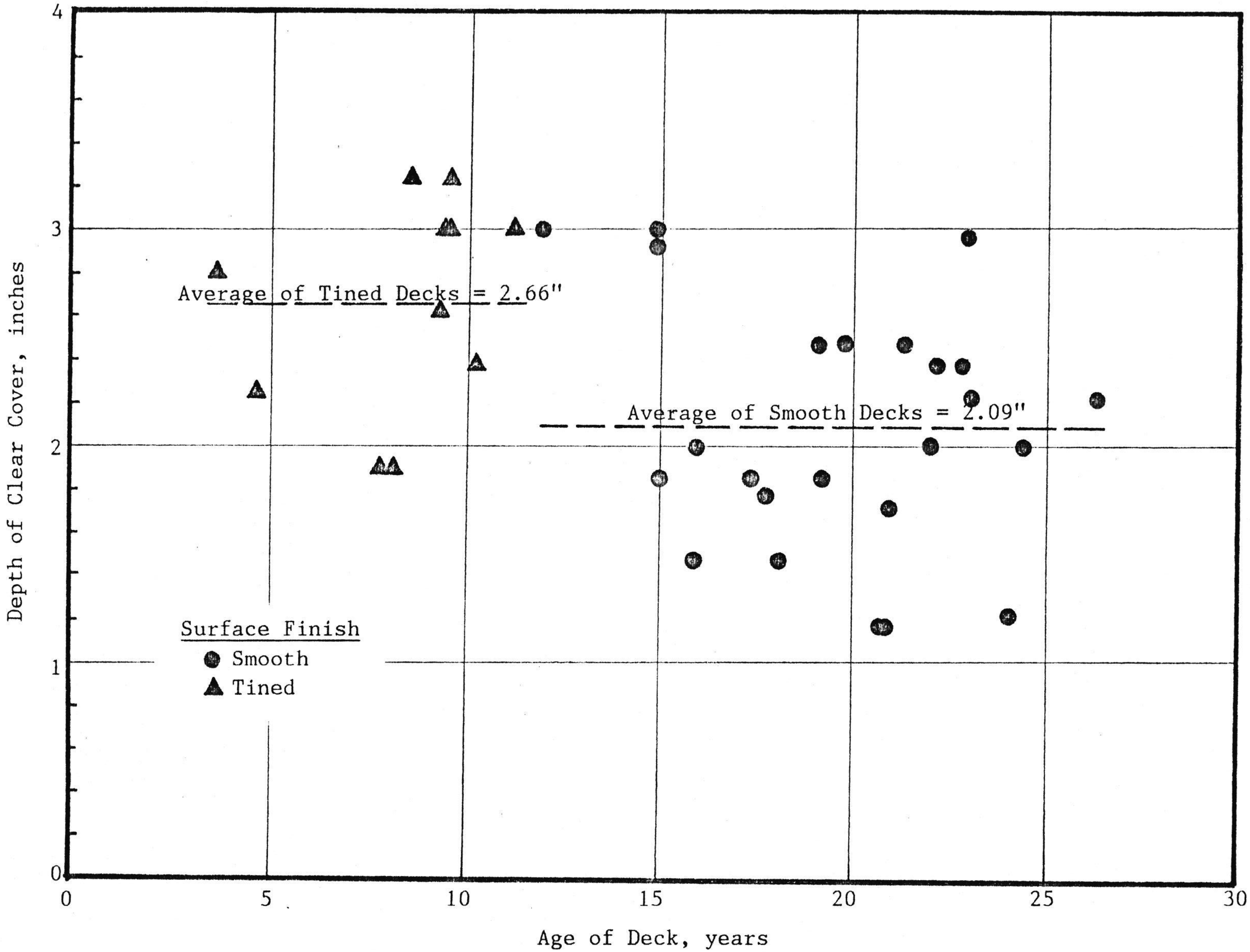


Figure 4.5 Depth of Clear Cover Vs. Age of Deck

Water/Cement Ratio:

The water/cement ratio was obtained from the records for 17 of the 45 bridges (Table 4.1). The average ratio is 0.46 with a low of 0.4 and a high of 0.5. There were too few water/cement ratio values given to contribute to the statistical analysis. The influence of the water/cement ratio on the porosity of the concrete was indirectly measured by Density and Strength for which a significantly larger number of values are available.

Slump:

The slump was found in the records for fourteen decks (Table 4.1). The average slump was 2.5 inches with a range of from 1.5 inches to a high of 3.0 inches. Again, too few values were available for statistical significance and the effect on "porosity" is given with other data.

Curing Method:

The method of curing was found in the records of thirteen bridges (Table 4.1). These included the use of burlap sacks, cotton matting, sprayed curing compound, and, in one case, retarding agents. Too few of the methods used were available for statistical significance, especially in the number of bridges using each method. Again, the effect is indirectly given in other data related to "porosity."

Range of Temperature:

The range of temperature for the day that the decks were cast was available for twenty-nine of the forty-three decks examined. Some ranges showed significantly low temperatures as well as others which showed quite high temperatures. Temperature was not included in the statistical analysis since it was difficult to quantify.

Chloride Content:

The chloride content was measured for thirty-eight of the forty-three bridges analyzed (Table 4.2). Samples were taken at three locations; usually the gutter, outside wheel path, and between the wheel paths. The concentration was reported in lbs.Cl-/cu.yd. The top half-inch tended to have the highest concentration except in delaminated areas. In delaminated areas, the highest concentration was found in the 1.5 to 2.0 inch depth. There was no significant difference in chloride concentration from location to location on a bridge.

The variation of chloride with depth for each set of samples from each deck are shown in the figures in Appendix C. Also plotted is the intersection of the level of clear cover and the threshold concentration appropriate to each deck (Table 2.1). The concentration decreases quite rapidly with depth within the first inch to two inches.

The importance of adequate cover is emphasized in the chloride concentration profiles of the decks (Appendix C). Of the thirty-eight profiles shown, the concentration at the cover level exceeds the threshold concentration in twenty-five decks. Of the thirteen remaining plots, ten are of decks with Ratings of 7 or above.

Age of Deck:

The age of the deck at the time of chloride sampling as measured from the date the deck was cast ("Agecast") is available all except for four decks. Two of the values are unavailable because chloride samples were not taken; two are unavailable because construction diary records are not available. Thirty-nine values of "Ageopen" are available when the eight values estimated from "Agecast" are included.

Density:

A measure of the density of the concrete in the deck is available for all but five of the forty-three decks examined.

The densities are quite uniform in value when plotted with depth below the surface of the slab (Appendix C). There is a typical pattern of the density being slightly lower at the slab surface and increasing with depth. This variation is consistent with the rising of bleed water.

The range of values of density was surprisingly wide with a minimum of 124.1 pcf, a maximum of 152.5, and a mean of 141.6. The smaller value was associated with a 15 year old deck with a Rating of 7, and the largest value came from a 12 year old deck with a Rating of 8.

Rebound Number:

Rebound number data is available for all of the forty-three bridges examined. The coefficient of variation for the rebound number readings at any particular depth varied widely. Therefore, little confidence is placed in the rebound number results. The rebound data influenced the statistical analyses slightly.

Compressive Strength:

Compressive strength values in psi are available for all of the forty-three bridges analyzed. On the whole good strength and probable corresponding low porosity are present in the decks. Unconfined compressive strength ranged between a minimum of 3630 to a maximum of 7569 with a mean of 5327 psi. All are above the minimum value called for in the AHTD's Standard Specifications for Structural Concrete. As a measure of porosity the Strength variable was included in the best predictive model.

Maintenance Cost:

Maintenance costs were examined for the last eight years (Table 4.3). The average total maintenance cost for the last 8 years was fairly low, $4,700. Most of the bridges had little maintenance done while a few seemed to be constantly needing repair (Figure 4.6). If the six bridges that required the most maintenance were excluded, the average maintenance cost dropped to $1,521. The bridges that did need a lot of maintenance tended to be older. However, several older bridges were in good condition without major repairs over the last eight years.

Summation of Traffic Intensities Over Life of Deck:

The summation of the Annual Average Daily Traffic Estimates over the traffic life of the decks to present were available for

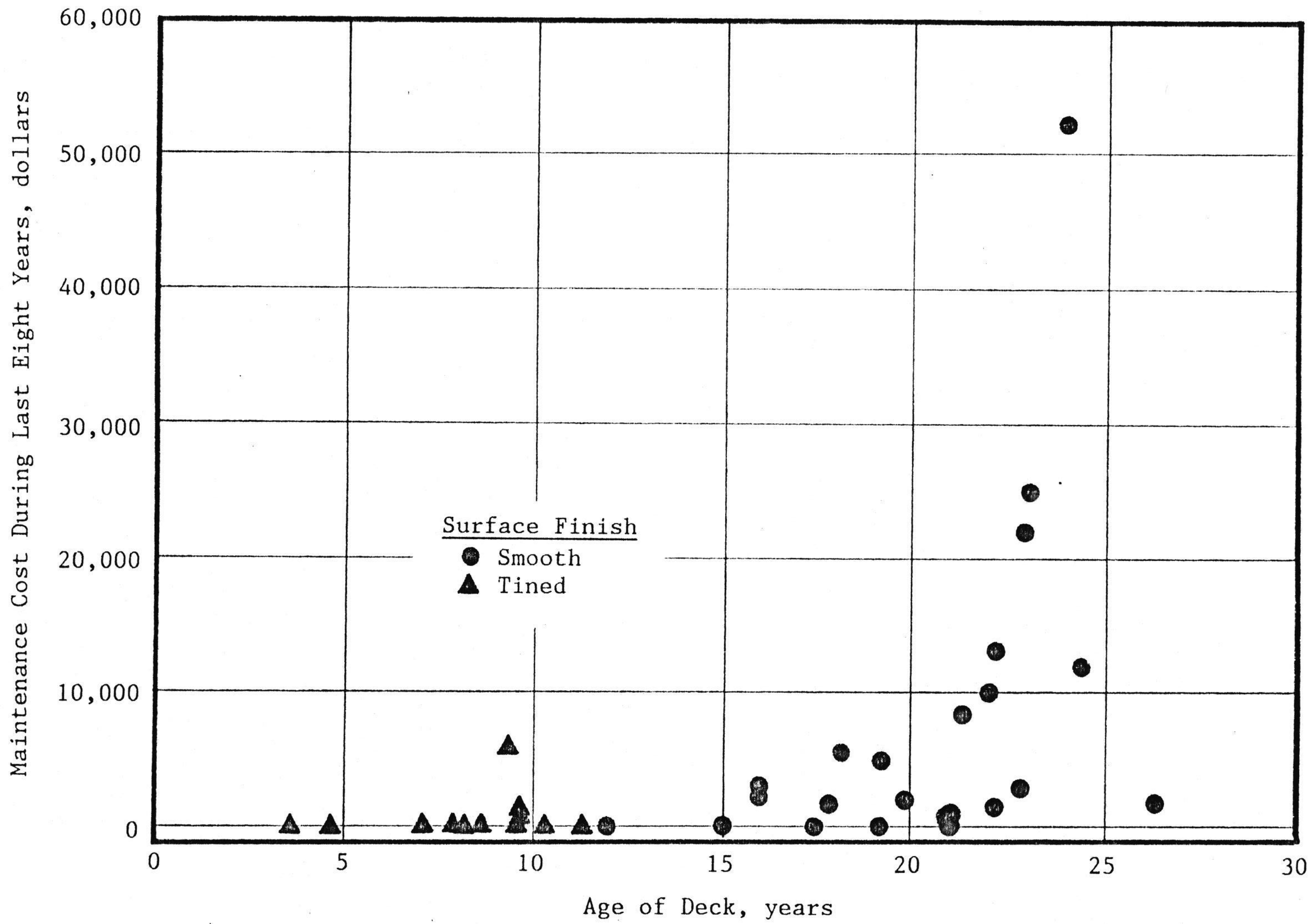


Figure 4.6 Maintenance Cost Vs. Age of Deck

all but three of the bridges. The use of the decks vary between 8.4 thousand cars to 494.8 thousand with a mean of 122.3 thousand. Traffic, identified as "Trafsum" in the analysis, has a significant effect.

STATISTICAL ANALYSIS

The Statistical Analysis System (SAS) at the University of Arkansas Computer Center was used to analyze the gathered data and determine if any statistical relationships existed between the bridge rating and the data collected in this study.

SAS is a computer system developed for data analysis. SAS can be used for information storage and retreival, data modifications and programming, report writing, statistical analysis, and file handling (SAS Basic User's Guide, 1982).

The first analysis was a direct correlation between the deck rating and all the other variables to get some initial identification of those variables that might be particularly important in contributing to deck deterioration as measured by the deck rating.

Correlation Analysis:

Correlation analysis is a statistical procedure that is used to measure the strength of a relationship between two variables (SAS Introductory Guide, 1978, pg. 49). When two variables correlate, there is an apparent linear relationsip between the values of one variable and the values of the other. Correlation coefficients, r, range from 1 to -1. A value of 1 or -1 means that the two variables are perfectly correlated. A value of zero means there is no correlation. A correlation is considered significant when r is 0.84 or larger.

The CORR procedure in SAS computes correlation coefficients between variables and the significance probability of the correlation. The correlation coefficients are computed by the Pearson product-moment method (SAS Intro. Guide, 1978, pg. 49). The significance probability is the probability that the computed correlation coefficient was obtained by chance alone and the correlation coefficient is actually zero. The significance probability is considered to be statistically significant if it is lower than 0.05. The Pearson product-moment correlation coefficients for rating versus all factors are given in Table 4.4.

Table 4.4

Correlation Coefficients

Variable	Number of Observations	Correlation Coefficients	Probability Significance
Agecast	39	-0.754	0.0001
Ageopen	39	-0.741	0.0001
Surface finish	43	0.536	0.0002
Cover	41	0.318	0.0425
Chloride at 2"	37	-0.378	0.0210
Chloride at Cover	36	-0.503	0.0018
Density	38	-0.025	0.8827
RN at Cover	39	-0.209	0.2021
RN average	41	-0.159	0.3206
Compr. Strength	41	-0.107	0.5060
Traffic Summa.	40	-0.294	0.0652
Maintenance Cost (last 8 years)	42	-0.549	0.0002

To test for correlations between Rating and the other factors, the surface finish was coded. A tined surface was coded as a 1 and a non-tined surface was coded as a 0.

Rating decreases, i.e., worsens, with increased age, high chloride content, decreased cover, smooth surface, higher maintenance costs, and larger traffic volumes. Rating also worsens with increased density and rebound number. These last two trends are opposite to what would normally be assumed. The rating also worsens with decreased compressive strength which is expected.

Stepwise Regression:

Statistically, the correlation coefficients are not high enough to state that there is a correlation between Rating and any of the individual factors mentioned above. However, the "r" values for age, cover, chloride at cover, traffic summation, and maintenance cost seem large enough to warrant the use of stepwise regression to build a predictive model of Rating decrease with time and a combination of other factors.

The "r" value for surface finish indicates deterioration from a smooth finish. The explanation, of course, is that the tined surface is relatively new and the bridges have not had time to deteriorate and, therefore, have a high Rating value.

The strong "r" value for maintenance cost occurs because high maintenance costs will be associated with deteriorating decks. Budget constraints and human decisions as to which decks will be repaired are probably why the correlation coefficient is not larger.

Stepwise Regression was used to identify the best method of predicting the age of the deck at which the chloride concentration reaches the threshold concentration at the cover level. The "Age From Threshold" thus calculated was then used in a second Stepwise Regression to determine if the deck Rating could be predicted by a linear combination of the variables, including the calculated "Age to Threshold" concentration time.

STEPWISE is a program of linear regression provided by SAS. A set of independent variables that are of interest can be put in the form of an equation, known as the model. STEPWISE regression starts with no variables in the model and computes the equation correlation coefficient for the one variable model with the highest correlation coefficients. SAS adds variables one at a time and computes equation correlation coeffcients for the new model. The variable that is added is the one that will produce the largest increase in the correlation coefficient. SAS also computes the probability significance for the model and each variable in the model. SAS will continue to add variables until all variables of interest are added or the remaining variables have a probability significance above a set limit. The STEPWISE procedure may not arrive at the model with the highest correlation coefficient if it does not contain all relevant variables in the model. STEPWISE is used when there are many independent variables and one wishes to know which variables should be included in a regression equation.

The best equation for prediction must meet two requirements. The correlation factor must be high and the probability significance for the equation and all variables in the equation must be low. The commonly accepted values is for a correlation factor (r) greater than 0.84 and a probability significance less than 0.05. Sometimes, if an equation has a variable whose probability significance is slightly higher than 0.05, the equation will still be used if the correlation coefficient is drastically reduced when the variable in question is excluded. The equation with the variable is used because it is more accurate at predicting the result without a significant reduction in confidence.

If any data points are missing, SAS will not include that observation in the analysis. Therefore, the variables used in each model were chosen so as to use as many variables as possible so as to exclude as few bridges as possible.

The best two models conforming to the simple theory of Figure 4.2 were the following:

		Significance Probability
"Cl- at Cover" =	- 7.5395	
	+ 0.1828(Agecast)	0.0027
EQUATION 1	- 0.007487(Trafsum)	0.0111
(r = 0.737)	+ 29.1743/Cover	0.0379
	- 22.6979/Cover**2	0.0665
"Cl- at Cover" =	- 7.5991	
	+ 0.1855(Ageopen)	0.0023
EQUATION 2	- 0.007414(Trafsum)	0.0109
(r = 0.740)	+ 29.9932/Cover	0.0315
	- 23.5008/Cover**2	0.0558

Equations 1 and 2 were then used to predict the age in years necessary for the chloride content at the level of cover of the deck to reach an intensity equal to the threshold concentration.

That is, they were each solved for the Age of the deck; either "Agecast" or "Ageopen." Values of Chloride content of 1.13 or 1.22 were substituted for what had been "Chloride at Cover" depending on whether the bridge had been built before 1972 or after. The resulting equations became:

"Age to Threshold From Casting" = 41.2249 + 5.4678(Threshold Cl-) + 0.04094(Trafsum) - 159.519/Cover + 124.108/Cover**2

EQUATION 3

"Age to Threshold From Opening" = 40.9633 + 5.3905(Threshold Cl-) + 0.03997(Trafsum) - 161.678/Cover + 126.681/Cover**2

EQUATION 4

Equations 3 and 4 were used to calculate predicted "Ages to Chloride Threshold" for decks for which all the above variables were available. The resulting ages, measured both from the Casting Date (Agecast) and from the Opening Date (Ageopen), are shown in Table 4.5.

Some values of "Age to Threshold ..." are negative, indicating the chloride content at the beginning of the deck's life was already at the threshold concentration level or above. This result would be consistent with high background levels of chloride concentration entering with the construction materials. Some values of "Age to Threshold ..." are greater than the age of the deck when the chloride samples were taken. This indicates that the

Table 4.5
AGE TO CHLORIDE THRESHOLD CONCENTRATION AT COVER

ID	Bridge	Chloride Threshold lbs/cy	Age to Threshold from Casting Date Equation 3 years	Age to Threshold from Opening Date Equation 4 years
1	B3900	1.13	6.410	5.523
2	B3114	1.13	13.319	12.227
3	3823	1.13	5.664	4.810
4	3386	1.13	3.839	3.005
5	A5611	1.22	5.489	4.621
6	A5500	1.22	0.548	-0.284
7	B5500*			
9	B5142	1.13	18.789	17.623
10	3089	1.13	10.321	9.484
11	5817	1.22	7.958	7.131
12	A3807*			
13	A5109	1.13	3.126	2.227
15	5464	1.22	9.060	8.266
16	5644**			
17	5466	1.22	8.856	8.058
18	A5088	1.13	3.661	2.758
19	B5088	1.13	1.207	0.444
20	A5535	1.22	13.764	12.911
21	B5535	1.22	13.764	12.911
22	A5536	1.22	13.764	12.911
23	B5536	1.22	11.714	10.848
24	A3227	1.13	15.195	14.091
25	B3227	1.13	15.195	14.091
26	A1538	1.13	21.278	19.991
27	A5307	1.22	15.705	14.745
28	B3888	1.13	10.630	9.658
29	1412	1.13	0.235	-0.588
30	5348	1.22	7.694	6.832
31	3612	1.13	3.428	3.001
32	A3612	1.22	2.107	1.286
33	A3587	1.13	7.166	6.650
34	B3316	1.13	3.493	2.591
35	B3967	1.13	4.116	3.195
36	3583	1.13	-0.498	-1.303
37	3735	1.13	-0.030	-0.854
38	3974	1.13	0.498	-0.338
39	2157	1.22	1.072	0.227
40	5614**			
41	A5203	1.13	11.792	10.889
42	B5203	1.13	12.830	11.937
43	B3162*			
44	B3166*			
45	2899	1.13	1.113	0.638

* casting and/or opening dates not available
** cover not available for use in equations

chloride concentration at the cover level has not yet reached the threshold concentration. A few other seeming inconsistencies exist in the results with respect to the physical data measured in the individual decks but that is to be expected when the model is based on a Stepwise Regression whose "r" was not large enough to assure "Statistical Significance."

Predicted ages for reaching the threshold concentrations were then used in various trial models for correlation with the Rating values of the decks. The best models attained are indicated below:

		Significance Probability
Rating =	- 1.5906	
	- 0.2101(Agecast - Agettfc)	0.0001
EQUATION 5	+ 45.5722/Cover	0.0001
(31 decks)	- 34.8768/Cover**2	0.0001
(r= 0.897)	- 0.007754(Trafsum)	0.0001
	- 8489.32/Strength	0.0155

Rating =	- 1.8390	
	- 0.2034(Ageopen - Agettfo)	0.0001
EQUATION 6	+ 43.3770/Cover	0.0001
(31 decks)	- 32.9834/Cover**2	0.0001
(r= 0.896)	- 0.008021(Trafsum)	0.0001
	- 8260.57/Strength	0.0207
	+ 25.9381/(RN Average)	0.1217

"Agettfc" is the predicted age at which the chloride concentration at the cover level would reach the "threshold concentration" as measured from the Casting Date. Thus, (Agecast - Agettfc) is the age of the deck at the date of chloride sampling measured from the assumed reaching of the chloride threshold.

Similarly, the (Agecpen - Agettfc) value is another model of the age at the date of chloride sampling measured from the assumed reaching of the chloride threshold, but using Equation 4. Equation 5 for rating is slightly more accurate and both are within the range of "r" value for statistical significance.

Equations 5 and 6 represent the use of thirty-one of the thirty-four decks for which all pieces of data were available. The three decks not included are those with ID numbers of 6, 34, and 45. If data for ID# 6 is included the "r" values for Equations 5 and 6 go to 0.840 and 0.826 respectively, at the edge of statistical significance. If data for ID# 34 is also included the "r" values decrease to 0.729 and 0.717 respectively, outside the range of statistical significance. Inclusion of data for ID# 45 with an actual rating of 3 further lowers the "r" values to 0.674 and 0.664 respectively.

Table 4.6 gives Ratings calculated by both of these equations for the thirty-four decks for which all of the active variables were available. Figures 4.7 and 4.8 show a graphical comparison of the calculated and actual ratings for the same decks. The points corresponding to the three omitted decks are plotted and identified in Figures 4.7 and 4.8. The three points in question are a) at the extreme of the range of calculated values of Rating at their particular level of measured Rating, and/or b) have low values of measured Rating. The latter would seemingly indicate that the predictive models of Equations 5 and 6 are adequate only for bridges in fairly good condition in the early stages of deterioration.

Table 4.6
MEASURED VERSUS CALCULATED RATINGS

ID	Bridge	Actual Rating	Calculated Rating Equation 5	Calculated Rating Equation 6
1	B3900	7*	6.913	6.167
2	B3114	5	5.578	5.756
3	3823	6	6.146	6.223
4	3386	6	5.831	5.951
5	A5611	8	7.611	7.558
6	A5500	6	8.832	8.849
7	B5500	8**		
9	B5142	4	5.279	5.264
10	3089	6	5.329	5.264
11	5817	9	9.505	9.323
12	A3807	6**		
13	A5109	7	7.429	7.367
15	5464	8	7.570	7.578
16	5644	7**		
17	5466	8	7.890	7.789
18	A5088	8	6.967	7.013
19	B5088	8	7.556	7.625
20	A5535	8	8.178	8.359
21	B5535	8	7.507	7.365
22	A5536	8	7.738	8.483
23	B5536	8	8.129	8.154
24	A3227	6	6.132	5.954
25	B3227	6	5.568	5.424
26	A1538	7	5.986	6.093
27	A5307	8	8.164	7.758
28	B3888	6	5.904	6.188
29	1412	6	5.615	5.541
30	5348	8	8.080	7.913
31	3612	7	6.518	6.532
32	A3612	9	9.197	9.233
33	A3587	6	6.662	6.601
34	B3316	7	5.970	5.698
35	B3967	8	7.631	7.693
36	3583	5	6.082	5.960
37	3735	6	6.475	6.622
38	3974	7*	6.972	6.942
39	2157	8*	8.990	8.939
40	5614	8**		
41	A5203	7	6.948	6.837
42	B5203	6	6.812	6.639
43	B3162	6**		
44	B3166	7**		
45	2899	3	5.589	5.717

* rating calculated but insufficient data for inclusion in rating equation regression

** insufficient data to calculate rating or for inclusion in rating equation regression

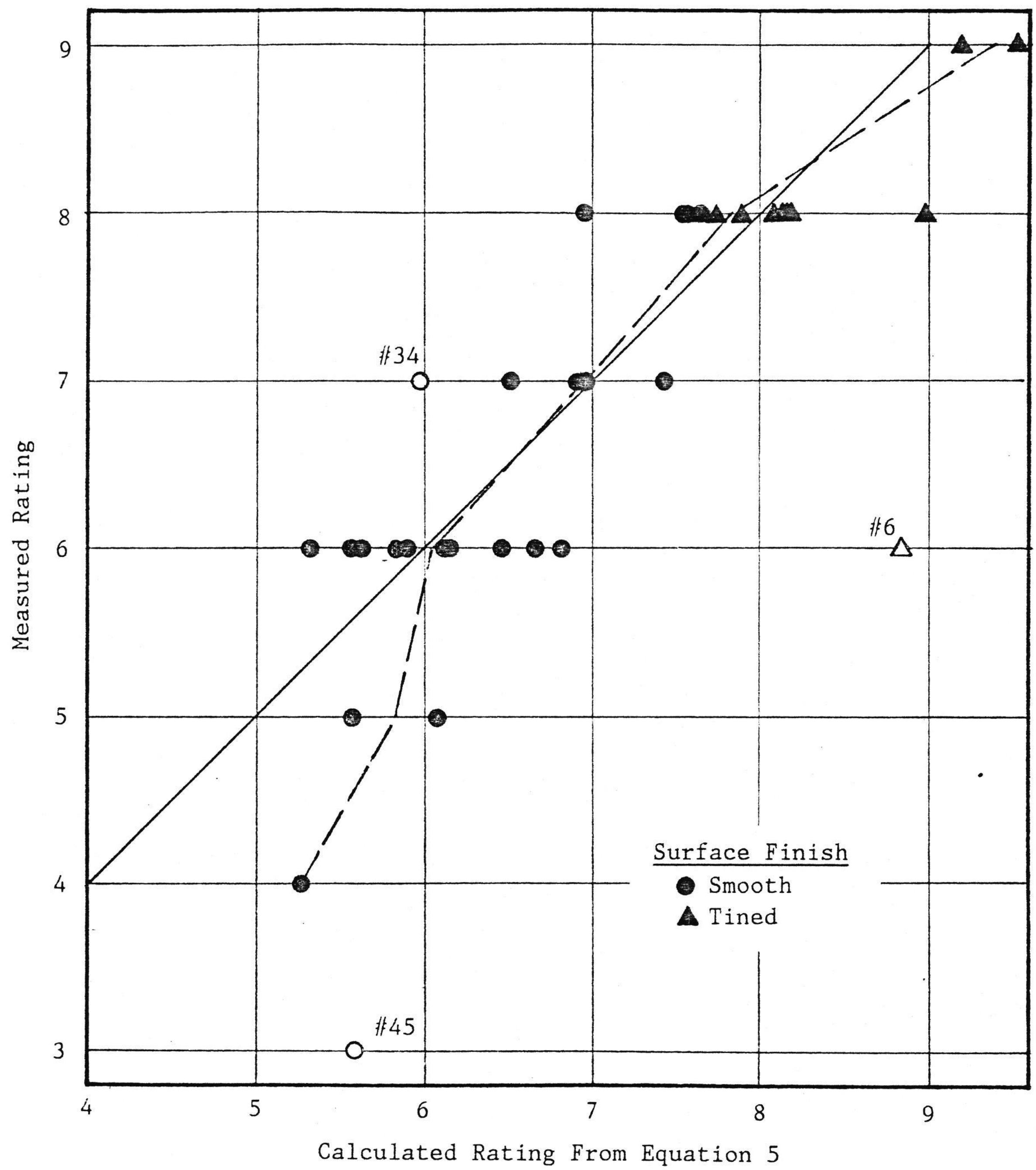


Figure 4.7 Measured Versus Calculated Rating From Equation 5

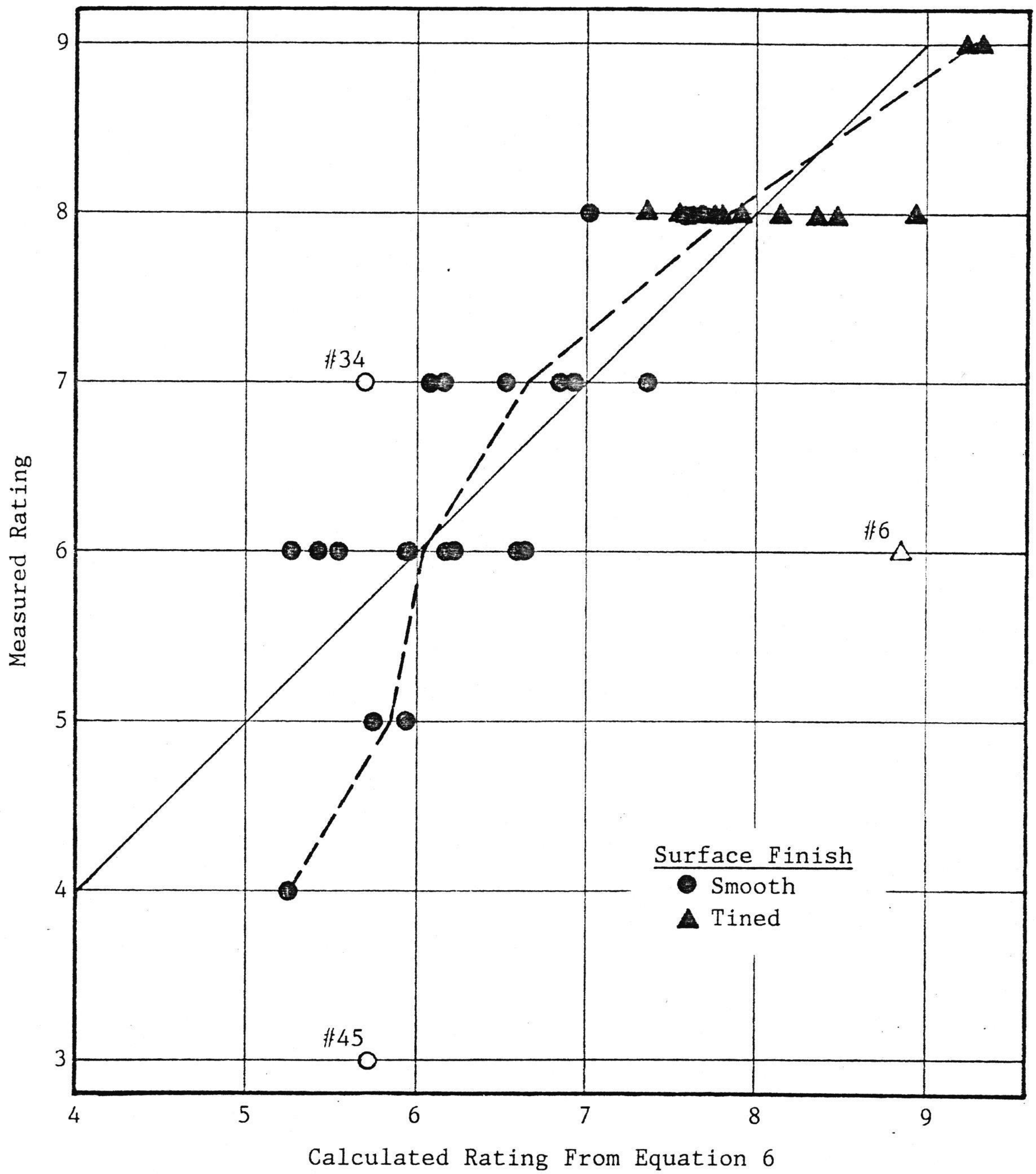


Figure 4.8 Measured Versus Calculated Rating From Equation 6

However, the dashed line in Figures 4.7 and 4.8 is drawn through the centroid of each set of points with the same measured Rating. The monotonic character of this line suggests that if the variables measured were analysed by a more sophisticated non-linear procedure they might correlate very well with a continuous measure of deterioration such as the percent of delamination.

In both equations the rating is reduced (worsened) by the increase of both the age of the deck as measured from the predicted reaching of the threshold, and the summation of traffic intensities. The summation of the level of traffic experienced by the bridge is obviously an important factor to be included in further refinement of the model.

The rating is increased (improved) by the "Cover" term. But the improvement is lessened as the cover depth gets larger. The rating is decreased (worsened) by the term containing the square of the cover (Cover**2).

There is a seeming contradiction in the effects of the compressive Strength of the concrete and the Rebound Number at the cover level.

Although the summation of maintenance monies spent was a factor in the initial correlation with Rating, it did not enter either Equation 5 or 6. Maintenance monies spent are the result of deterioration rather than part of the physical system of deterioration. Moreover, the nature of the decision of whether to spend them or not may exclude a close correlation between the amounts spent and the extent of deterioration.

Although the average chloride concentration at the depth of cover was included in the regression procedure it did not appear in either equation. Reaching the threshold concentration at the steel level is sufficient to trigger the corrosion process. The spread of the corrosion in the form of delamination then correlates best with the time since the threshold was reached, not with increasing chloride presence beyond the threshold concentration.

Possible Uses of the Predictive Model:

Equation 5 or 6 can be used for prediction of future rating values of existing decks with a reasonable degree of accuracy for ratings as low as 5. Use of the equation may aid in the planning of maintenance resources. The equations might also be useful in predicting a design rating at the end of a selected period of time. However, the equations represent a model that is only marginally significant statistically because of the problems inherent in the use of the Rating term. They reflect only a statistical analysis of a limited data base and should not be used for design of a specific bridge deck for a long design life.

Chapter Five

CONCLUSIONS

Deterioration Severity:

In 1978 the NCHRP Synthesis of Highway Practice #57 reported that "nearly one-third of all highway bridge decks in the United States are seriously deteriorated due to corrosion of reinforcing steel." By comparison, Arkansas bridge decks do not appear in as bad a condition. Of the forty-three decks investigated, only seventeen (39.5%) evidenced deck Ratings of 6 or less indicating moderate deterioration or worse. Only four (9.3%) of the seventeen had Ratings of 5 or less indicating greater than 20 percent delamination. Those four ranged in age from 21.3 to 26.3 years since cast.

The difficulty with evaluating the "severity" of deterioration is the need for comparison. There is no present standard for deck life expectancy. A suggestion for a future standard was implied in the objectives of a recent RFP from NCHRP (NCHRP, 85) "A long-term objective of research in this program area is to develop a guide for the design and construction of reinforced concrete bridge decks with a service life of 50 years or more." Arkansas bridge decks do not presently meet this projected standard.

Tined Finish:

This study found nothing conclusive as regards the possible contribution of tined finishes to the accelerated deterioration of bridge decks. The tined finish has been used for such a short period of time (since 1973) that only one of the fourteen tined decks examined showed a moderate deterioration of even 2% delamination. A better comparison in the future, if the data is available, should be between the statistical histories of deterioration of smooth decks in the same age range as that since 1973 for the tined-finish decks. Such a comparison, of course, would have to consider the different levels of deicer applications during the two comparison periods.

There is a coincidence in the beginning of the use of the tined finish and the increased use of deicer chemicals in the state. There are no smooth decks in the same period for use in comparison. The tined finish and the resulting deck surface texture may, in fact, trap a significantly larger proportion of surface chemicals for a longer period than a smooth finish. This may in turn increase the ingress of chlorides near the gutter, contributing to the differential concentration in the deck that drives the corrosion process. The data is presently not available for establishing whether this is true or not.

Deck Salting:

Arkansas bridge decks are deteriorating faster since the use of salt to clear ice was begun. Use of deicer chemicals in recent years has been the major factor in faster deck deterioration in other states.

A number of variables are known to contribute to the corrosion problem. The results of the statistical analysis performed in this study are consistent with what has been found elsewhere. Chief among the variables, of course, is the use of chloride salts as deicer chemicals. If the use of salt for deicing is stopped, the life of bridge decks would be extended. Stopping the use of deicer chemicals will not, however, add significantly to the life of existing decks in which the threshold concentration has been exceeded.

Clear Cover:

The depth of clear cover is the most important factor which determines the life of a bridge deck. On heavily traveled routes, a minimum clear cover of three inches is recommended. One reason a large depth of clear cover is important is that the effectiveness varies as the square of the cover; i.e., a cover of 3 inches is four times as effective as a cover of 1.5 inches.

Permeability of the concrete in the clear cover is also an important factor. Concrete with low permeability will protect the reinforcement steel better. Concrete with high density and strength has lower permeability.

These major variables identified in the analysis of deck deterioration are consistent with a summary in the Committee 222 report: "In reinforced concrete members exposed to chlorides and subjected to intermittent wetting, the degree of protection against corrosion is determined primarily by the depth of cover to the reinforcing steel and the permeability of the concrete." (ACI Committee 222, 1985)

Equations 5 and 6 of this report can be used to predict deck rating on bridges which are being designed.

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Appendix A

Appendix A contains the laboratory procedure used in the measurement of chlorides for this project, and the modifications made to the procedures for measurement of rebound number and compressive strength.

Laboratory Procedure for Measurement of Chlorides

The samples were tested by the following procedure: Steps 1-10 are based on AASHTO T-260-82. Steps 11-16 are from the mercuric nitrate method for measuring chlorides found in Standard Methods for Examination of Water and Wastewater.

1. Seive powdered concrete sample through a #50 seive (Figure A.1).
2. Weigh out 3.0 grams of sample.
3. Add 10 ml. of distilled water to sample.
4. Add 3.0 ml of nitric acid to sample.
5. Add hot distilled water to sample until volume equals approximately 50 ml.
6. Stir thoroughly
7. Add 5 drops of methyl orange indicator and stir. If yellow to yellow-orange color appears, add sufficient nitric acid until a faint pink or red color persists.
8. Cover with a watch glass and heat the solution to boiling. Boil for about one minute.
9. Filter solution through double filter paper, using Whatman #41 over #40. (Figure A.2)
10. Wash filter paper with hot distilled water until filter solution equals about 150 ml.
11. Add sodium hydroxide until solution's ph is approximately 8.0 (Figure A.3).
12. Filter solution through #41 filter.
14. Dilute to 200 ml.
15. Pour out 100 ml in a beaker. Add one Diphenylcarbazone Reagent Powder Pillow (Hach #836) and stir.
16. Titrate sample with 0.0141N mercuric nitrate titrant to definite purple end point (Figures A.4 and A.5).
17. Determine blank by titrating 100ml distilled water containing 10 mg. $NaHCO_3$.

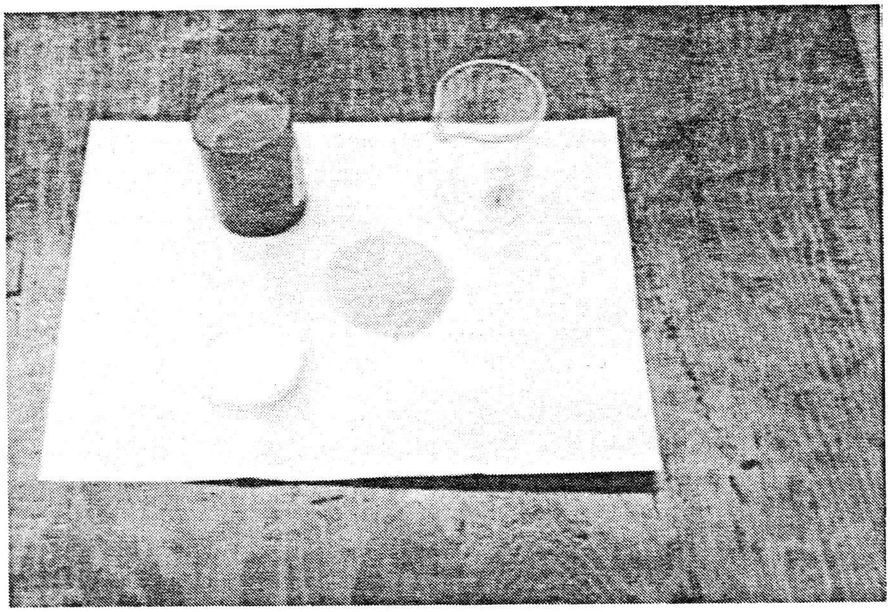

Figure A.1 Sample

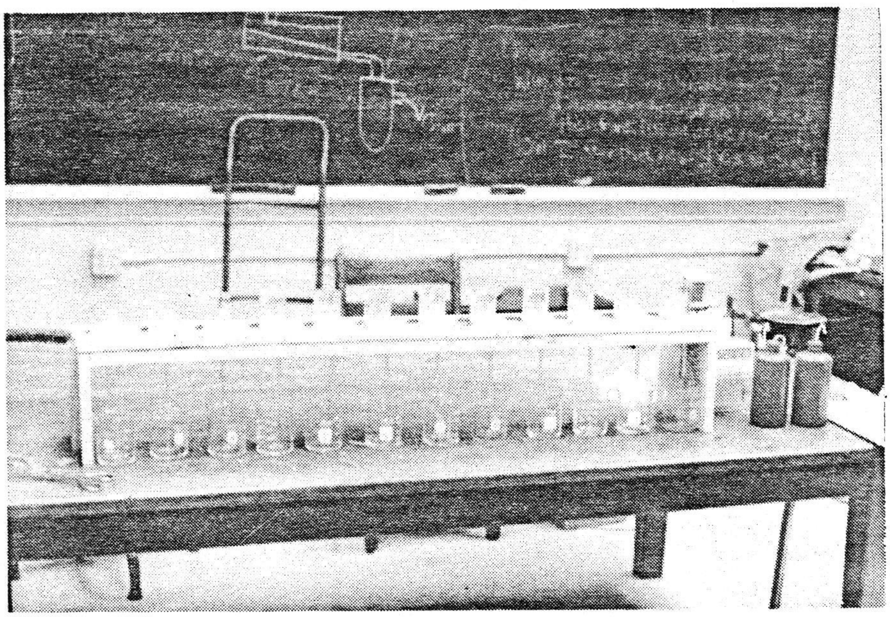

Figure A.2 Filtering Samples

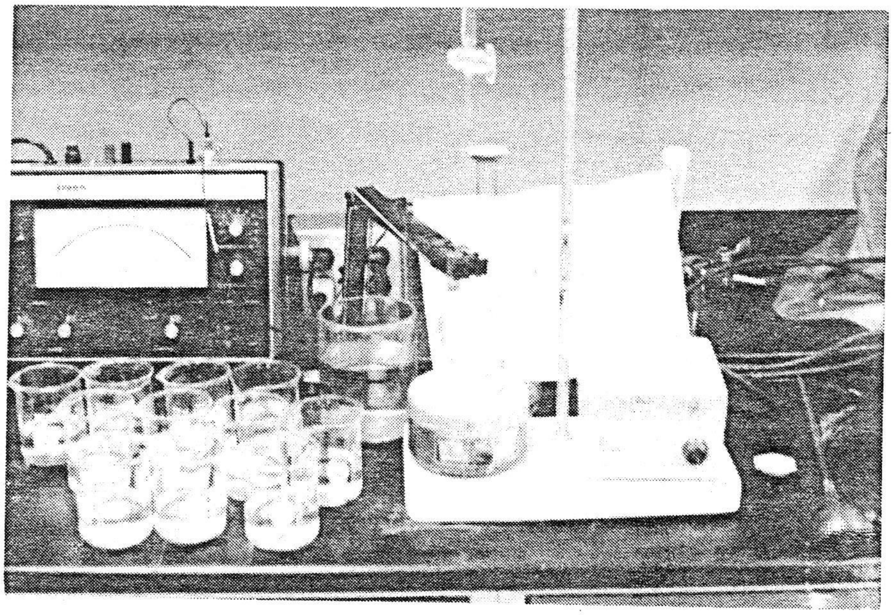

Figure A.3 Raising pH

Figure A.4 Sample Before Titration

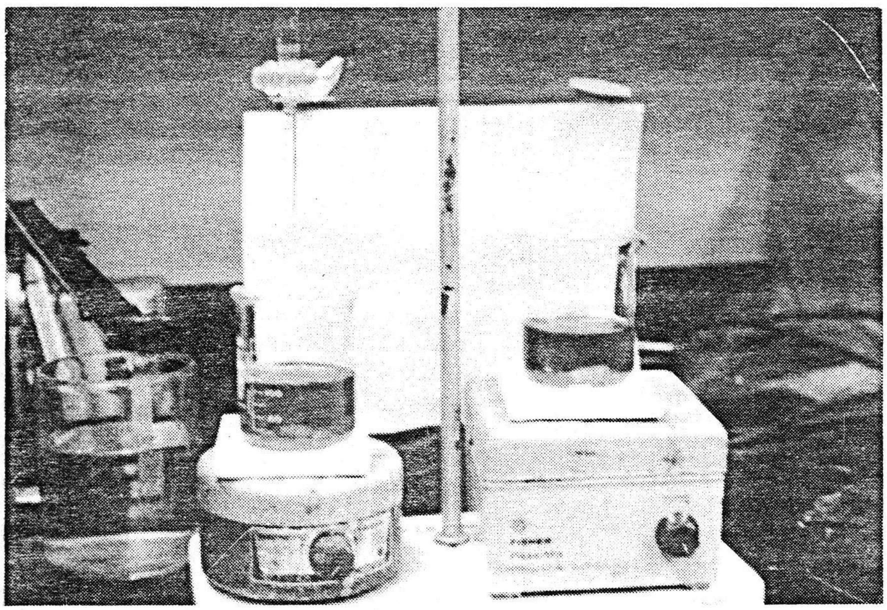

Figure A.5 Sample After Titration

Determine mg Cl/l by: mg Cl /l = (A-B)xNx35,450/(ml sample)

where: A-ml titration for sample

B-ml titration for blank

N-Normality of mercuric nitrate

The mg Cl/l is the milligrams of chloride that you would have in one liter of solution. Since the three gram sample was diluted into 200 milliliters and 100 milliliters were tested, multiply the mg Cl/l from the equation by two-fifths to get the milligrams of chloride in the three gram sample. Divide the milligrams of chloride by three thousand to get the percent chlorides. This percentage was multiplied by 4050 (lbs of concrete per cubic yd. based on 150 lb/cu. ft.) to convert to lbs. of chloride per cubic yard of concrete.

Changes in Laboratory Procedure for Measurement of Rebound Number and Compressive Strength

The rebound number and compressive tests were performed in accordance with the appropriate ASTM Standards as listed previously with the following modifications.

The cylinder, after having been properly capped and submerged in a saturated lime-water solution for more than forty hours was removed and placed in a universal testing machine. The core was loaded to a force of 12,500 lbs. which corresponds to a stress of approximately 1,000 psi on a 4-inch diameter cylinder. At this loading the Schmidt hammer was used to take twelve readings evenly spaced around each of four circumferences at depths of 1, 2, 3, and 4 inches below the top of the specimen. The upper and lower values for each circumference were discarded and the remaining ten values averaged. Readings taken at the location of embedded reinforcing steel were also discarded. The cylinder was then loaded to failure to evaluate the compressive strength.

Appendix B

Appendix B is a summary of information taken from the construction diaries

Summary of Bridge Deck Construction Diaries

Bridge	Span	Date Cast	Temp L/H	Weather	Remarks
3316B	1	7-17-73	72-99	Partly Cloudy	Mention of contractor
""	2	7-19	72-108	Partly Cloudy	being lax on curing
""	3	7-20	72-105	Partly Cloudy	and finishing
5348	1	5-22-75	68-88	Fair	Right side diary
""	2	5-27	65-87	Partly cloudy	15 spans in plans Only 3 spans mentioned in diary. Diary very sketchy. Mention of forming span #3, but not of casting it. Oil applied in May
5348	1	8-11-75	70-92	Partly Cloudy	Left Side diary
2157	1	8-11-76	58-90	Clear	Linseed Oil Used
""	2	8-6	60-90	Partly Cloudy	1st coat-9-16
""	3	8-6	60-90	Partly Cloudy	2nd coat-9-17
""	4	8-6	60-90	Partly Cloudy	Concrete Mix Design
""	5	8-5	59-88	Clear	look at Br. 5614
""	6	8-5	59-88	Clear	
5614	1	9-10-77	53-84	Partly Cloudy	4.9% Entrained Air
""	2	9-10	53-84	Partly Cloudy	1 3/4 in. slump 0.44 w-c ratio Burlap cure- It snowed on bridge after casting Maintenance required after snow melted
2899	1	?	?	?	Diary just covered substructure. Slump-2.5 in. 0.51 w-c ratio?
5611A	1	6-23-74	73-96	Partly Cloudy	Design cover-2 in.
""	2	6-23	73-96	Partly Cloudy	5.8% entrained air
""	3	6-23	73-96	Partly Cloudy	2.5 in slump, 0.44 w-c ratio, Burlap cure possible use of linseed
3166B		No Job File			1.5 in. design cover 18 spans, air entrained

Bridge	Span	Date Cast	Temp L/H	Weather	Remarks
3162 B		No Job File			1.5 in. design cover
					3 spans
5525A	1	1-15-75	22-48	Clear	1 3/4 in slump, SIP forms
""	"	1-22	28-61	Clear	4.7 % entrained air
""	2	1-19	26-52	Clear-rain	0.49 w-c ratio, 2 in. de-
""	"	1-22	28-61	Clear	sign cover, curing compound
""	"	1-23	32-65	Clear	used, Linseed oil 2-21-75
""	3	1-19	26-52	Clear-rain	
""	"	1-23	32-65	Clear	
5535B	1	1-21-76	32-55	Clear	Linseed oil 2-23-76
""	"	1-30	38-58	Clear	
""	2	1-12	28-58	Clear	
""	"	1-29	32-60	Clear	
""	"	1-30	38-58	Clear	
""	3	1-21	32-55	Clear	
""	"	1-29	32-60	Clear	
5307A	1	2-12-75	41-55	Fair	3.8 % entrained air
"'	2	2-19	32-49	Fair	2.75 in slump
""	3	2-25	32-52	Clear	0.44 w-c ratio
""	4	2-17	34-55	Partly Cloudy	Burlap cure
""	5	2-13	28-56	Fair	Linseed oil- 2 coats
					4-7-75
3900A	1	8-6-66	68-88	Cloudy	No air entrainment
""	2	8-6 ?	?	?	some typos, mentioned
""	3	7-30	70-90	Partly cloudy	casting spans 6 & 7
""	4	8-3	58-88	Partly cloudy	twice
""	5	8-25	65-79	Partly cloudy	
""	6	8-27	70-82	Partly cloudy	
""	7	8-30	64-85	Partly cloudy	
""	8	9-1	65-86	Partly cloudy	
""	9	9-3	66-85	Partly cloudy	
""	10	9-6	65-85	Partly cloudy	
""	11	Probably cast around 9-8			
""	12	9-9	62-80	Partly cloudy-rain	
3114B	1	6-19-58	60-86	Fair RH=47	18.5 in slab
""	2	6-30	60-95	Fair RH=76	Sono-tubes in deck
""	3	7-13	63-88	Fair RH=38	
""	4	7-15	67-93	Fair RH=35	
""	5	7-18	72-87	Cloudy-rain RH=94	
3823	?	?	?	?	Sono-tubes in deck
					Plan has 3-30' decks
					Diary mentions 28 spans

Bridge	Span	Date Cast	Temp L/H	Weather	Remarks
5109A	1	9-26-69	53-86	Partly cloudy	Linseed oil applied
''''	2	9-26	53-86	Partly cloudy	week of March 22-28
''''	3	9-26	53-86	Partly cloudy	1970
''''	4	8-8	74-98	Partly cloudy	
''''	5	8-8	74-98	Partly cloudy	
''''	6	8-8	74-98	Partly cloudy	
3386	1	11-9-61		Clear, cold	
''''	2	11-17	Cold	Partly cloudy	
''''	3	11-21	Cold	Partly cloudy, rained the next day	
''''	4	11-27	Cold	Partly cloudy	
''''	5	11-30	Cold	Partly cloudy	
''''	6	12-4	Cold	Partly cloudy	
''''	7	12-8	Cold	Cloudy, rained the next day	
''''	8	12-19	Cold	Clear	
5500B	?	?	?	?	Too many typos to make sense, linseed oil was used.
5142 A&B	No records, Bridge in Texas (Texarkana)				
3089	1	10-21-61	36-73	Fair	
''''	2	10-20	37-67	Fair	
''''	3	10-12	55-84	Cloudy	
''''	4	10-7	55-79	Fair	
''''	5	10-4	41-75	Fair	
''''	6	9-19	50-76	Fair	
''''	7	9-16	52-78	Fair	
''''	8	9-15	48-75	Clear	
''''	9	9-14	45-72	Partly cloudy	
5109B	Conflicting diary entries. Entries of wrecking forms before casting decks and pouring decks twice.				
5817	1	7-23-80	73-94	Clear	3.6% ent. air
''''	2	7-23	73-94	Clear	2.75 in. slump
''''	2	8-4	80-98	Clear	0.42 w-c ratio
''''	3	7-28	73-94	Clear	Cotton mats used
''''	3	8-4	80-98	Clear	in curing
''''	4	8-1	72-97	Clear	Linseed oil used
''''	5	8-1	72-97	Clear	
''''	6	11-8	56-80	Clear	
''''	7	11-5	44-78	Clear	
''''	8	10-28	49-50	Cloudy	
''''	9	10-15	64-80	Clear	
''''	10	9-3	74-101	Clear	

Bridge	Span	Date Cast	Temp L/H	Weather	Remarks
5817	11	9-3	74-101	Clear	
""	12	9-3	74-101	Clear	
""	13	8-21	74-105	Clear	
""	14	8-21	74-105	Clear	
""	15	8-14	80-99	Clear	
""	16	8-14	80-99	Clear	
5466	1	8-17-73	68-92	Partly cloudy	Linseed oil applied
""	2	8-7	65-94	Partly cloudy	9-12-73
""	3	8-3	50-92	Clear	
""	4	7-24	74-95	Rain	
3227A	1	6-8-62	68-87	Cloudy-rain	0.44 w-c ratio
""	2	6-6	69-92	Partly cloudy	2 in. slump?
""	3	6-5	67-90	Partly cloudy	Wet burlap cure
""	4	5-24	69-94	Fair	Sono-tubes
""	5	5-18?	63-93	Partly cloudy	
""	6	5-17	63-96	Fair	
""	7	5-15	65-92	Fair	
3227B	1	6-18-62	70-95	Partly cloudy	Same as 3227A
""	2	6-15	58-85	Partly cloudy	
""	3	6-13	62-81	Fair	
""	4	6-12	68-89	Partly cloudy	
""	5	5-31	62-87	Cloudy	
""	6	5-30	62-87	Cloudy	
""	7	5-25	69-94	Partly cloudy	
1538A	1	6-1-61	67-89	Fair	3 in. slump
""	2	6-2	64-89	Fair	0.44 w-c ratio
""	3	6-6	70-88	Fair	No air entrainment
""	4	6-7	70-88	Fair	Wet burlap cure
""	5	6-8	68-88	Partly cloudy	
""	6	6-12	71-90	Partly cloudy	Curing done by
""	7	6-17	59-78	Cloudy	covering with 2
""	8	6-21	60-82	Fair	layers of burlap
""	9	6-28	65-91	Fair	and keeping wet for
""	10	6-26	61-89	Fair	5 days.
""	""	6-29	65-94	Fair	
""	11	7-13	72-92	Partly cloudy	
""	12	7-7	72-91	Partly cloudy-rain	
""	""	7-10	60-86	Fair	
""	13	7-14	69-90	Partly cloudy	
""	14	7-17	67-91	Fair	
""	15	7-21	72-96	Fair	
""	16	7-26	72-94	Partly cloudy-rain	
""	17	7-29	72-96	Fair	
""	18	8-3	75-97	Partly cloudy	

Bridge	Span	Date Cast	Temp L/H	Weather	Remarks
1538A	19	8-10	75-95	Fair	
''''	20	8-21	63-83	Fair	
''''	21	8-25	61-85	Partly cloudy	
''''	22	8-26	63-87	Fair	
''''	23	8-30	72-95	Partly cloudy	
1412	1	4-18-60		Fair	
''''	''	4-19		Fair	
''''	2	4-25		Cloudy-rain	
''''	''	4-26		Cloudy-rain	
''''	''	4-28		Partly cloudy	
''''	3	3-31		Cloudy-hot	
''''	''	4-4		Partly cloudy	
''''	''	4-6		Fair	
''''	4	5-5		Fair	
1412	''	5-6		?	
''''	''	5-9		?	
''''	5	3-30		Fair	
''''	''	4-12		Fair	
5644	1	12-9-76	24-48	Cloudy	0.4 w-c ratio
''''	2	12-8	20-36	Partly cloudy	4 % entrained air
''''	3	12-3	26-56	Fair	3 in. slump
''''	4	12-1	19-41	Partly cloudy	Curing compound used
''''	5	11-24	34-67	Clear	Linseed oil used
''''	6	11-23	22-43	Cloudy	4-13-77 & 4-14-77
''''	7	11-19	32-52	Partly cloudy	
''''	8	11-17	38-65	Clear	
''''	9	11-16	30-52	Partly cloudy	
''''	10	11-15	30-40	Cloudy	
''''	11	11-10	18-35	Cloudy	Snowed between 11-11
''''	12	11-9	32-56	Fair	and 11-14
''''	13	11-5	32-56	Clear	
''''	14	11-3	46-61	Clear	
''''	15	11-1	38-58	Partly cloudy	
''''	16	10-29	26-60	Cloudy	Mention on this day of
''''	17	10-27	35-46	Partly cloudy	enclosed concrete and
''''	18	10-22	38-68	Partly cloudy	heating equipment.
''''	19	10-20	25-50	Cloudy	
''''	20	10-18	35-64	Partly cloudy	
''''	21	10-15	40-70	Fair	
''''	22	10-12	45-75	Fair	
''''	23	10-11	43-73	Fair	Typo?,Listed as span 11
''''	24	10-7	46-61	Cloudy	
''''	25	10-6	48-68	Cloudy	
''''	26	10-1	48-88	Fair	
''''	27	65-88	53-83	Partly cloudy	
''''	28	9-27	65-88	Cloudy	
''''	29	9-21	55-85	Partly cloudy	
''''	30	9-17	53-86	Partly cloudty	

Bridge	Span	Date Cast	Temp L/H	Weather	Remarks
5644	31	9-15	55-88	Partly cloudy	
""	32	9-23	56-88	Clear	
""	33	12-15	18-40	Clear	
""	34	12-16	18-40	Clear	
5536A	1	1-19-75	26-52	Clear	5 % entrained air
""	"	1-22	28-61	Clear	0.46 w-c ratio
""	2	1-15	22-48	Clear	SIP forms
""	"	1-22	28-61	Clear	Linseed oil 2-19
""	"	1-23	36-65	Clear	
""	3	1-19	26-52	Clear	
""	"	1-23	36-65	Clear	
""	4 ?	?	?	?	
5536B	1	1-21-75	32-55	Clear	Same as 5535A
""	"	1-30	35-58	Clear	Span 4 in drawings but
""	2	1-12	28-58	Clear	not in diaries
""	"	1-30	35-58	Clear	Linseed oil 2-23
""	3	1-21	32-55	Clear	
5088A	1	8-20-68	74-96	Fair	No air entrainment
""	2	8-22	73-96	Fair	
""	3	8-26	67-91	Fair	
5088B	1	8-29	57-82	Fair	
""	2	8-30	62-86	Fair	
""	3	9-5	70-78	Partly cloudy	
3888B	1	7-16	71-95	Partly cloudy	Sono-tubes
""	2	7-14	74-93	Partly cloudy	
""	3	7-10	76-94	Partly cloudy	Very sketchy diary
""	4	?	?	?	
""	5	?	?	?	
""	6	7-7	71-90	Partly cloudy-rain	
""	7	7-26	72-95	Partly cloudy	
""	8	?	?	?	
""	9	?	?	?	
3612A	1	3-19-80	40-53	Cloudy	2-3/4 in. slump
""	2	1-25	45-60	Cloudy	5% entrained air
""	3	1-9	30-45	Partly cloudy	Retarder used
""	4	1-17	48-68	Partly cloudy	0.44 w-c ratio
""	5	1-11	52-62	Partly cloudy	Burlap-Burlene ? cure
""	6	5-23	60-78	Partly cloudy	Using heaters
					Linseed oil, 2 coats

Bridge	Span	Date Cast	Temp L/H	Weather	Remarks
3612	1	9-30	50-80	Fair	Terrible diary
""	2	10-11	60-96	Fair	0.5 w-c ratio
""	3	11-1	48-75	Fair	No air entrainment
""	4	11-19	55-70	Partly cloudy	Wet burlap cure
""	5	11-25	34-62	Fair	
""	6	10-25	60-85	Fair	
3587A	1	2-7-64	26-58	Clear	3 in. slump
""	2	2-4	33-58	Cloudy	0.5 w-c ratio
""	3	1-23	50-68	Cloudy rain	No air entrainment
""	4	1-10	12-52	Clear	
""	5	1-6	28-55	Partly cloudy	
""	6	11-25-63	28-63	Cloudy	
""	7	8-23-63	65-100	Partly cloudy	
""	8	8-15	60-85	Partly cloudy	
""	9	In plans, but not in diary			
5203A&B	1	8-28-69	69-91	Partly cloudy	Linseed oil 11-21
""	2	9-4	66-86	Cloudy	0.53 w-c ratio
""	3	10-15	62-82	Partly cloudy	Wet burlap cure
					2 3/4 in slump
3967B	1	10-14-66	65-85	Cloudy-rain	
""	2	10-11	37-85	Clear	
""	3	10-10	44-80	Clear	
3735	1	7-9-65	74-99	Partly cloudy	
""	2	7-14	70-101	Partly cloudy	
""	3	7-20	71-86	Partly cloudy	
""	4	7-23	66-84	Cloudy	
5500A	1	9-25-76	68-94	Partly cloudy	4.2% entrained air
""	2	9-25	68-94	Partly cloudy	0.49 w-c ratio
""	3	9-25	68-94	Partly cloudy	1.5 in slump
					Curing compound used
					Deck damaged by vandals
					night of 9-25-76
5464	1	9-29-72	45-71		0.47 w-c ratio
""	2	9-26	65-81		3.5 in. slump
""	3	9-14	71-84		Wet burlap cure
""	4	9-7	70-89		used retarder and
""	5	9-1	62-83		linseed oil

Bridge	Span	Date Cast	Temp L/H	Weather	Remarks
3583	1	9-25-62	58-78		
""	2	9-27	52-80		
""	3	10-1	49-68		
""	4	10-4	55-80		
""	5	10-11	58-83		
""	6	10-17	51-72		
3807A	1	6-28-66	62-95		
""	2	7-8	68-97	Partly cloudy	
""	3	7-2	68-98		
""	4	6-24	60-90		
3974	1	4-27-67	37-62		
""	2	4-28	40-65		
""	3	4-27	37-62		

Appendix C

Appendix C contains graphs that show the profiles with depth of chloride content, average rebound number, and density for each bridge deck. It also contains tables of data for density and rebound number.

The graphs are numbered consecutively C.1 through C.45. Graphs C.8 and C.14, however, are omitted as data was not received for the two decks with corresponding ID numbers.

Table C.1
DENSITY DATA

ID	Bridge	Depth of Section Centroid Below Top of Slab Inches	Measured Density lbs/cf
1	B3900	1.0	138.98
		4.3	146.41
		6.0	146.65
2	B3114	1.0	141.97
		3.1	142.72
		5.6	143.56
3	3823	0.6	140.89
		6.0	142.71
4	3386	1.1	144.30
		3.3	146.15
		5.4	148.34
5	A5611	1.0	133.03
		4.2	135.78
		5.7	135.72
6	A5500	0.7	144.17
		4.0	145.25
		7.0	147.28
7	B5500	1.0	145.40
		3.8	145.08
9	B5142	1.0	139.47
		3.0	145.56
		5.0	141.54
		6.6	141.34
10	3089	1.5	144.63
		4.1	143.89
		6.2	144.41
11	5817	1.0	146.04
		3.1	146.93
		5.2	146.28
		7.2	148.43
12	A3807	0.75	139.82
13	A5109	1.0	124.14
		2.9	137.75
		4.0	146.59
		5.7	145.74

Table C.1 (cont.)
DENSITY DATA

ID	Bridge	Depth of Section Centroid Below Top of Slab Inches	Measured Density lbs/cf
15	5464	1.0	153.13
		3.0	150.51
		4.9	152.41
		7.0	150.14
16	5644	1.7	133.77
		4.6	132.63
		8.6	136.80
17	5466	1.1	136.64
		4.6	139.16
18	A5088	0.8	140.32
		4.0	145.18
19	B5088	1.0	147.48
		3.9	144.93
		5.6	145.04
20	A5535	1.0	138.13
		3.3	139.38
		6.3	138.68
21	B5535	0.8	140.51
		2.5	140.32
		4.1	141.59
		5.8	136.75
22	A5536	1.2	132.55
		3.1	136.45
		4.6	136.12
23	B5536	1.0	135.18
		3.1	135.83
		6.1	140.52
24	A3227	0.9	143.98
		2.9	144.85
		5.5	145.82
25	B3227	1.0	140.78
		2.7	143.15
		4.85	143.20
		6.25	144.15

Table C.1 (cont.)
DENSITY DATA

ID	Bridge	Depth of Section Centroid Below Top of Slab Inches	Measured Density lbs/cf
26	A1538	1.0	144.18
		3.1	143.15
		5.1	145.04
		6.6	146.97
27	A5307	1.0	139.04
		3.2	140.28
		5.4	140.24
28	B3888	1.0	143.69
		3.1	143.31
		5.2	144.08
29	1412	1.7	143.44
		2.6	145.02
		4.2	148.42
		5.4	148.57
30	5348	1.0	145.27
		3.2	144.08
31	3612	0.9	143.61
		2.8	143.51
		4.7	143.00
32	A3612	1.5	143.00
		3.7	142.59
		5.8	142.20
		7.9	141.49
33	A3587	0.4	143.72
		1.8	142.05
		3.1	143.40
34	B3316	0.9	142.22
		5.6	141.72
35	B3967	0.7	145.45
		3.9	143.80
		5.9	150.12
36	3583	0.65	145.97

Table C.1 (cont.)
DENSITY DATA

ID	Bridge	Depth of Section Centroid Below Top of Slab Inches	Measured Density lbs/cf
37	3735	1.0	134.42
		3.1	133.16
		5.6	134.28
38	3974	0.9	149.39
		2.7	149.98
		6.1	151.38
39	2157	1.0	142.95
		3.0	141.30
		4.7	140.31
		6.5	143.00
40	5614	0.85	143.80
		2.6	142.21
		4.4	143.35
		6.0	143.37
41	A5203	0.85	138.96
		2.65	140.53
		5.6	142.10
42	B5203	0.8	142.29
		2.4	143.23
		5.0	144.16
43	B3162	0.7	141.11
		2.1	140.20
		3.2	139.43
44	B3166	0.6	140.35
		2.0	140.00
		6.5	143.94
45	2899	0.6	142.39

Table C.2

REBOUND NUMBER DATA

ID	Bridge	Average Rebound Number at Distances Below Top of Slab in Inches 1	2	3	4	Average
1	B3900	44.00	36.20	40.40	47.20	41.95
2	B3114	32.60	40.60	33.50		35.57
3	3823	50.80	51.20	53.40	52.40	51.95
4	3386	33.50	41.00	40.10	37.70	38.08
5	A5611	35.70	34.90	41.30	41.10	38.25
6	A5500	36.80	36.70	40.00	35.70	37.30
7	B5500	37.80	41.30	45.10	41.50	41.43
9	B5142	30.70	30.10	26.30	33.30	30.10
10	3089	43.90	45.70	38.00	41.10	42.18
11	5817	37.50	34.80	36.10	35.00	35.85
12	A3807	42.40	41.60	41.10		41.70
13	A5109	32.60	48.80	49.50	48.60	44.88
15	5464	41.50	29.00	32.80	34.20	34.38
16	5644	28.70	28.00	28.70	22.70	27.03
17	5466	39.70	40.10	33.20	33.60	36.65
18	A5088	30.20	37.70	33.80	35.80	34.38
19	B5088	31.00	38.50	37.60	32.80	34.98
20	A5535	32.20	34.70	29.60	31.50	32.00
21	B5535	37.00	32.00	37.40	47.70	38.53
22	A5536	20.20	19.40	16.60	20.00	19.05
23	B5536	42.70	37.80	38.00	38.22	39.18
24	A3227	46.70	44.60	41.20	40.60	43.28
25	B3227	41.40	42.20	40.80		41.47
26	A1538	24.20	21.50	25.50	23.20	23.60
27	A5307	43.30	48.30	48.40	46.30	46.58
28	B3888	26.00	22.60	19.40	20.50	22.13
29	1412	35.30	36.40	39.70	36.10	36.88
30	5348	43.60	48.30	44.60		45.50
31	3612	40.40	46.60	37.90	48.20	43.28
32	A3612	28.60	35.00	35.00	34.00	33.15
33	A3587	40.30	45.60	45.80	44.60	44.80
34	B3316	44.10	46.00	41.00	44.00	43.78
35	B3967	29.60	21.60	27.00	22.60	25.13
36	3583	41.20	45.00	43.50	45.40	43.78
37	3735	36.40	39.30	44.40	42.40	40.63
38	3974	44.80	44.80	42.40	45.40	44.35
39	2157	38.40	35.80	35.20	34.60	36.00
40	5614	42.20	42.60	42.40	44.60	42.95
41	A5203	39.50	39.40	40.50	41.00	40.10
42	B5203	40.70	46.60	46.40	46.20	44.98
43	B3162	47.50	42.30	36.70	39.10	41.40
44	B3166	43.10	42.40	44.20	43.70	43.35
45	2899	41.80	41.00	42.40	41.10	41.58

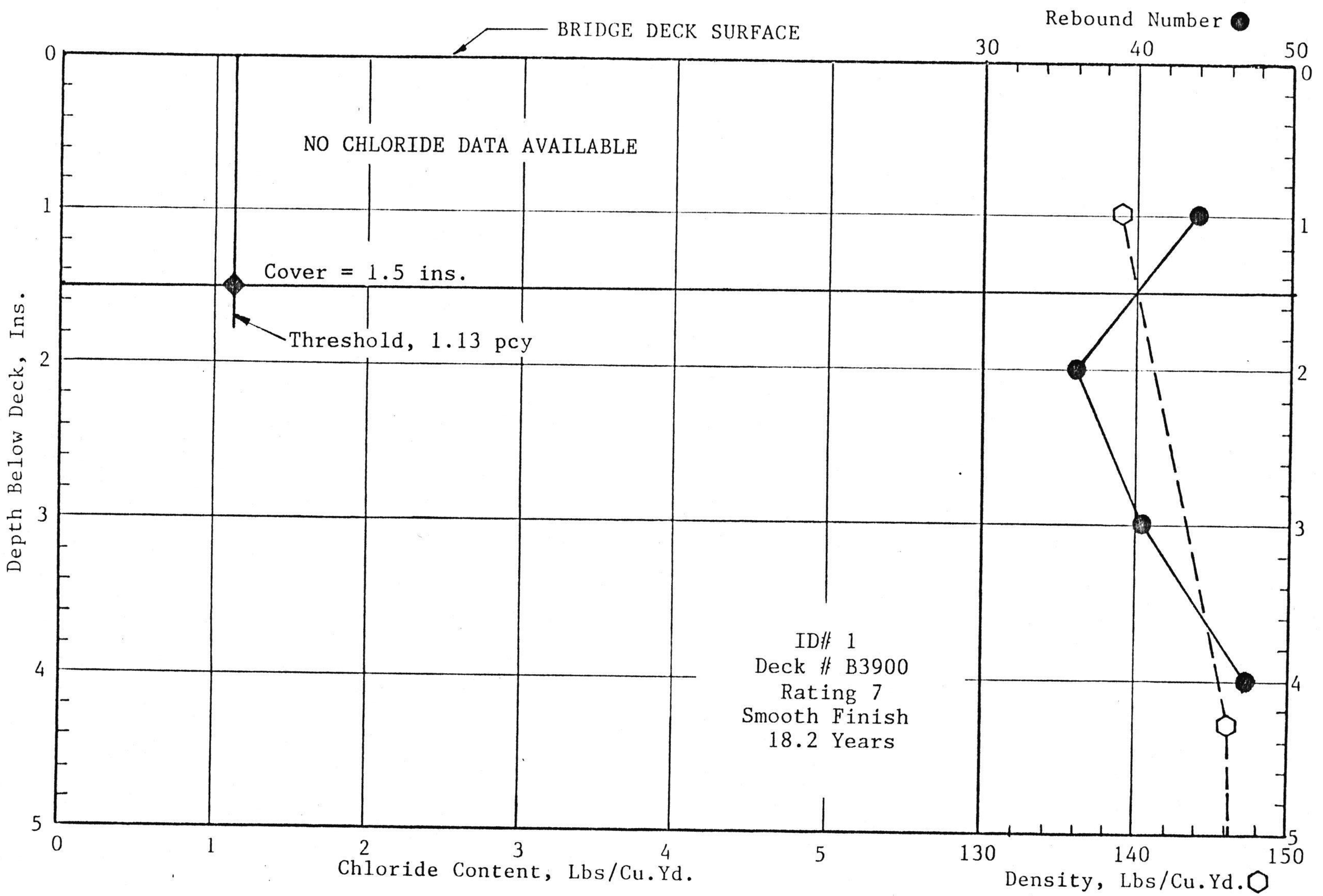

Figure C.1 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B3900

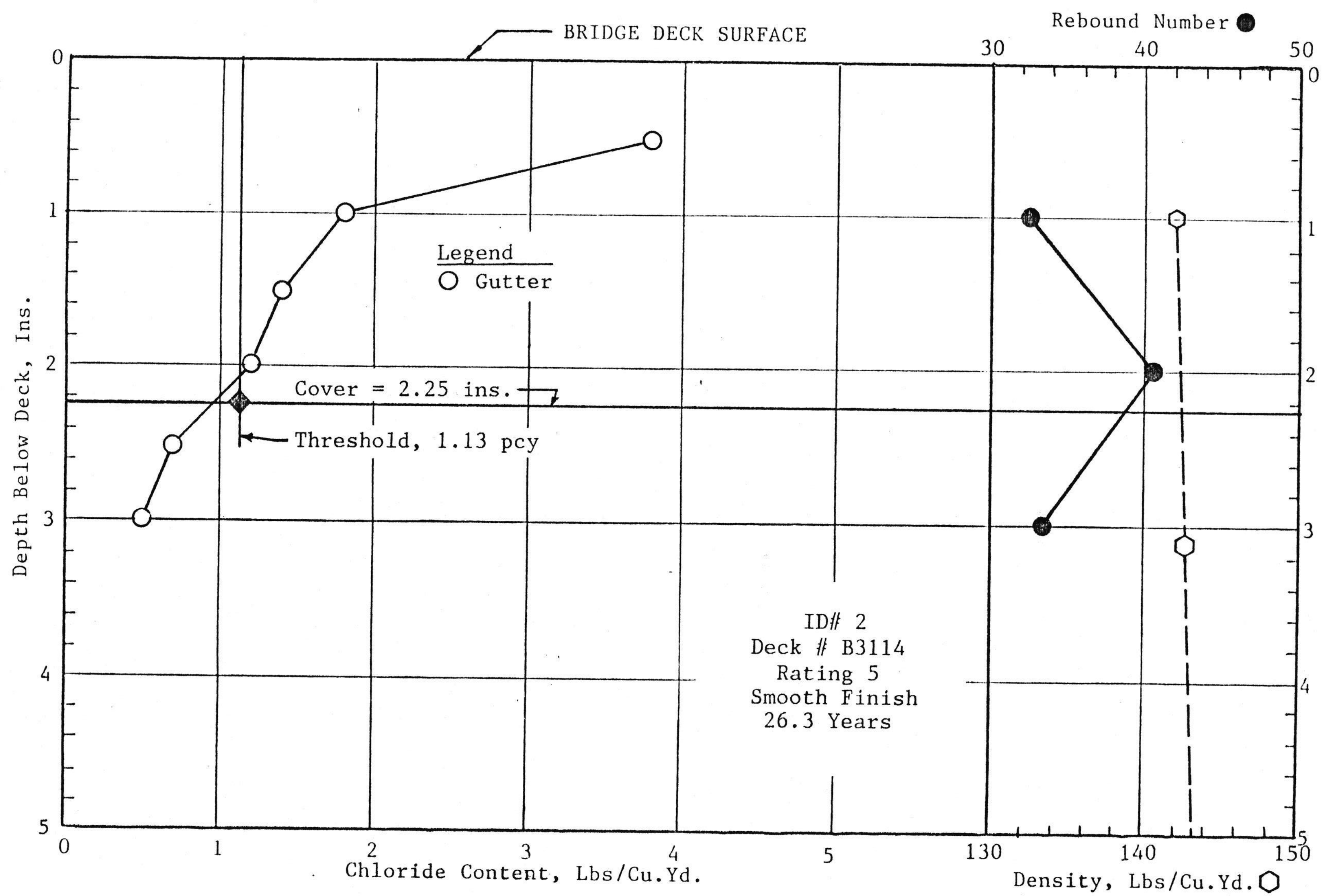

Figure C.2 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B3114

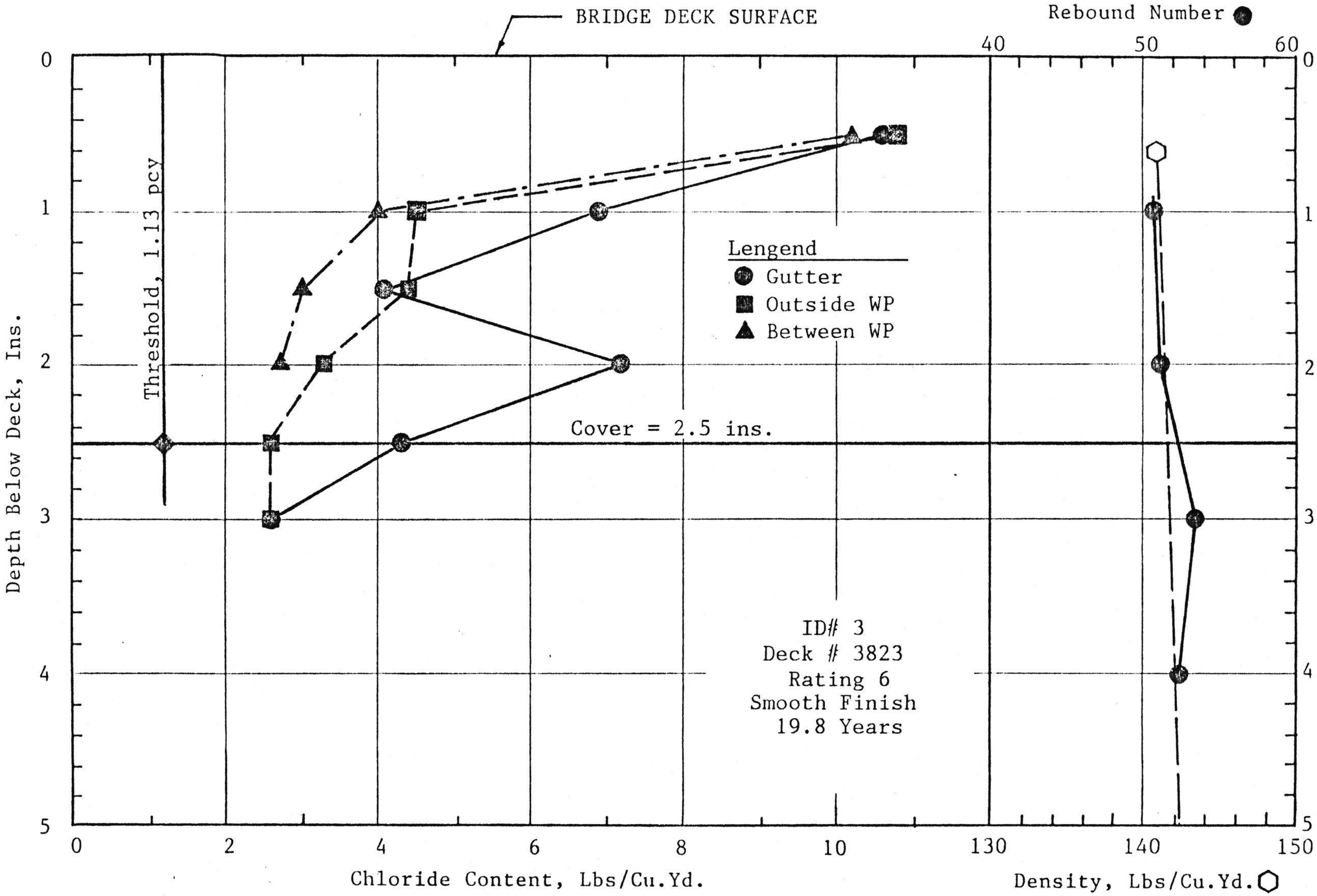

Figure C.3 CHLORIDE CONTENT, DENSITY AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 3823

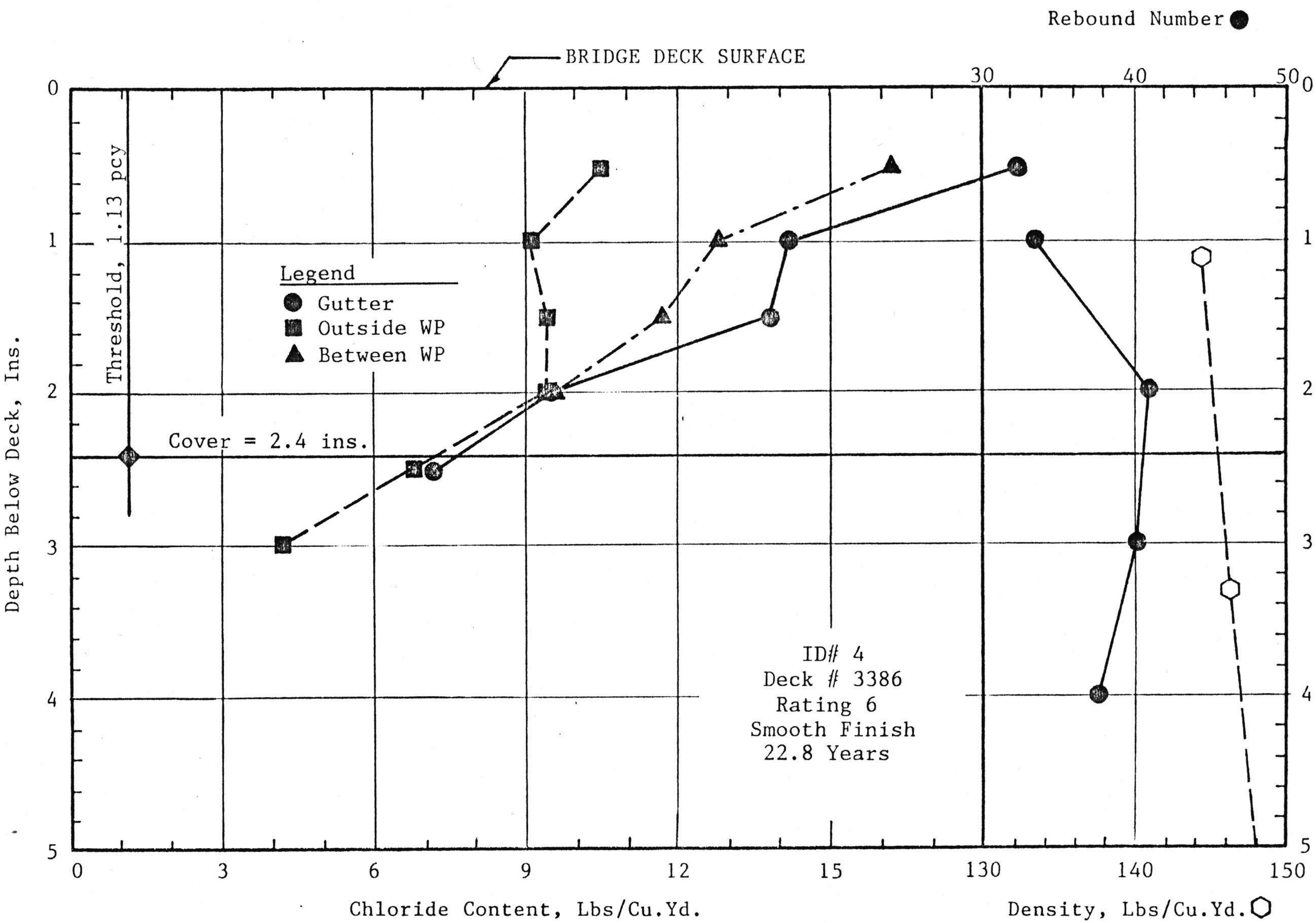

Figure C.4 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 3386

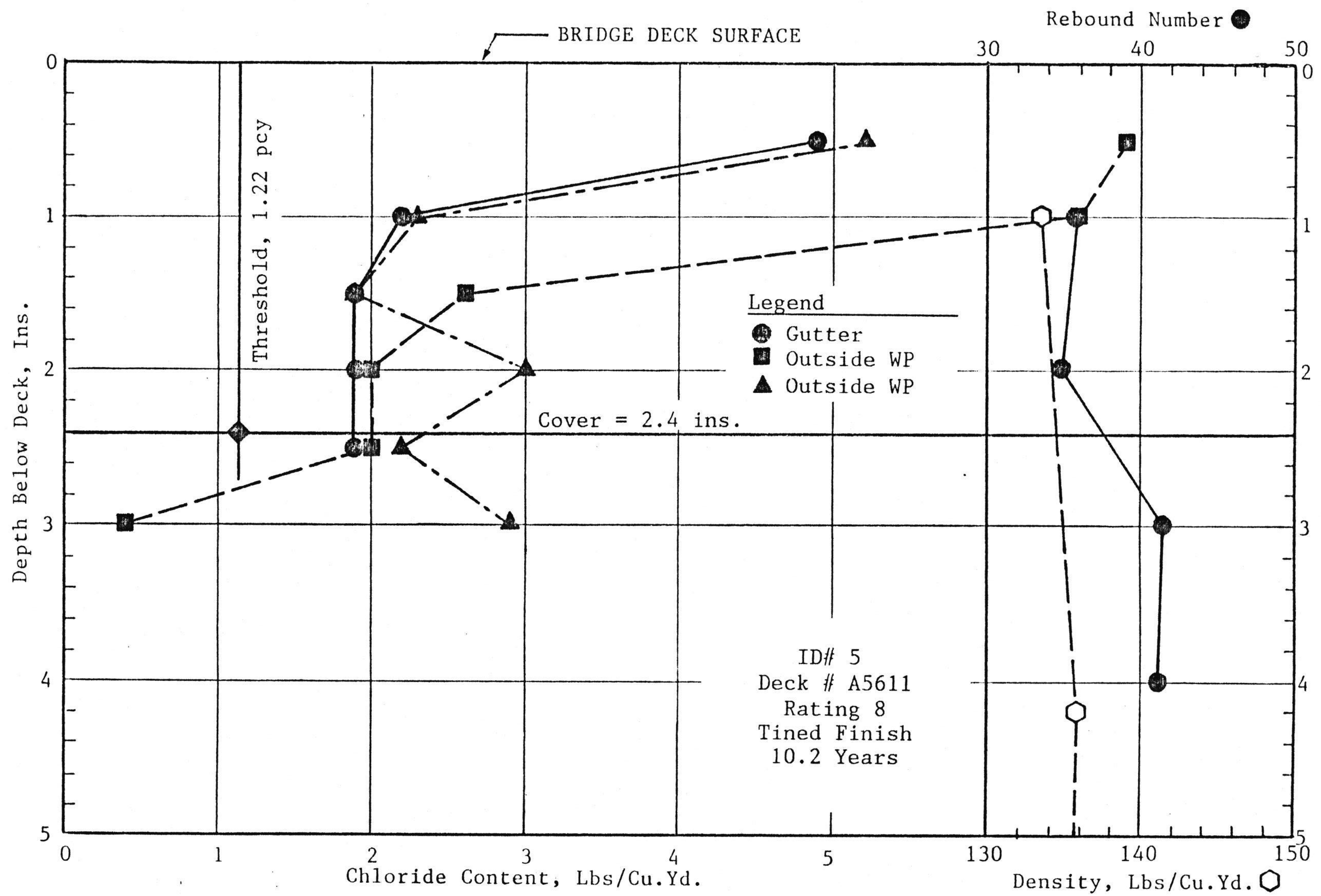

Figure C.5 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A5611

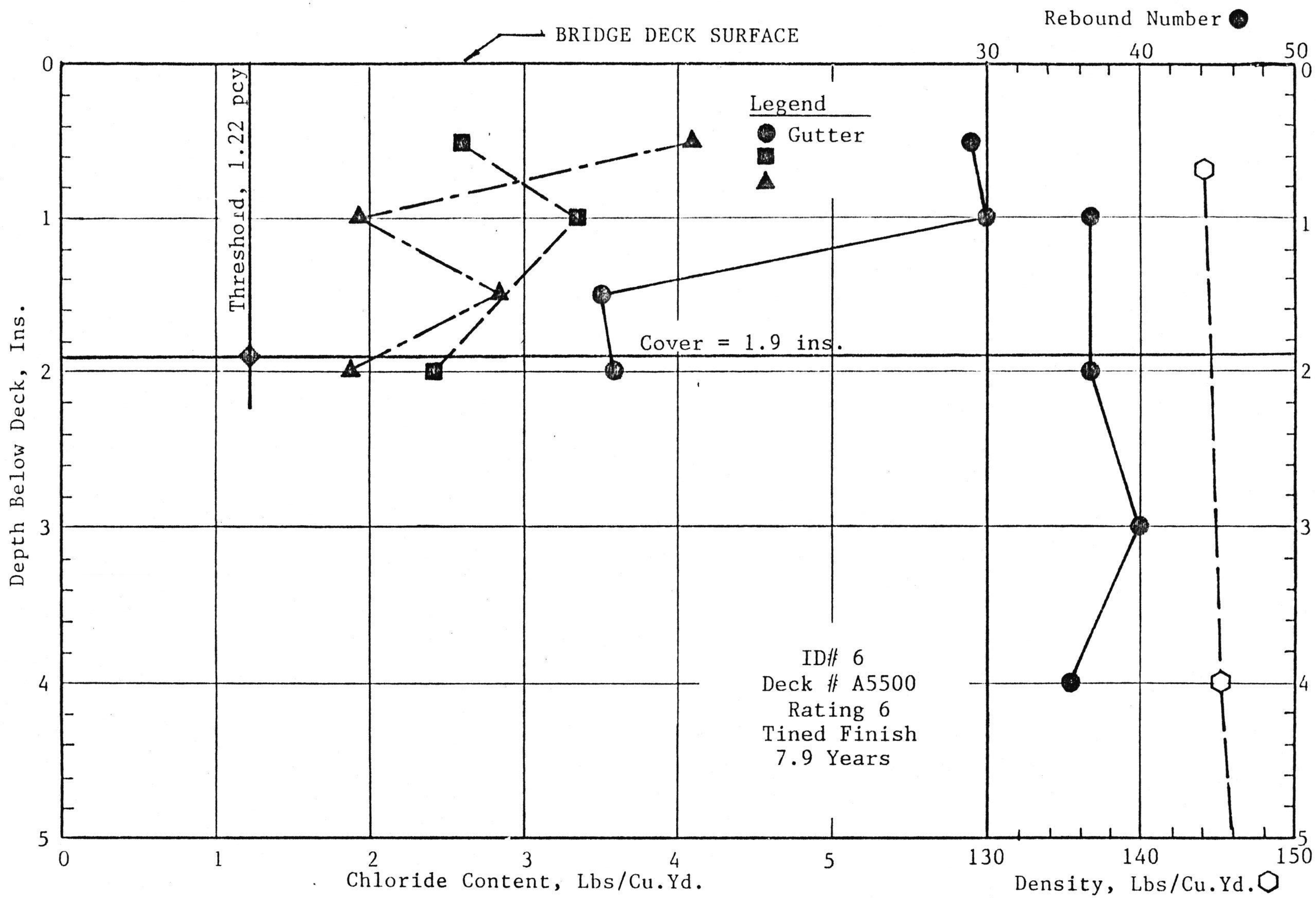

Figure C.6 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A5500

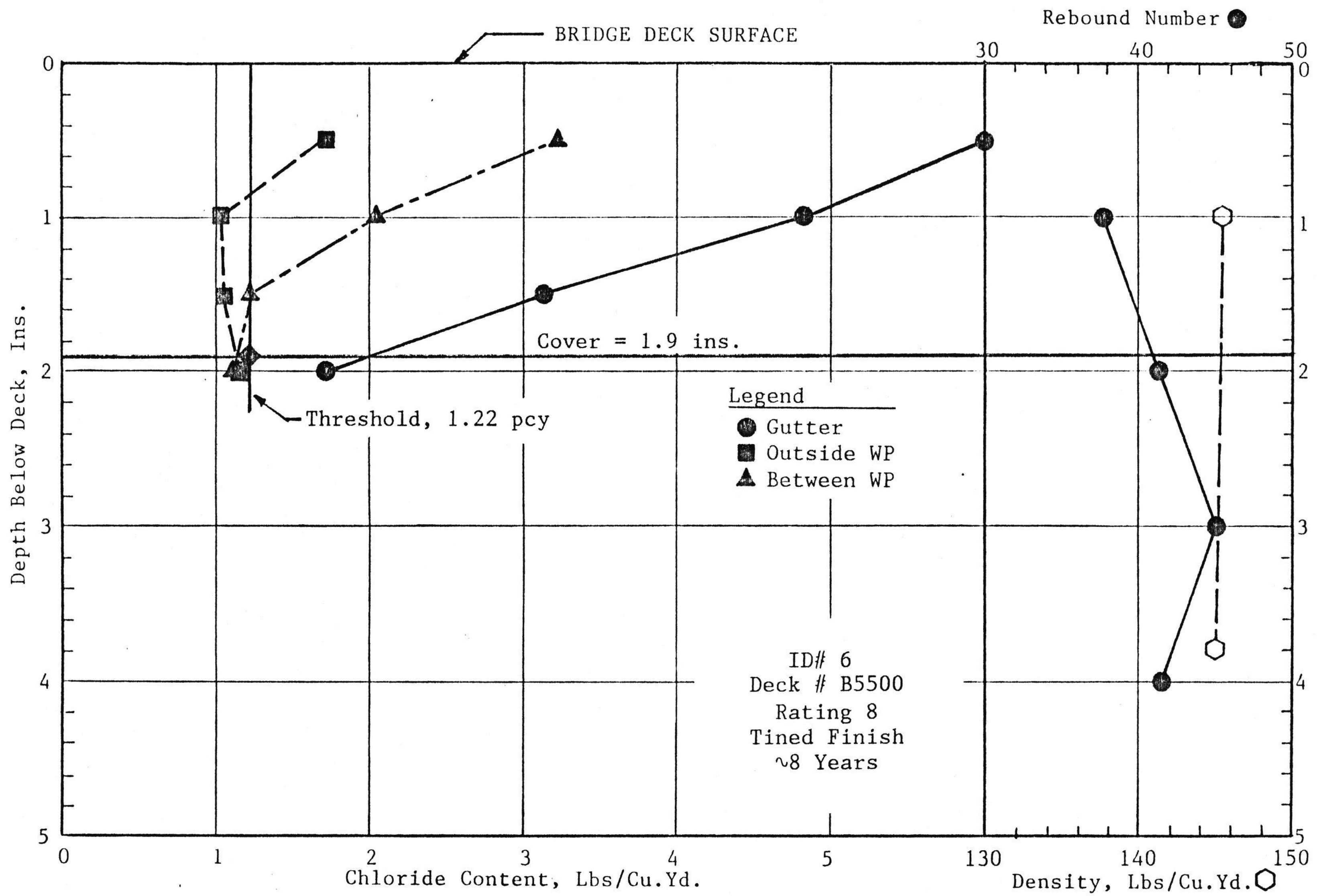

Figure C.7 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B5500

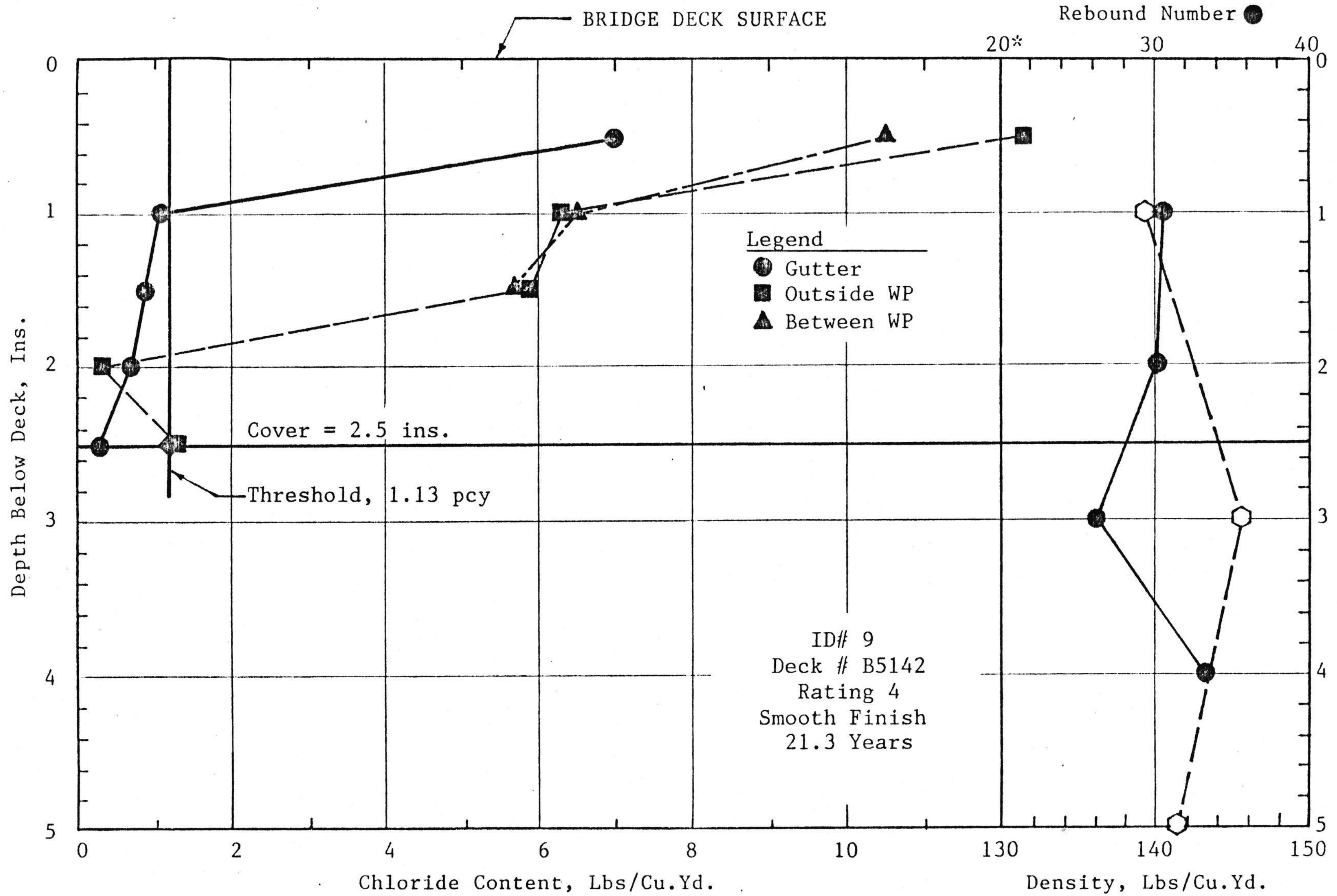

Figure C.9 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B5142

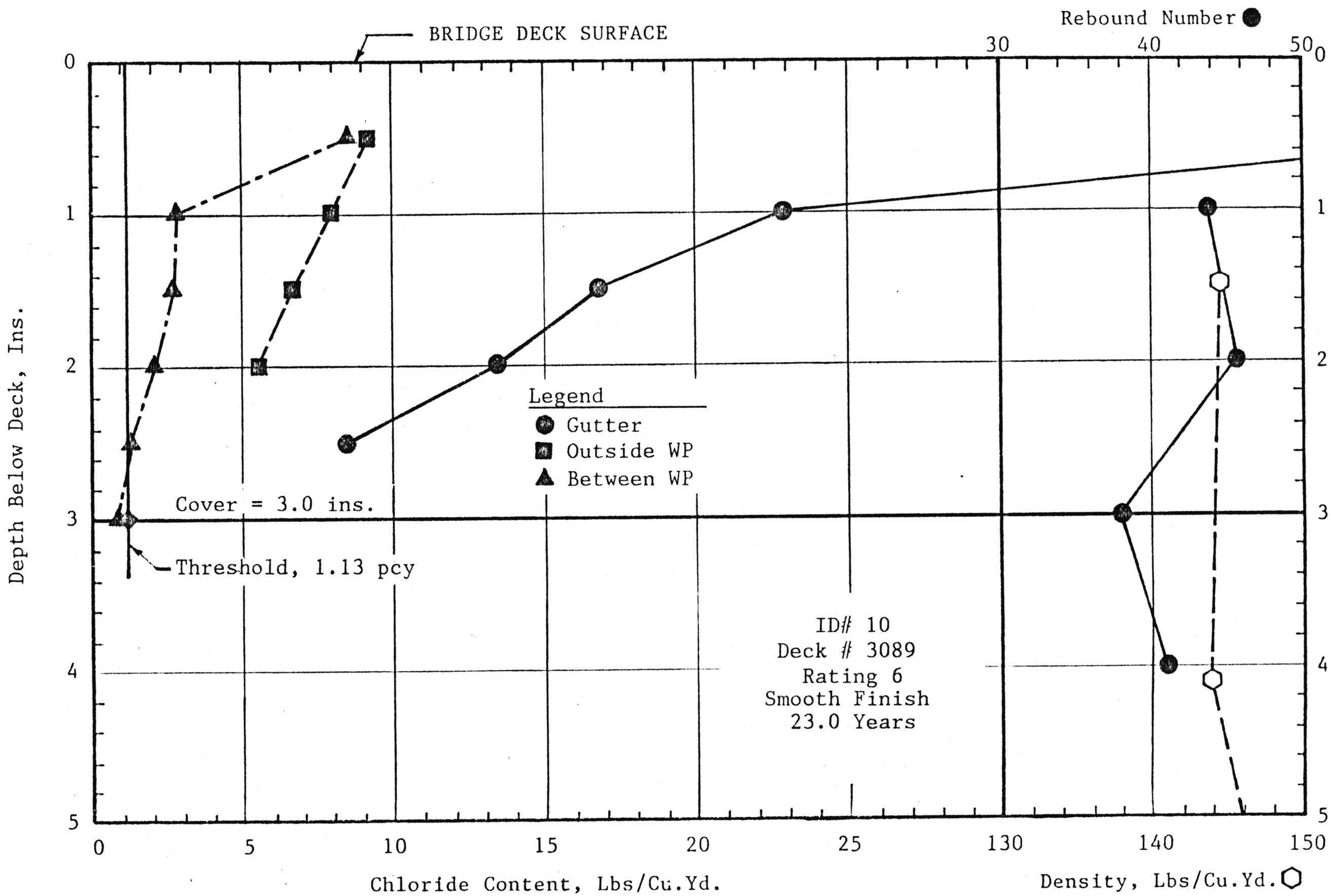

Figure C.10 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 3089

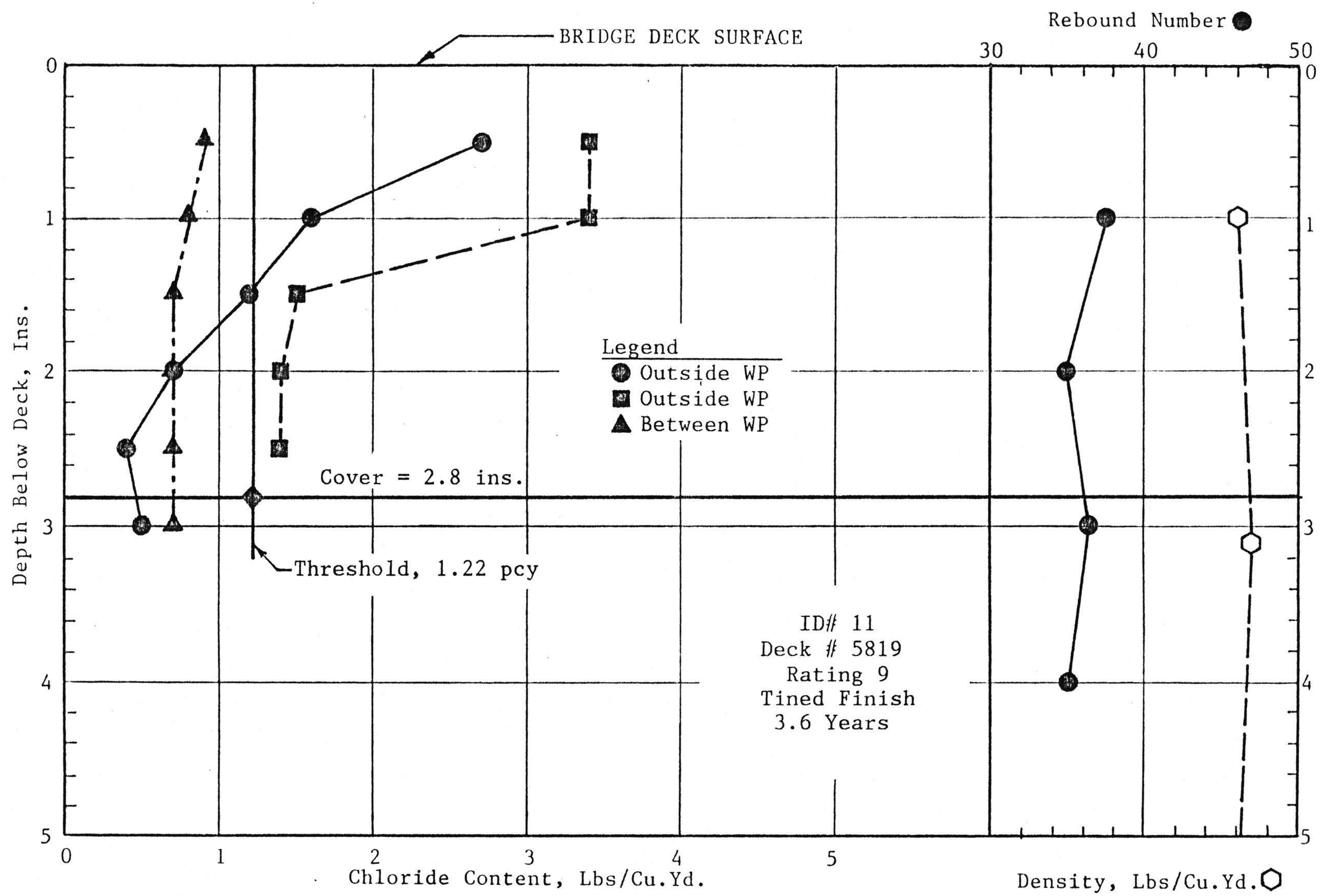

Figure C.11 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 5817

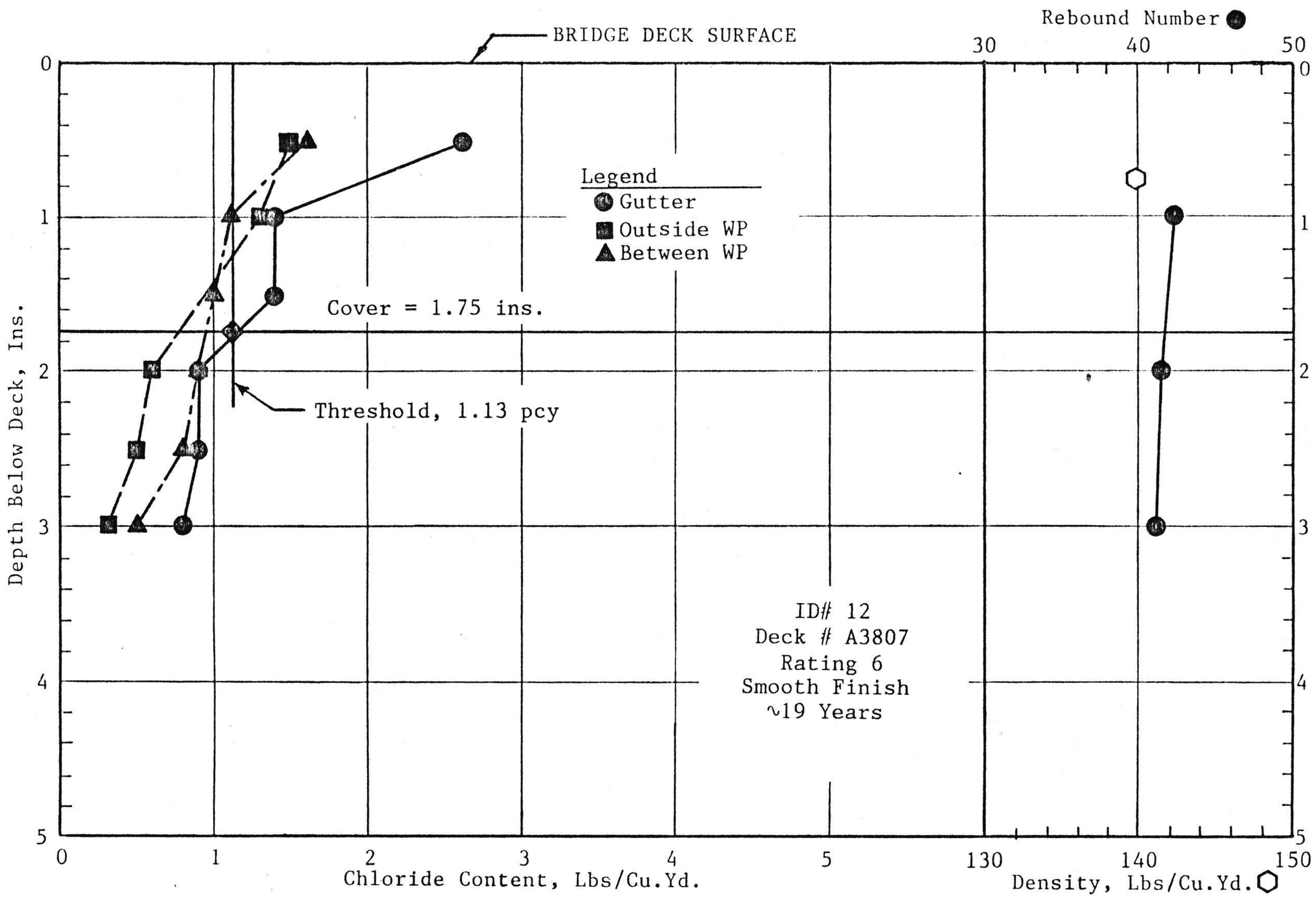

Figure C.12 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A3807

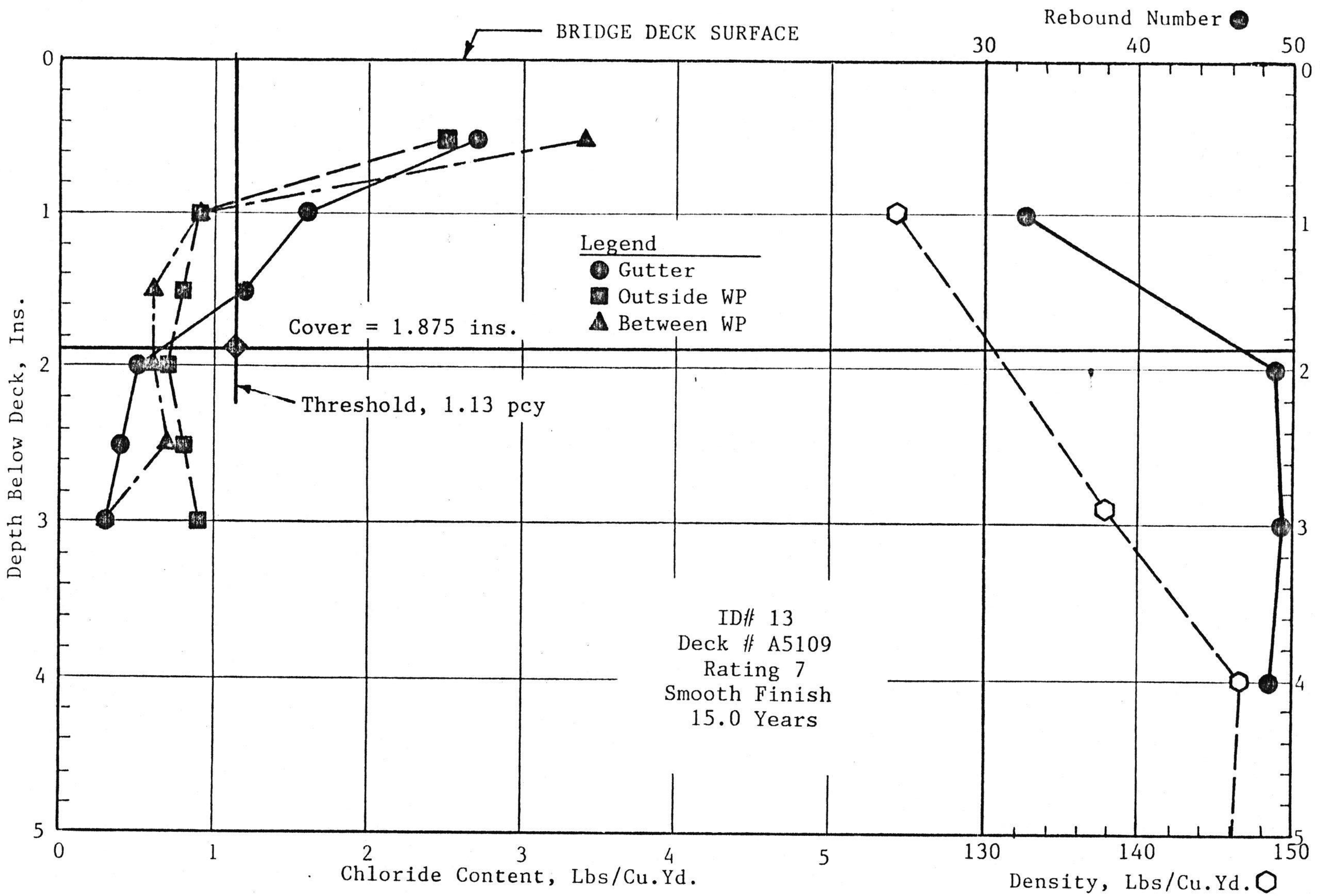

Figure C.13 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A5109

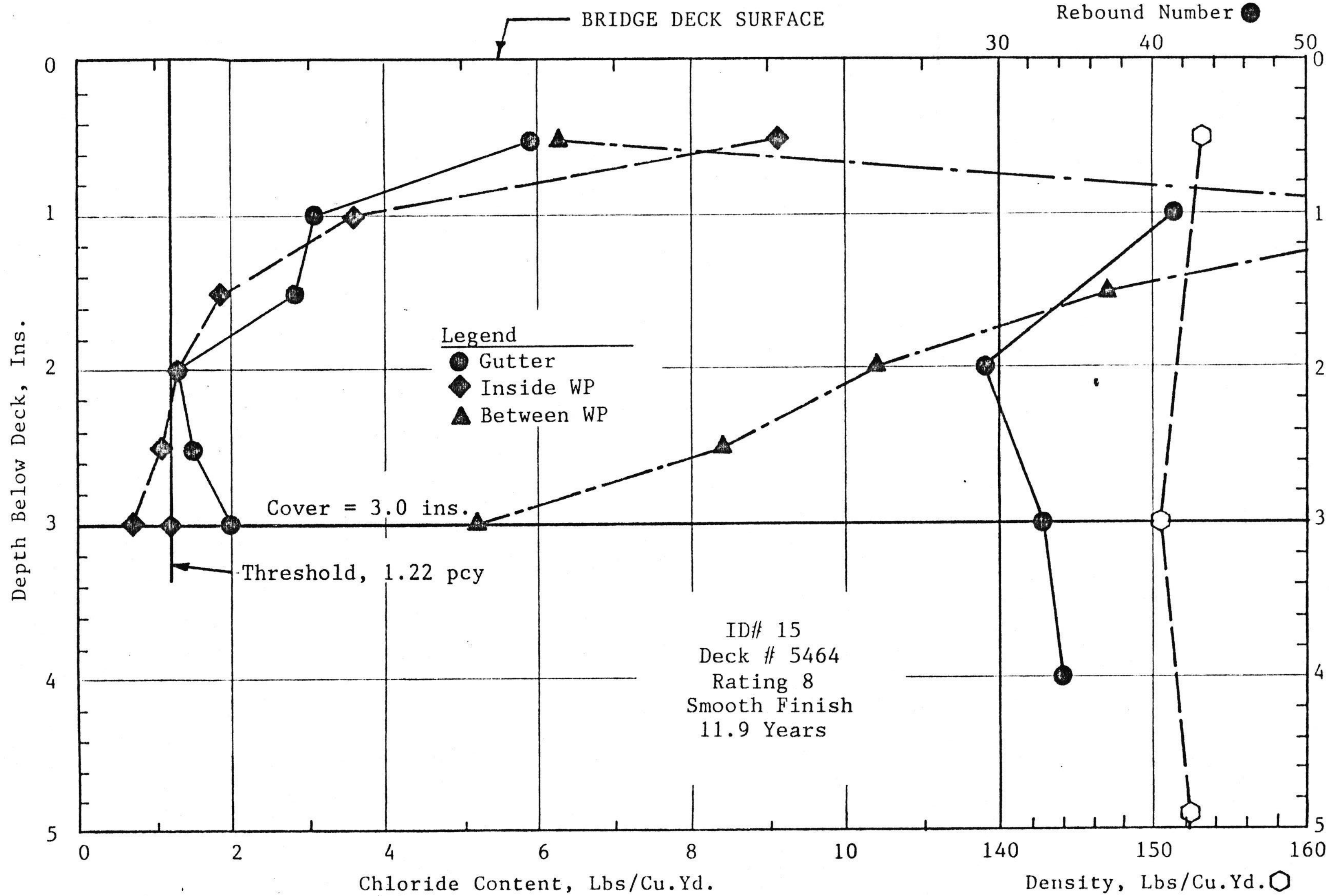

Figure C.15 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 5464

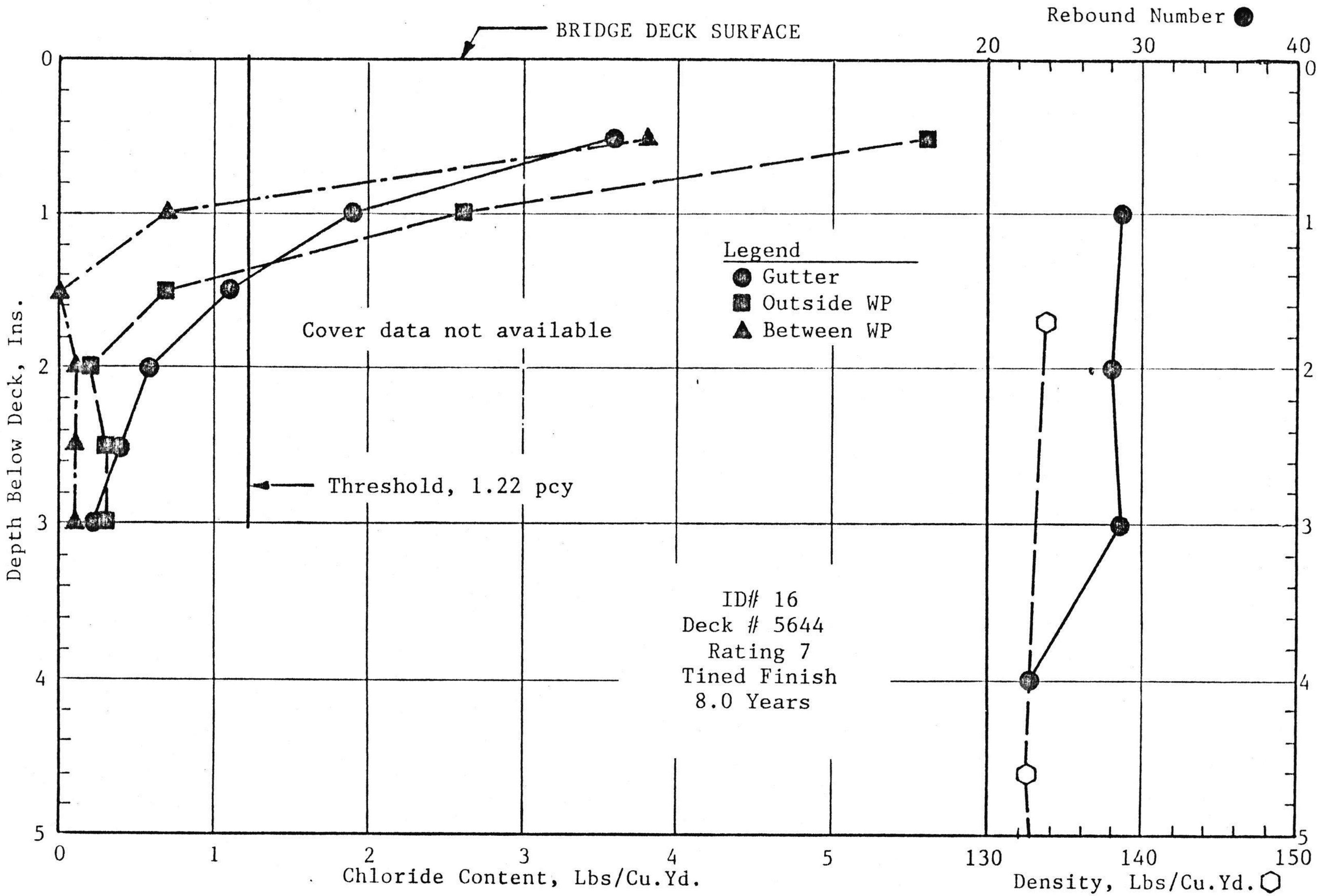

Figure C.16 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 5644

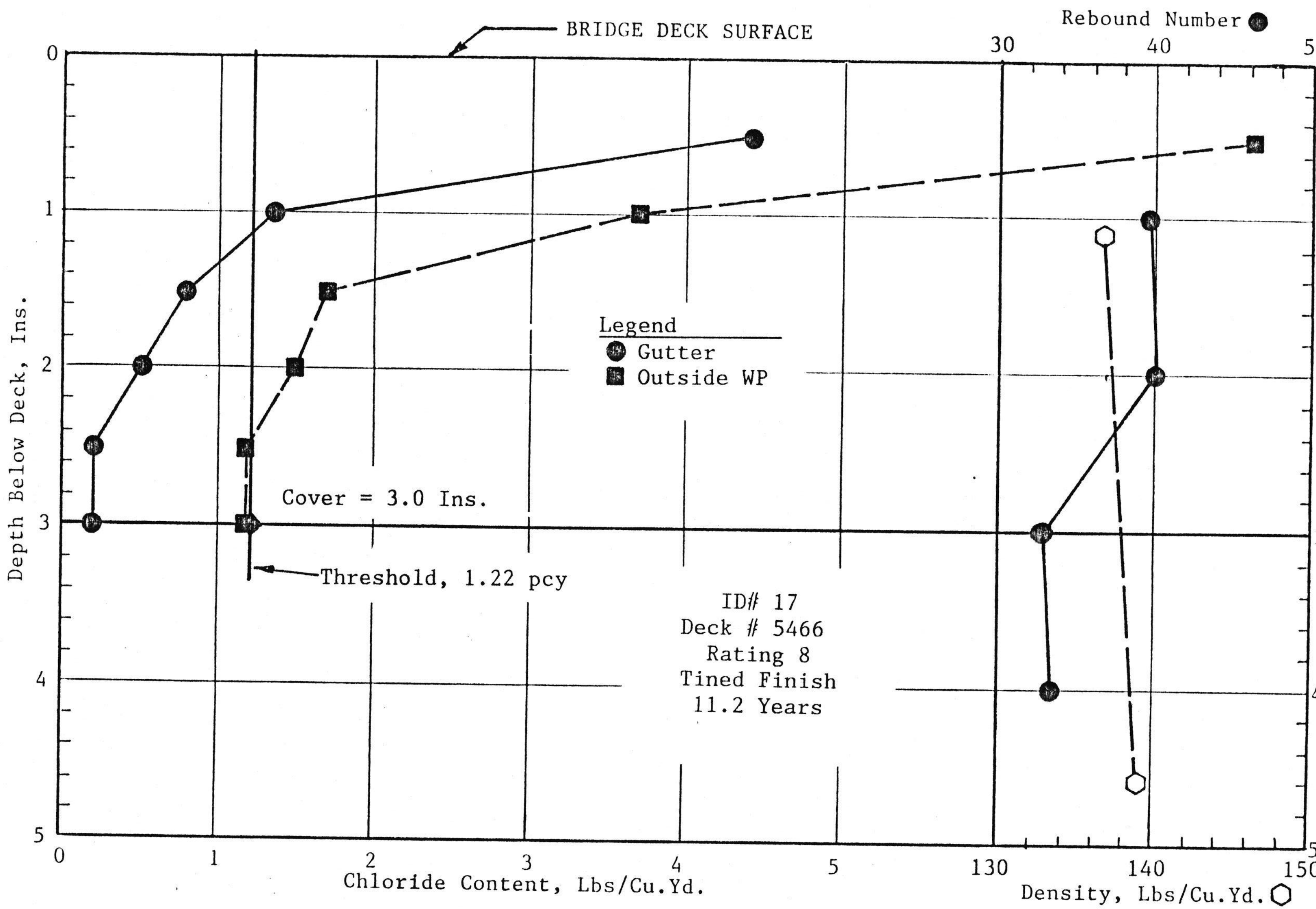

Figure C.17 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 5466

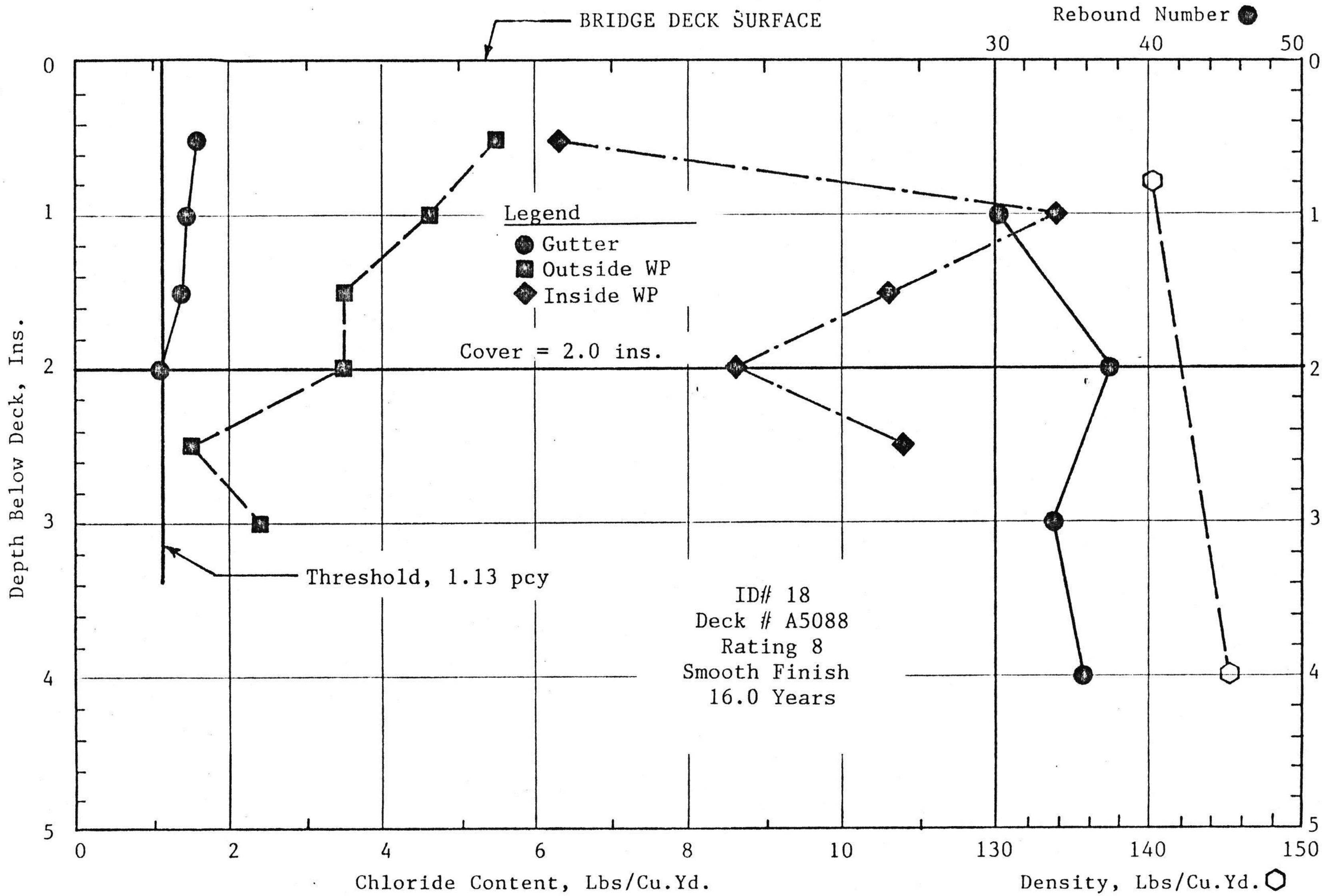

Figure C.18 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A5088

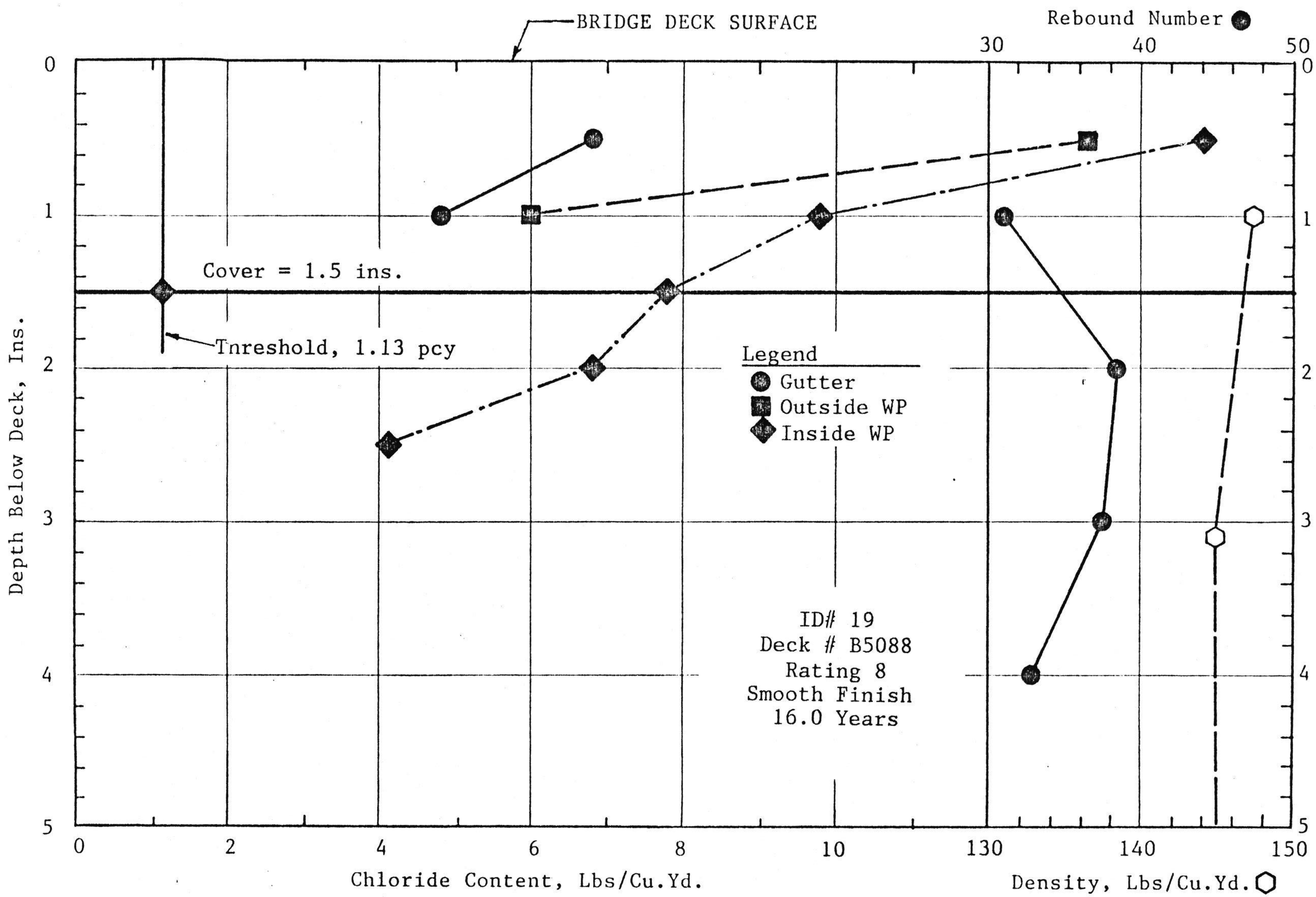

Figure C.19 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B5088

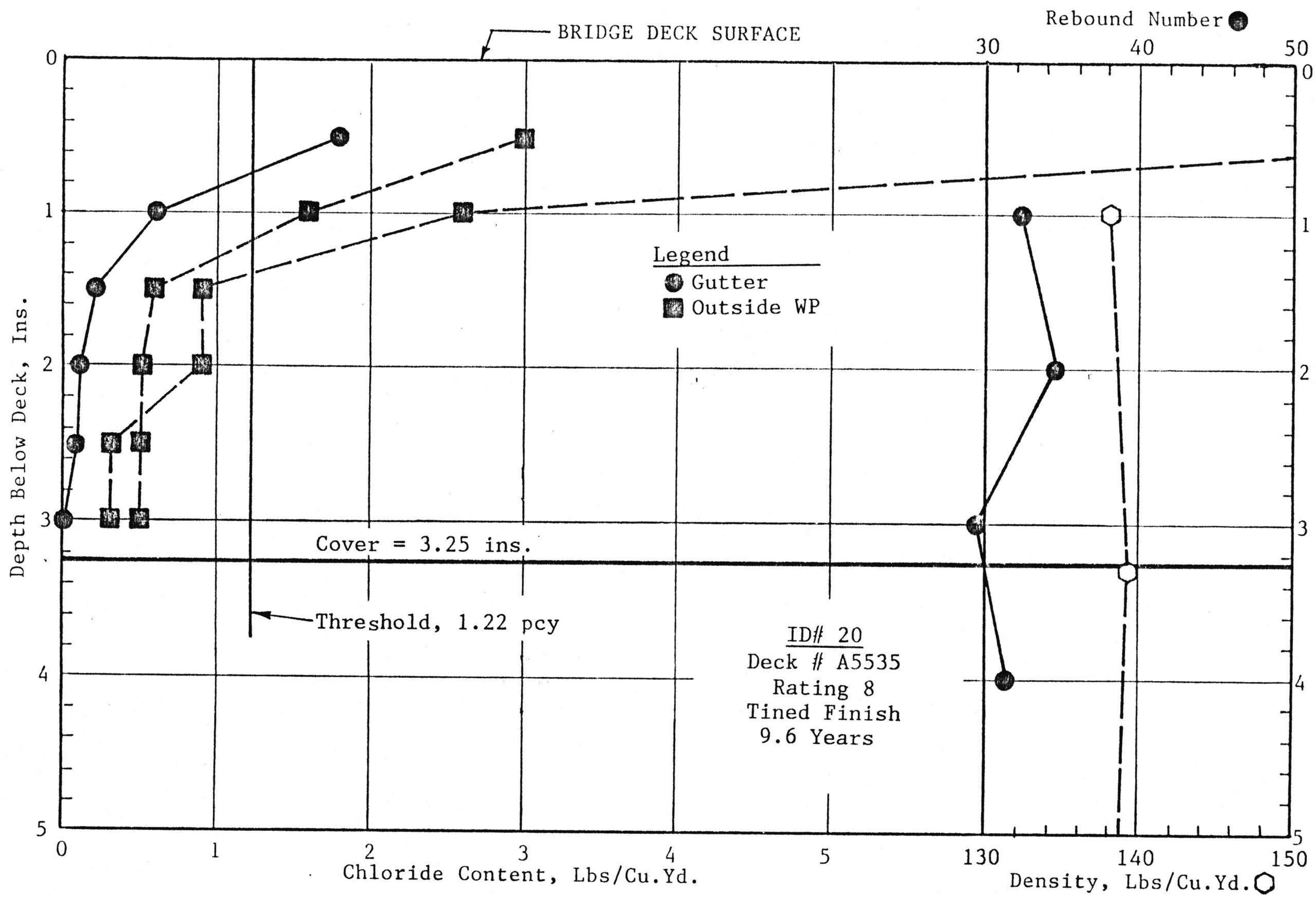

Figure C.20 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A5535

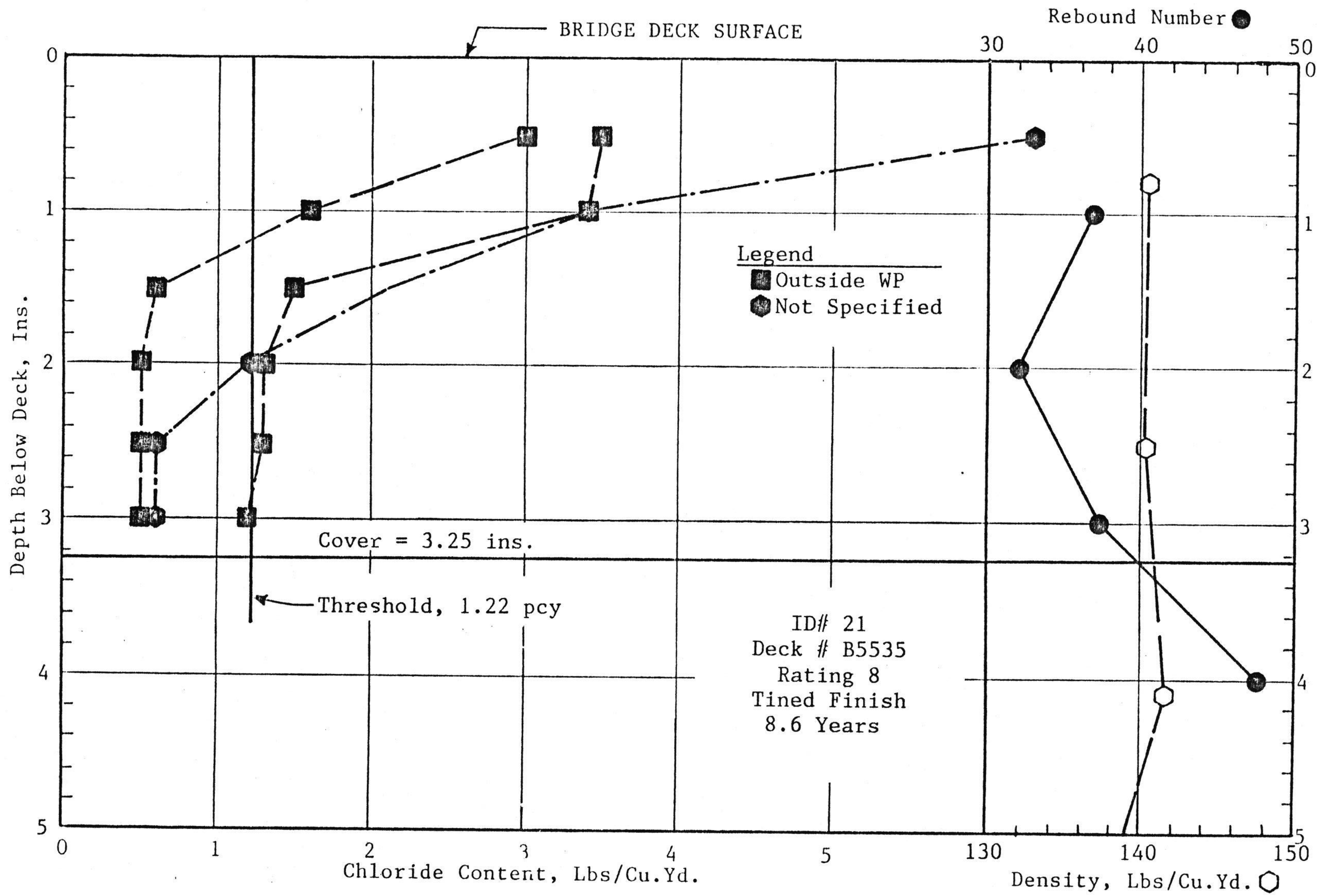

Figure C.21 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B5535

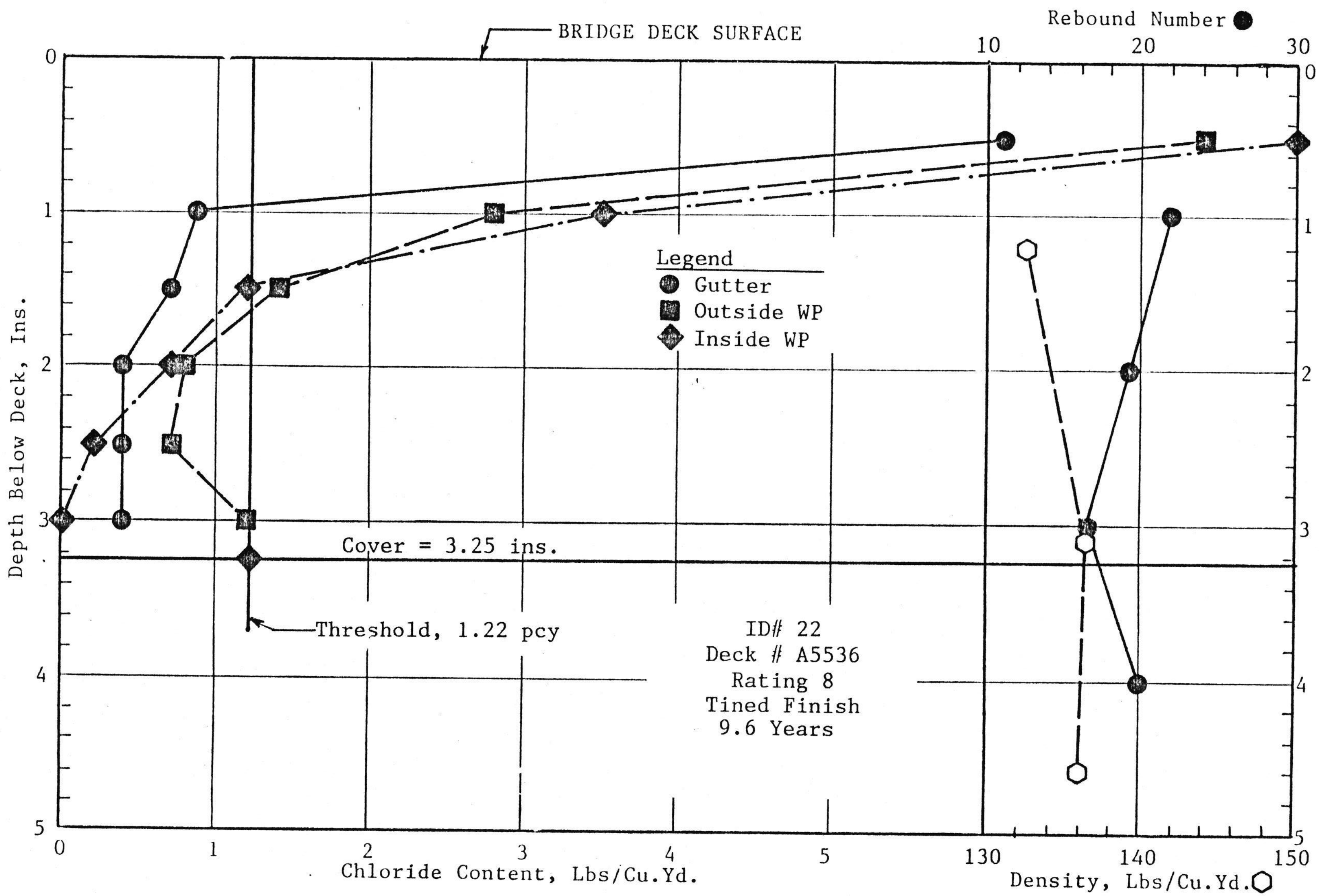

Figure C.22 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A5536

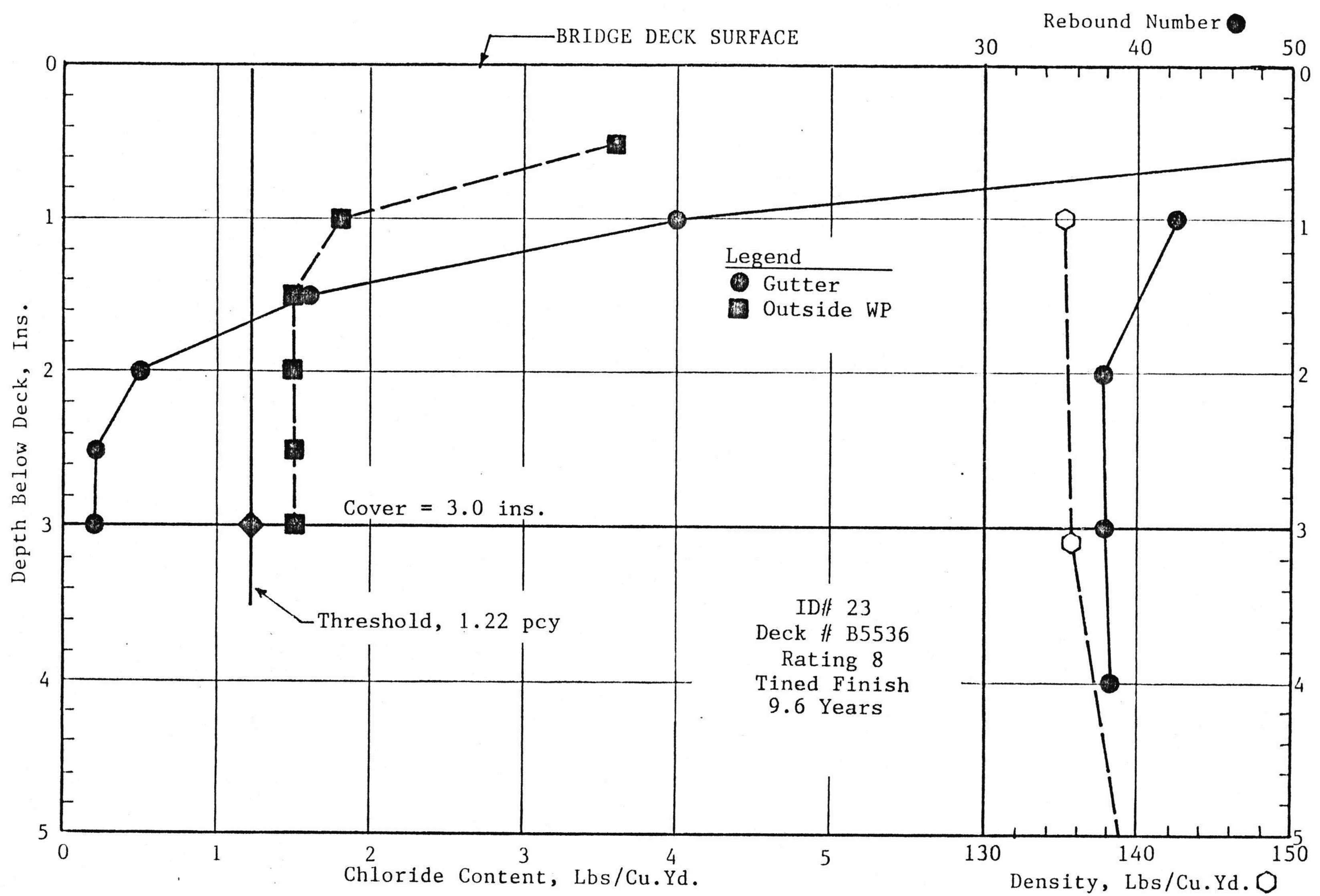

Figure C.23 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B5536

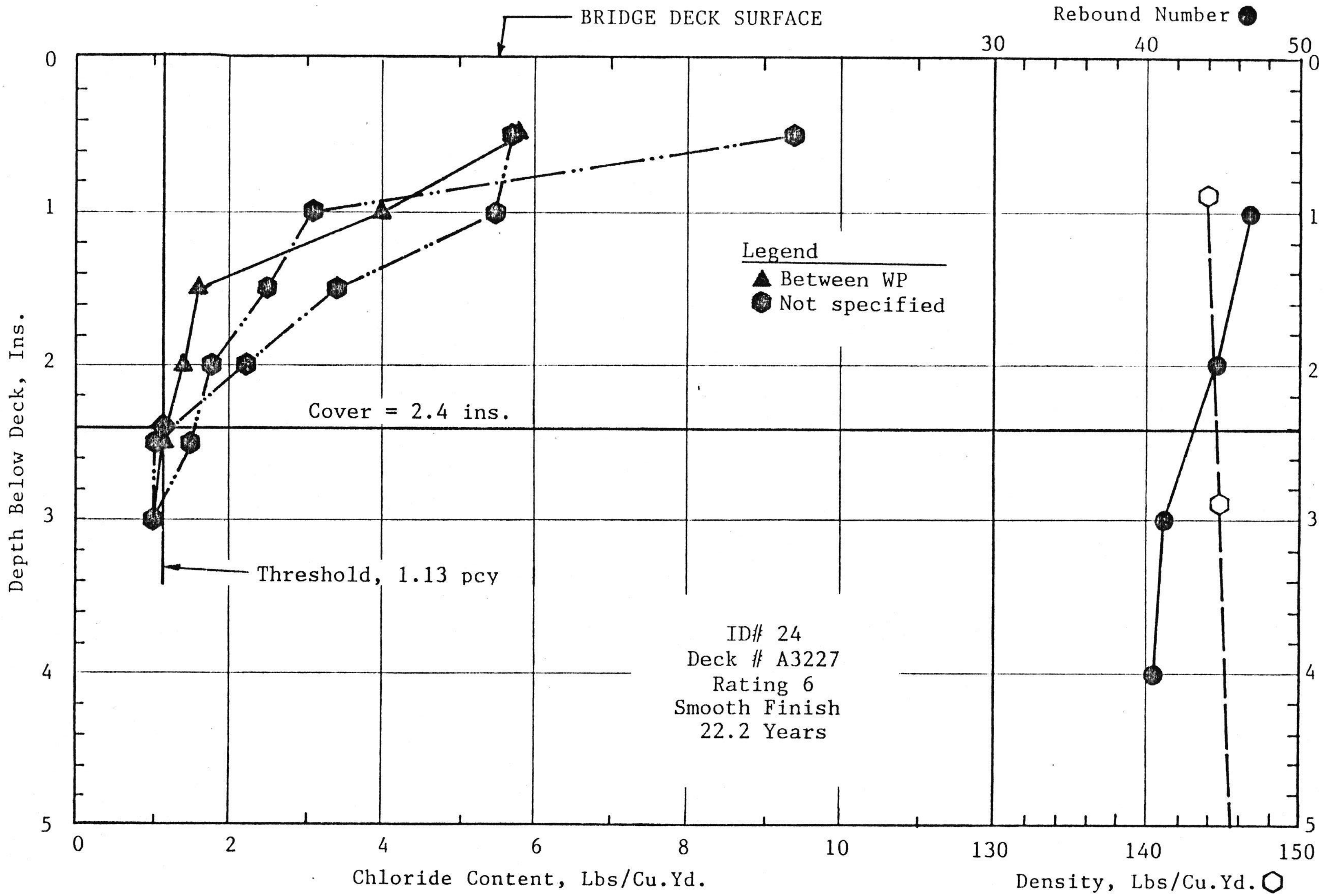

Figure C.24 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A3227

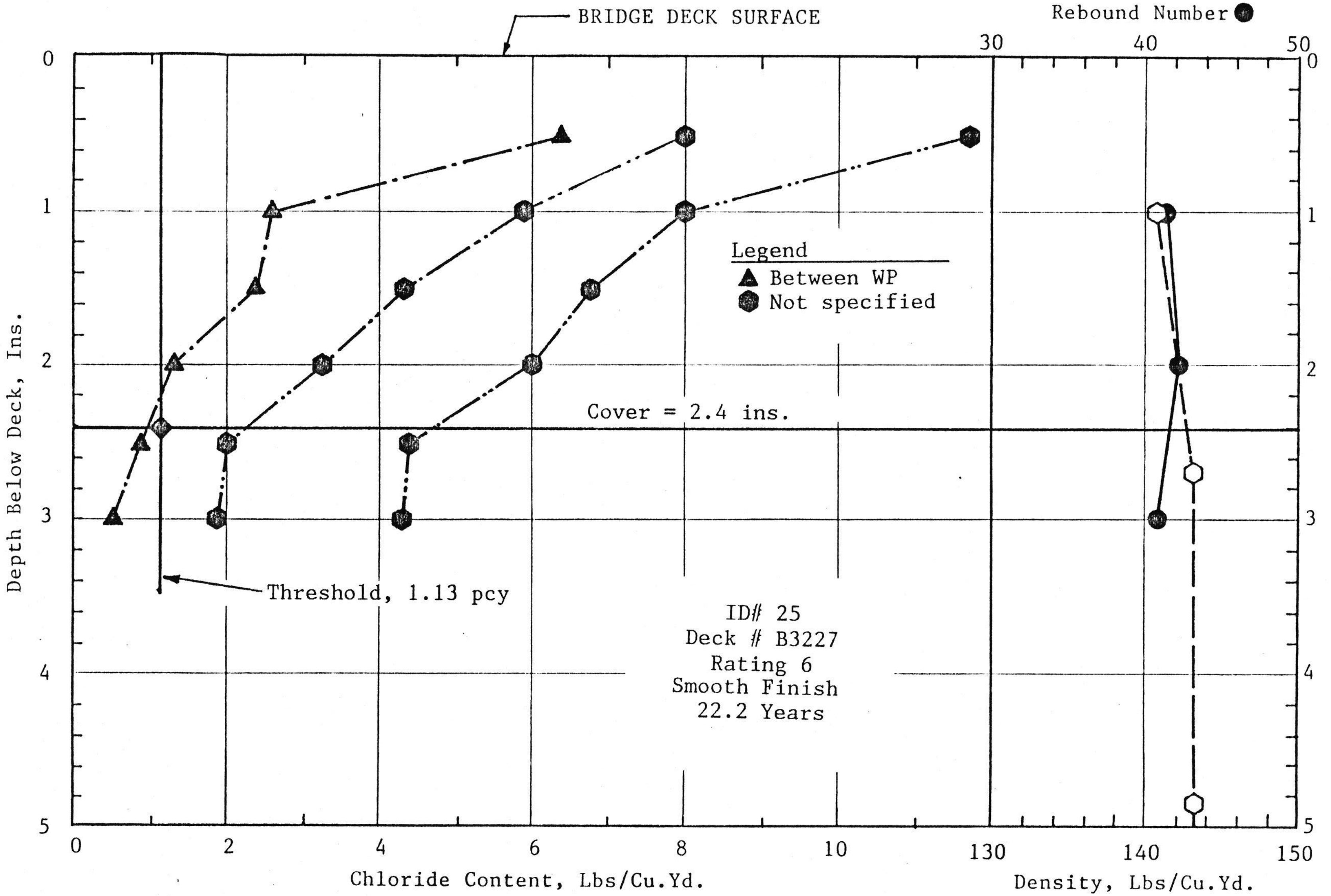

Figure C.25 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B3227

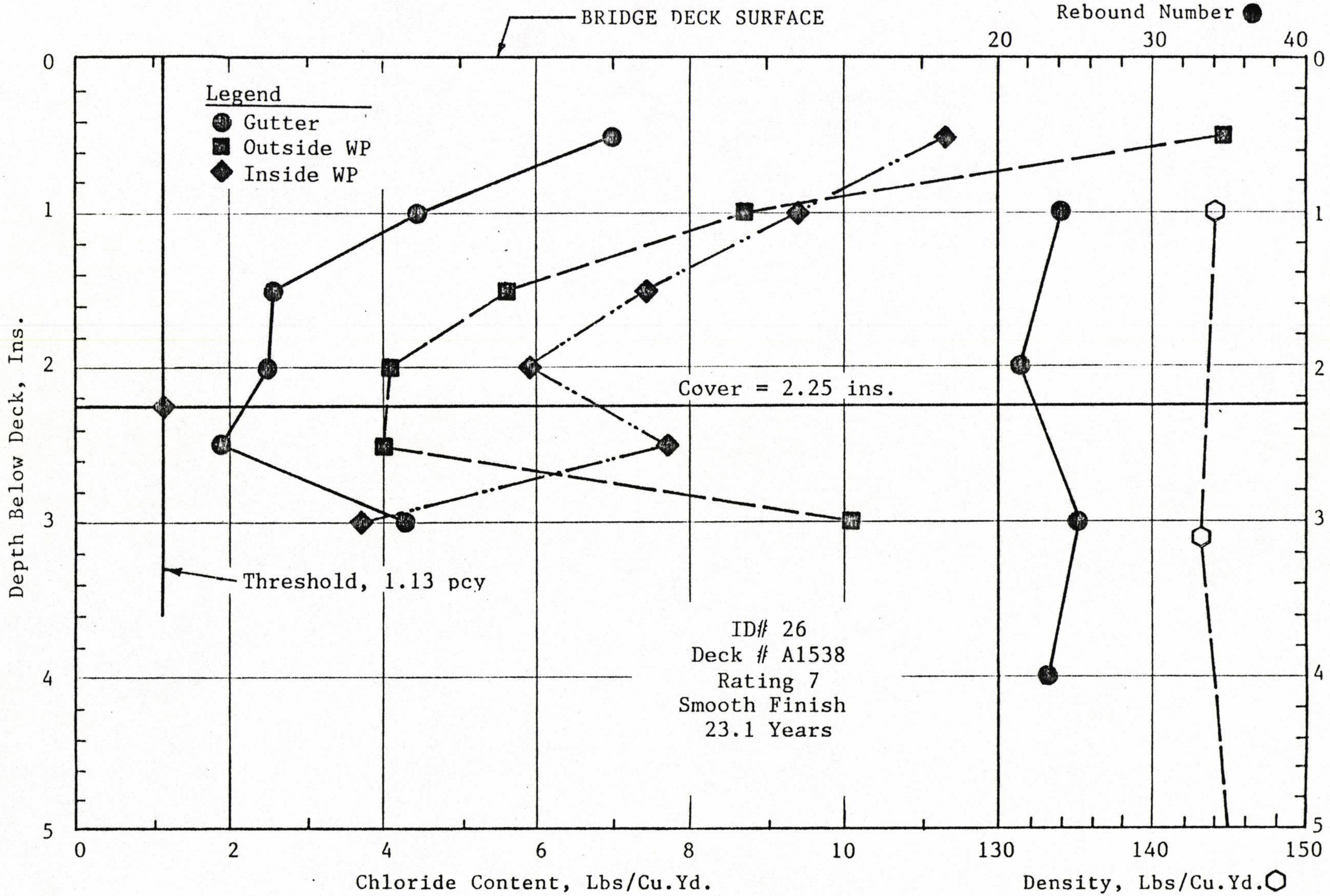

Figure C.26 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A1538

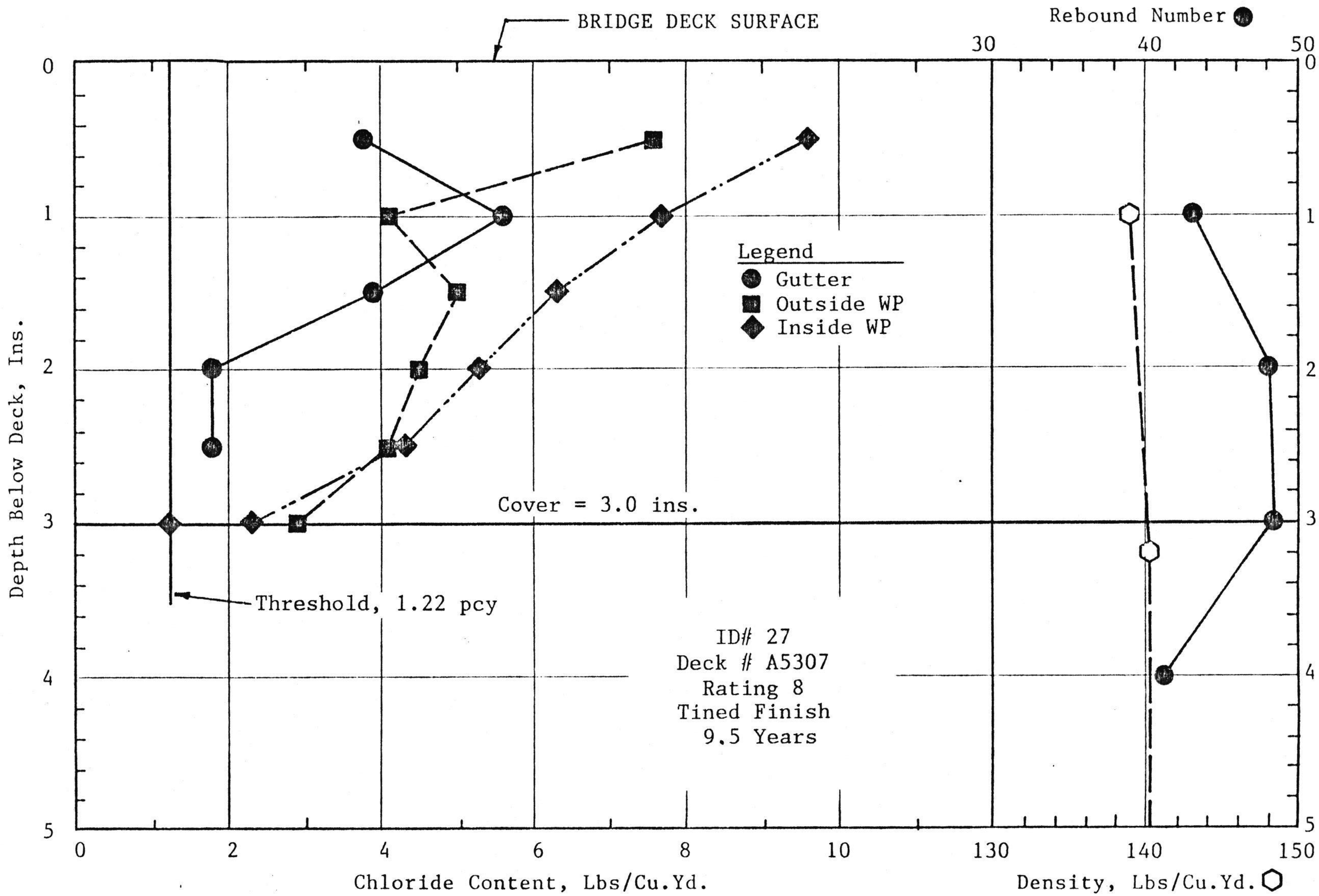

Figure C.27 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A5307

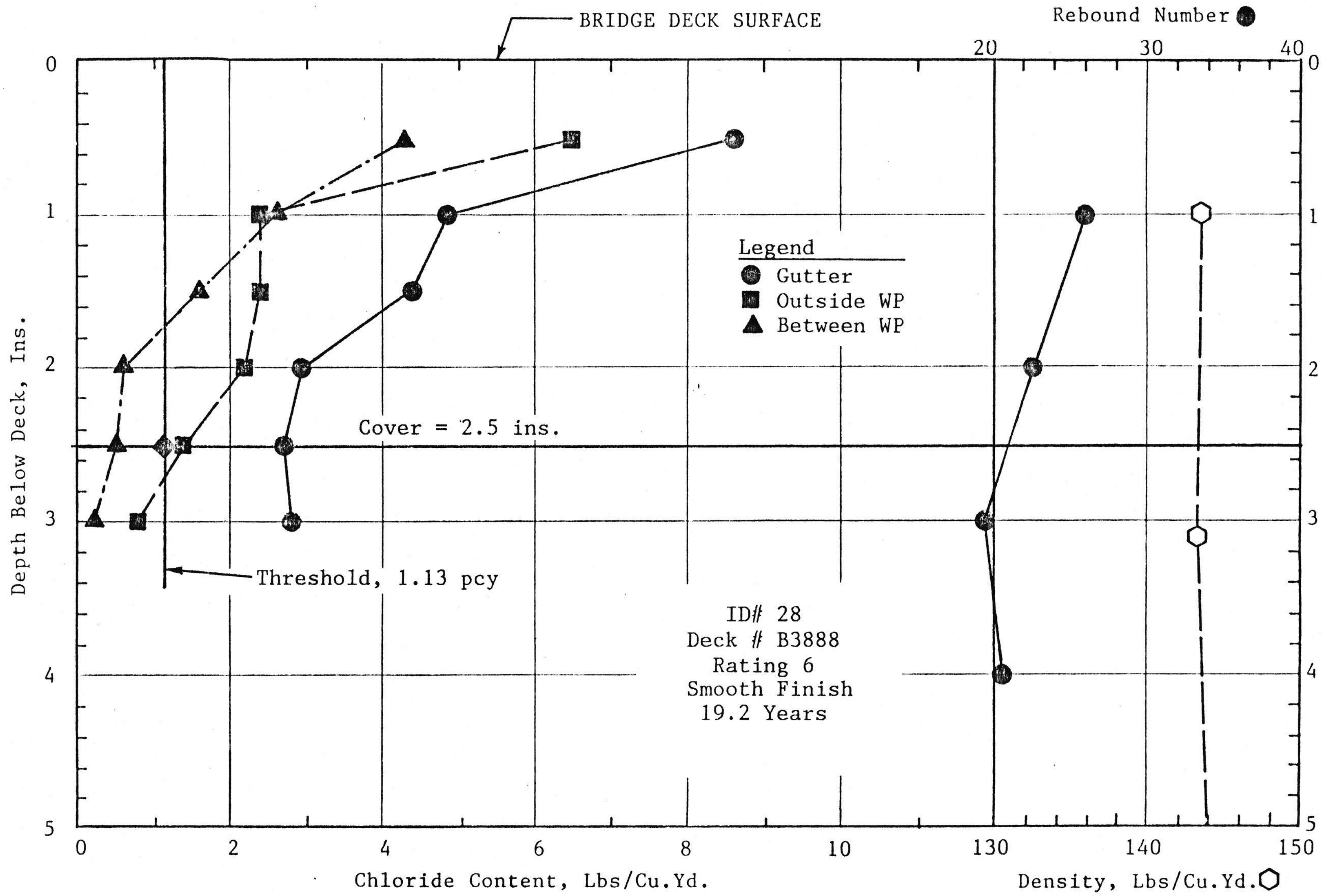

Figure C.28 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # B3888

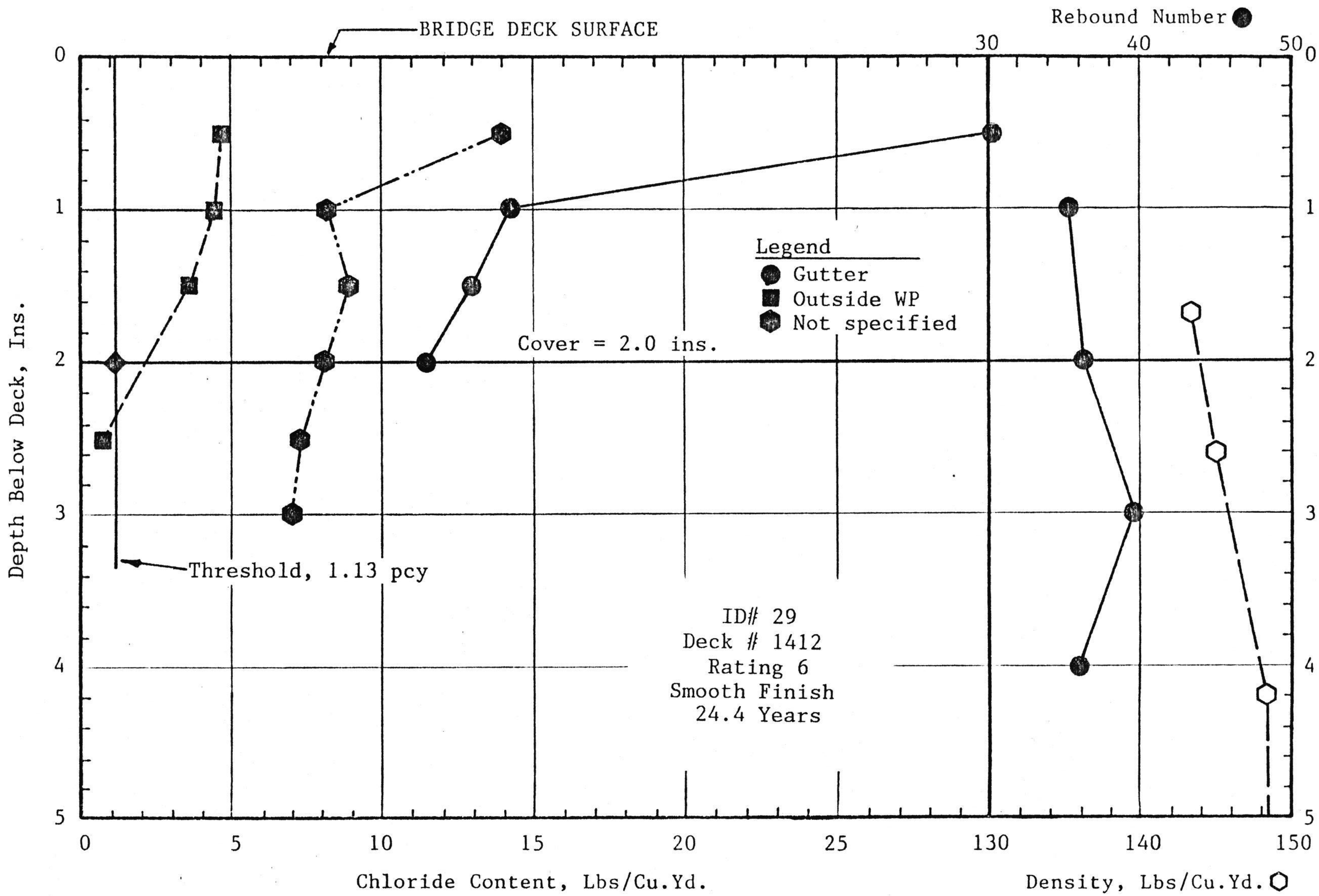

Figure C.29 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 1412

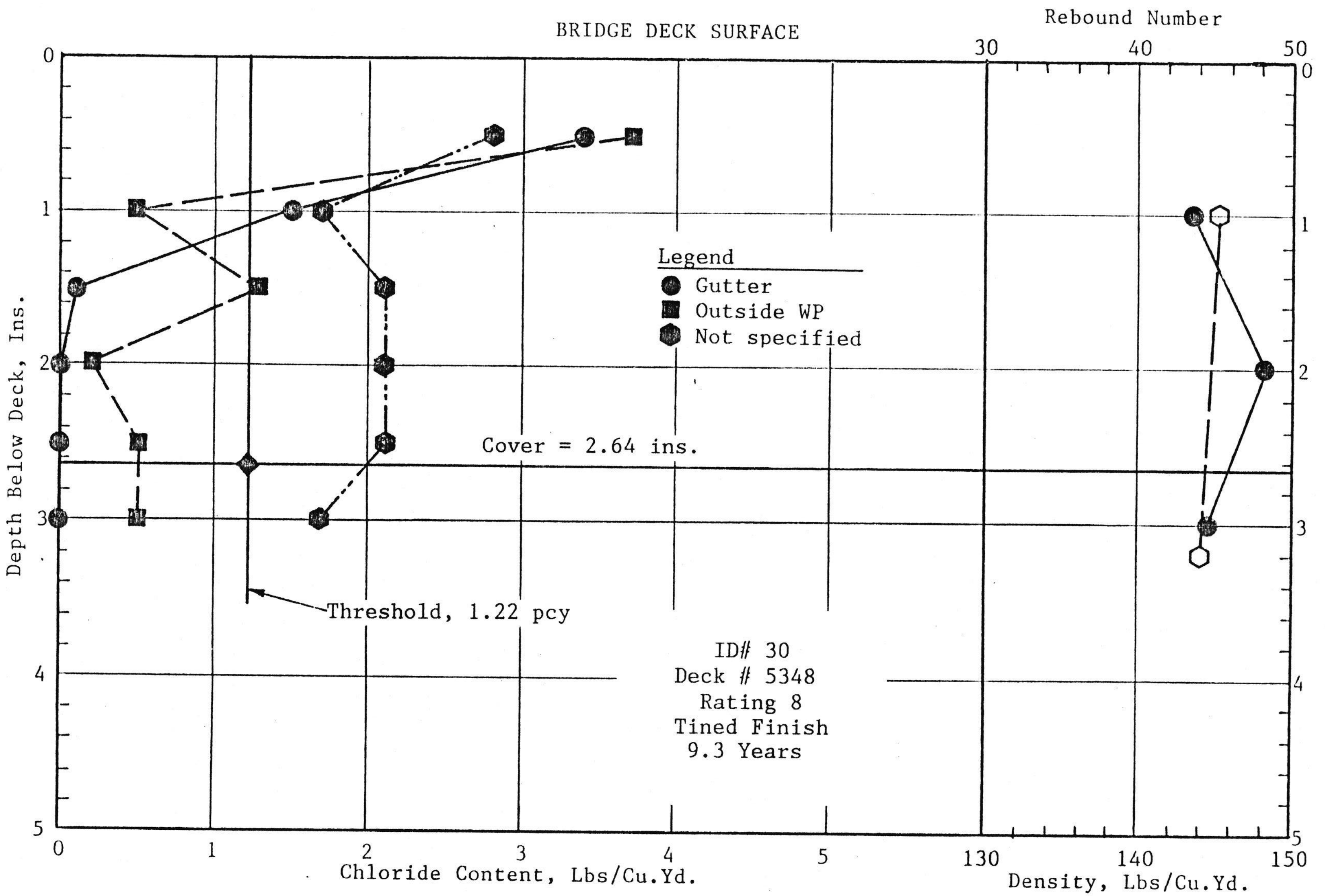

Figure C.30 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 5348

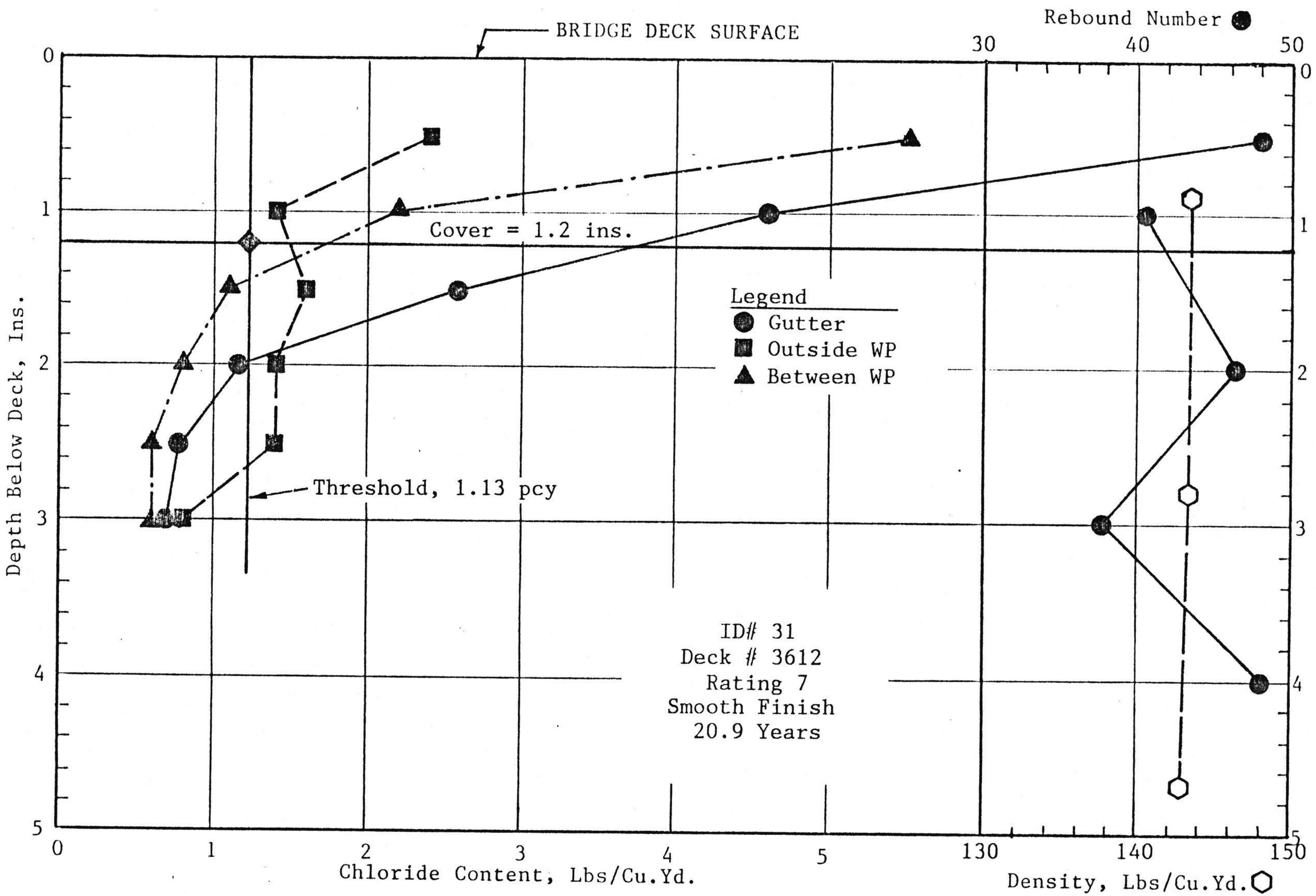

Figure C.31 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # 3612

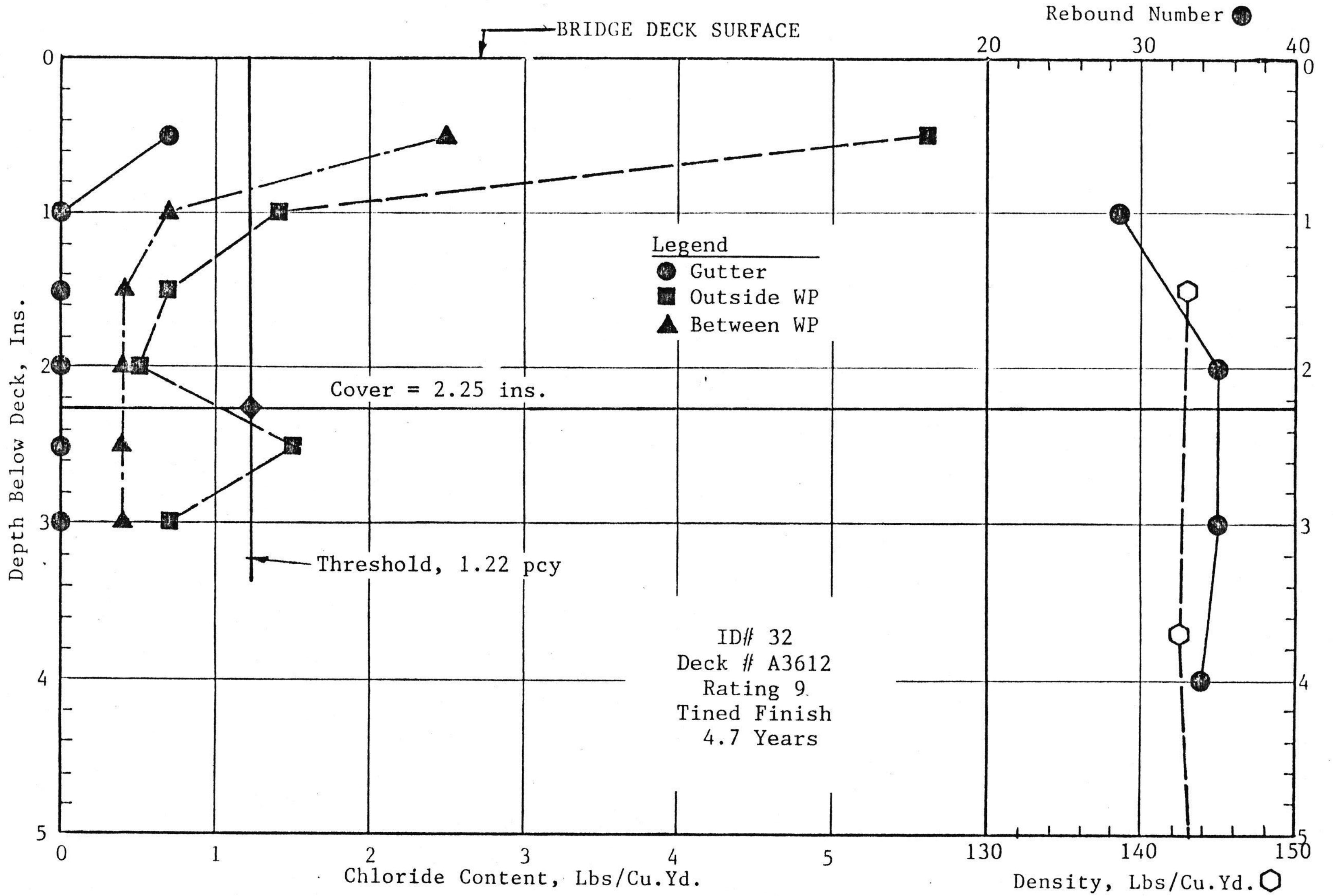

Figure C.32 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A3612

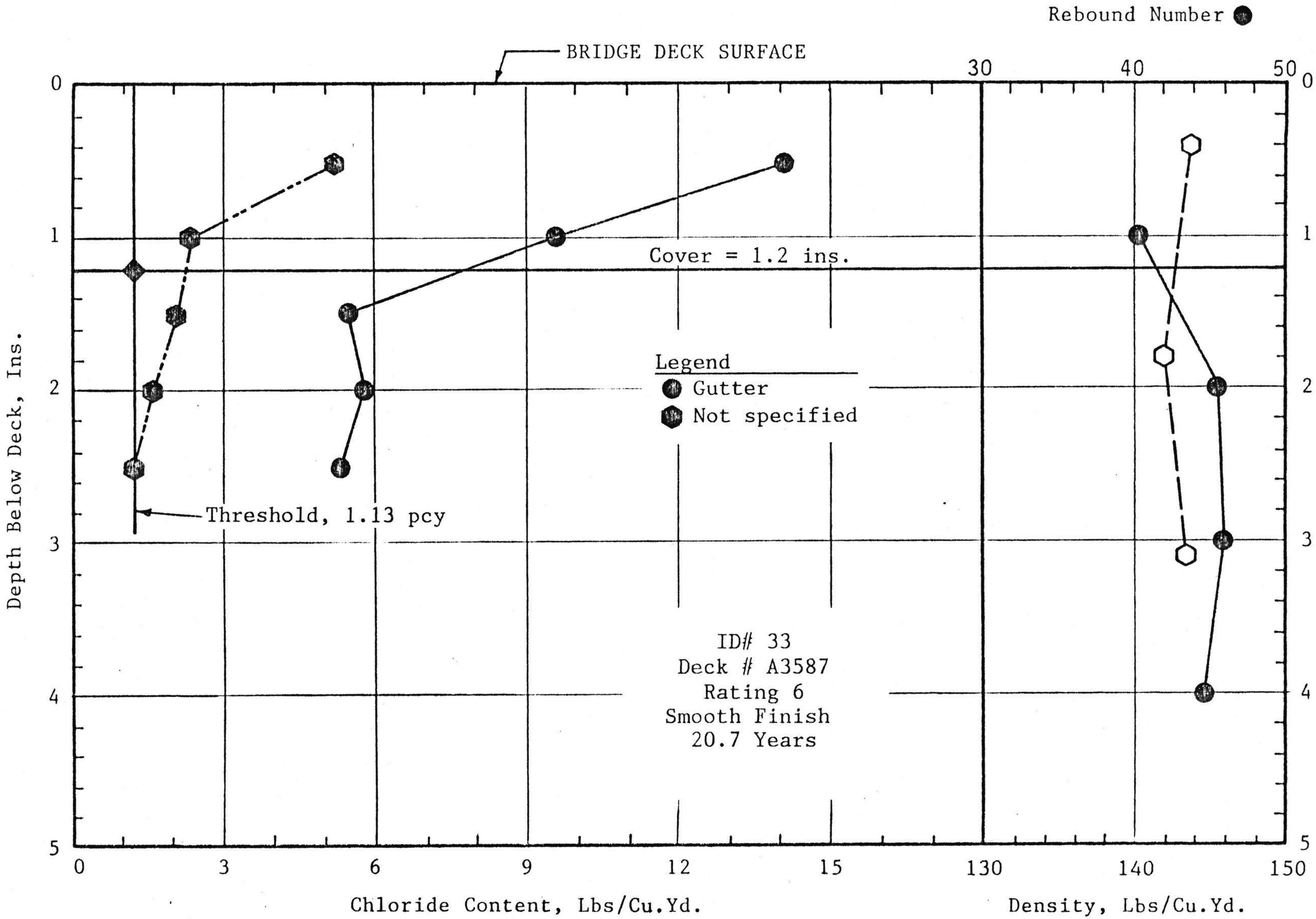

Figure C.33 CHLORIDE CONTENT, DENSITY, AND AVERAGE REBOUND NUMBER VERSUS DEPTH FOR DECK # A3587