REPAIR OF SPALLING BRIDGE DECKS

John C. Kliethermes, Federal Highway Administration

Moisture, humidity, concrete cover, and age coupled with the increasing rate of chloride applications are causing embedded reinforcement steel to corrode and result in an alarming amount of bridge deck spalling. The spalling reduces the riding quality of the bridge and may have an effect on the structural integrity of the structure. The annual national cost associated with the repair is estimated to be approximately $40 million per year. The spalling problem is dealt with throughout the country by using various patching techniques. The permanency, i.e., time to replacement, of these patches has become critical especially in high traffic volume areas. Many patches are failing after relatively short service periods and cause numerous traffic interference problems. This paper discusses several patching techniques that will increase service life. The California Division of Highways through a highway planning and research project developed a nondestructive instrument that will detect corrosion in reinforced concrete structures. This paper also describes how this instrument may be put into operational use. Based on a bridge inventory using this equipment, a deck classification system is proposed that defines the type and extent of repairs that can be made. The classification also permits an administrative evaluation for maintenance and reconstruction scheduling.

•CONCRETE spalling and concrete delamination are generally recognized as the most serious and troublesome kinds of bridge deck deterioration. This deterioration results primarily from corrosion forces that radiate from the embedded steel. The forces normally produce cracks in the deck surface, which spall and ultimately expose the reinforcement. As a result, riding quality is impaired and structural integrity and safety may be severely reduced. It is now known that about 50 percent of the states are faced with a major deck repair or replacement program. The remaining states have not escaped the problem but are effected to a lesser degree.

In November 1971, the Federal Highway Administration (FHWA) completed its demonstration of a corrosion detection device in 46 states. As a result of the demonstration, we made some general observations and noted several trends in bridge deck repair. We have analyzed data collected during the demonstration program and found that the most serious deck spalling can be related to general geographical areas. A definite correlation was noted between salt usage and deck condition. In areas where little or no salt was used, spalling was not evident regardless of the age of the structure. Where structures had been exposed to heavy salting, deck spalling was found to be a serious maintenance problem. We also found that the method of repairing spalls varies from state to state and that numerous membranes and special deck treatments are being evaluated. It was apparent that there was considerable concern and interest in finding a way to control the effects of de-icing chemicals.

Much work has been done to analyze what happens when concrete is exposed to chemicals. Steel in concrete is protected from corrosion by the natural alkalinity of the concrete. This protection is related to the pH factor of the concrete, which is usually between 12 and 13. When sufficient amounts of chlorides are absorbed by the

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concrete, the pH factor will eventually decrease until the concrete can no longer protect the steel. If moisture, oxygen, and chlorides (in sufficient quantities) are present at the level of the steel, corrosion will take place. The result is that as the metal corrodes it will expand and exert an outward force of approximately 4,000 psi, which causes delamination and spalling of concrete.

The corrosion of reinforcing steel is the result of an electrochemical process whereby corrosion cells are created by variable amounts of chloride, oxygen, and moisture along the length of the reinforcement. These cells produce a flow of electric current between two half-cells, the anode and the cathode. The corrosion cells may be minute with the anode and cathode microscopically spaced, such as seen when steel corrodes in air, or they may be spaced several feet, as frequently found in bridge decks. The steel corrosion detection device used in the FHWA demonstrations and developed by the California Division of Highways identified the location of the anode areas by measuring the potential difference between the reinforcement and a reference half-cell. The California laboratory work consisted of placing 200 concrete specimens in a salt solution and recording the voltage change as it occurred with time. From this experiment it was determined that the steel was in a passive stage and not likely to corrode as long as the voltage remained below a 0.3-V level. When the voltage was increased to a level above 0.3 V, the pH factor had been sufficiently reduced to where the reinforcement was no longer protected. This voltage level is considered active, and with proper conditions the corrosion cell will form.

It is of major significance that salt usage has increased approximately 400 percent in the past 5 years. It is anticipated that this trend will continue but at a diminishing rate. Those states that now use little or no salt, where icing or frosting occurs, are beginning to feel public pressures for a bare-pavement policy.

The time to deck deterioration can reasonably be correlated with the increased salt usage and the age of the structure. To date, we have found that, if de-icing salts are extensively used, some structures will spall in 4 to 6 years. Some severe spalling was observed on 8-year old structures. This spalling, however, was generally observed on decks with an early exposure to salt. Many structures in the 20- to 30-year category, which were not exposed to salt until several years after construction, were also observed as showing some deterioration but to a lesser degree.

With a high degree of confidence, it can now be said that most spalling results from the expansive forces associated with corrosion. It can also be said that the predominate cause of corrosion is the salt that is absorbed by the concrete. A cooperative study by the Portland Cement Association and several states identified some of these factors. The study concluded that the percentage of chloride ions in concrete varies with depth, and the deck condition can be related to the percentage of chloride ions at the level of reinforcement. Our work during the past 2 years supports their conclusions. One factor, however, has not been clearly documented: the extent and scope of the problem. In conjunction with our demonstrations we attempted to define the geographical areas that are affected and the cost that is involved. We reviewed research and maintenance reports, corresponded with various state highway departments, and made a geographical spot check to determine the current cost of deck repairs. From this exercise, several things become apparent.

1. Annual maintenance costs do not adequately indicate the scope of the problem. Most states that have a severe problem would spend more if funds were available.
2. Some states have areas of severe deterioration and areas of light or no deterioration. This complicates any attempt to show general affected locations.
3. The scope is changing rapidly. Many states indicate that both the cost and the number of bridges requiring maintenance are increasing.

After evaluating all conditions, we arrived at the following conclusions. The severe, moderate, and light problem locations fall into geographical areas (Fig. 1). There is, of course, no distinct division line, and some overlapping will occur. Based on spot checks within these areas, it was estimated that the national cost of repair for decks in 1971 was more than $40 million.

The challenge of what can be done to keep this cost at a minimum falls into two categories:

1. Establish an effective and permanent repair procedure for existing decks, and
2. Develop a technique that will prevent the problem from reoccurring by a change in new designs.

Extensive research is under way in both areas. This research includes the use of polymers in concrete, protective coatings for reinforcement, and cathodic protection. Many states use or are now considering the use of protective membrane treatments for both new and existing decks. We are, however, finding that the effectiveness of these waterproofing systems over concrete that has been contaminated with chlorides is highly speculative. We are especially concerned with overlays that are porous and that trap chlorides between the overlay and the deck. It is the opinion of many researchers that, once the corrosion cell has started, it will continue, and no corrective treatment, short of total removal, will be totally effective. They further contend that the membrane may provide additional service life, but it should not be considered a totally effective technique.

This paper is devoted primarily to what can be done on existing decks. I will offer some suggested techniques for patching spalled areas and also recommend a deck evaluation program by summarizing data collected with the corrosion detection device.

An informal survey conducted with the demonstrations indicated that a large variety of methods and techniques are being used to patch deteriorating decks. However, we have little confidence in any one method, and, without complete surface or total deck removal, no effective permanent repair method was found.

We found that many patching methods and/or patch materials do not protect the steel against corrosion and may accelerate the rate of deterioration. Because of this acceleration, an elaborate and costly patching procedure may only provide a temporary repair. Accelerated deterioration results from patching materials that are designed for rapid strength gain but that contain additives such as chlorides or other set accelerators that are highly corrosive to steel. The patching materials create strong anodes, and corrosion begins in the patch area soon after placement. The opposite is true when concrete is removed from a spalled area in a salt-contaminated deck and replaced with concrete that does not contain set accelerators. The new patch will be free of chlorides and will create a differential environment corrosion cell. The repaired area will take the position of a strong cathode and create a large potential difference between the patch and the remaining portion of the deck. This potential difference will cause a current flow resulting in accelerated deterioration.

As a result of observing and evaluating deck repairs during the demonstration program, in addition to work done by California State, we are now recommending a procedure for repairing deck spalls, which could produce a more permanent patch.

The first question to be answered is how much concrete area should be removed from around the spall. The maintenance engineer has four general choices: (a) remove only the concrete in the spalled or delaminated area, (b) remove the concrete to clean steel or just beyond the edge of visible corrosion, (c) remove all concrete considered active by an electrical potential survey, or (d) remove the entire deck surface. These limits will vary because of local conditions; however, several factors are now apparent.

1. The spalled area does not represent the total area of corrosion. We found that the corrosion extends beyond the immediate spall; therefore, a patch that merely replaces the spall is surrounded by corrosion and has a high probability of early failure.
2. The excavation, if extended from the spall to blue steel, does not represent the total active steel area. Active readings were found to extend beyond the corrosion limits. The active steel can be associated with the probability that the patch will accelerate corrosion in the remaining portion of the deck or that the patch itself will ultimately fail.

The probability of success can be increased by removing the concrete that surrounds active steel. In many situations, this will require total deck removal. Funding limitations and common practice often restrict this approach. In these situations and where the deck is of acceptable quality (even though active corrosion is suspected throughout

the deck), we believe that a method used by California state to repair bridge piers in a marine environment can be applied to deck patching. Theoretically, the reinforcement bar in the area of the patch can be eliminated from the corrosion circuit.

In order to accomplish this, we had to first remove all of the concrete surrounding the steel where the voltage level is greater than 0.3 V and then apply a uniform coating of epoxy to clean steel in the patch area. The epoxy will break the immediate electrical contact between the concrete and steel. The concrete should be removed to a depth below the steel, which permits uniform distribution of the maximum-sized aggregate. In this manner the epoxy environment electrically isolates the steel, and the remaining deck will act independently of the patch. We also recommend that a bonding agent be used when patching the interface with a concrete coat.

When the corrosion demonstration program was initiated, the principal objective was to explain the theory of the corrosion cell and its relation to concrete spalling and to demonstrate equipment that nondestructively could be used to analyze the corrosive condition of reinforced concrete.

We did not propose a formal operational procedure for the corrosion detection device. Some informal recommendations were made, but this challenge was generally left to the individual users. Based on our observations in some 46 states, we believe that corrosion detection equipment can be used as an operational tool; therefore, we are now recommending a general procedure that can be applied to a local or a statewide area. Little field work has been done based on these recommendations; however, I believe that the concept is sound and that it lays the foundation for further refinements.

We find that spalling bridge decks are in various stages of deterioration. I believe that, by categorizing these stages with readings obtained with the corrosion detection device, an efficient maintenance or rehabilitation program can be developed. By using a classification system, several decisions can be made.

1. The limits of concrete to be removed beyond the spalled area can be determined. As mentioned earlier, we recommend removing all concrete down to a passive level, i.e., less than 0.3 V. This will require an analysis of the readings obtained, which isolates the hot spots and calculates the area to be removed.
2. A decision can be made as to the type of patch and patch material to use. We believe that some patching methods are too elaborate to fit the corrosion condition of a deck; on some decks a more elaborate patching technique may guarantee adequate extended service life.
3. A decision can be made if a membrane is to be placed on the deck after patching. As mentioned earlier, placing an expensive membrane on a deck impregnated with salt and in the advanced stages of deterioration may be highly speculative.
4. An administrative decision can be made that reflects the number and types of decks that can be repaired or rehabilitated as related to the available resources. On some decks it may be economically sound to temporarily repair a deck with minimum traffic interference until resources become available for complete rehabilitation.

The decision to place a deck in a specific category will largely depend on the confidence placed in readings obtained with the corrosion detection device. We have analyzed the readings taken on 120 exposed concrete decks from 33 states. Data from the other states visited during the demonstration program were not included because in several states membranes are routinely used or the data had not been compiled at the time of this writing. The decks were objectively classified during the demonstration program as poor, fair, or good. After classification, readings were taken with the corrosion meter and recorded. We then grouped the maximum readings and established a frequency curve for the various classifications (Fig. 2).

All bridges classified as poor, i.e., spalled and cracked, contained readings that exceeded 0.4 V. For those decks classified as fair, i.e., cracked but not spalled, 90 percent of all readings were less than 0.45 V. For those bridges classified as good, 90 percent of all readings were less than 0.3 V.

This information confirms our original conclusions. Equipotential measurements do provide a good indication of the deck condition. It further signifies that, as the readings increase, the probability of deck spalling also increases.

When this information is considered in conjunction with several other variables, we believe three general condition classifications can be established. Of course, there will be some overlapping, but it does permit an objective approach to evaluating repair needs and methods.

The significant principle for classification should be the percentage of deck area considered active. The amount of cover and the chloride ion content can be used to assess priorities within any classification. These priorities should be subjective and can be coupled with local values, such as traffic, location, and highway classification.

It will be necessary to first take readings on the deck, draft the equipotential contours, and compute the percentage of deck area considered to be in an active stage. Second, sufficient concrete samples should be taken to establish the chloride ion content at the level of steel, and, third, sufficient measurements should be made to establish the depth of cover and the variation in cover.

The first classification should include all decks in an advance stage of deterioration with the following properties.

1. Corrosion readings indicate that active cells exist in from 50 to 100 percent of the deck area.
2. Concrete cover is variable.
3. Core samples indicate that chloride has impregnated a large percentage of the deck area.

A deck in this classification will normally require continual patching. Patching can be considered analogous to a cancer cell that has spread throughout a human body. Some types of corrective treatment may afford additional life, but they should be considered temporary. The common practice of sawing and patching with concrete is expensive, normally requires a traffic lane closure or detour, and, if the patch is incorrectly placed, fails in a short period of time. It is for this reason that we recommend a temporary patch—preferably a cold-mix bituminous patch or some other low-cost material that can be easily placed with a minimum delay to traffic. This type of maintenance will be satisfactory for surface spalls until a complete rehabilitation program can be scheduled. In those areas where spalling has progressed to the point that structural integrity is jeopardized, early patch failures have occasionally been associated with fatigue. In these areas, underbracing may be appropriate to significantly slow down the rate of failure.

We do not recommend placing a waterproof membrane on a deck in this category. An example of a deck in this classification is shown in Figure 3.

The second proposed classification indicates a reduction of active areas and could have the following properties.

1. Corrosion readings indicate that active cells are in 20 to 60 percent of the deck area. The cells can be isolated into hot spots and are surrounded by a substantial area of less than 0.3-V readings.
2. Concrete cover is reasonably uniform.
3. Core samples indicate that chloride is largely found only in spalling areas.

A deck in this classification can be considered appropriate for further evaluation. I recommend that the concrete be removed to a depth below the top mat, patched as recommended earlier, and thereafter periodically evaluated with the corrosion meter. In effect, an attempt should be made to remove the contaminated chloride areas and evaluate the results with the corrosion meter. To place a membrane at the time of patching would be speculative and is not recommended without the evaluation period. An example of a deck in this classification is shown in Figure 4.

The third proposed classification will indicate minor deterioration with properties as follows.

1. Corrosion detection readings indicate active areas ranging up to 25 percent of the deck area. These active hot spots can be isolated and are surrounded by a sizable area of less than 0.3-V readings.

Figure 1. Corrosion of reinforcing steel in highway structures.

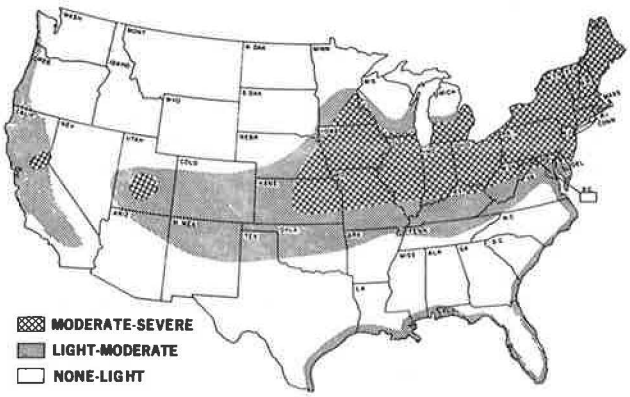
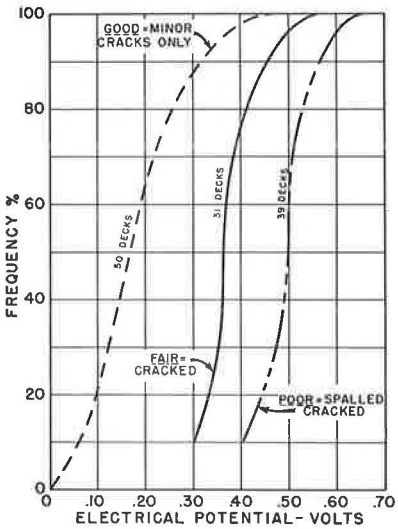
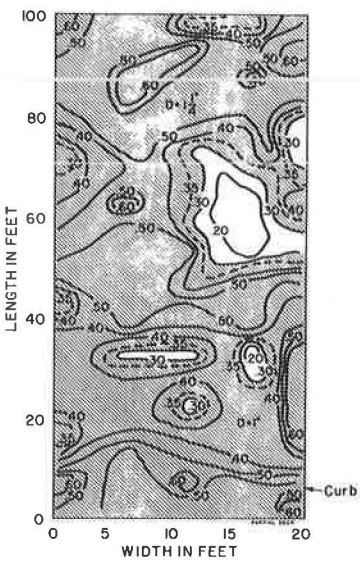


Figure 2. Bridge deck condition classification versus electrical potential.



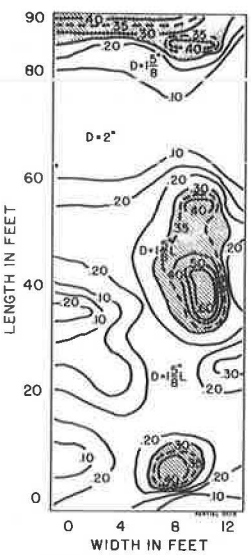
FHWA CORROSION DETECTION DEMONSTRATION 1970-1971
120 EXPOSED DECKS, 33 STATES

Figure 3. Bridge deck condition classification 1.



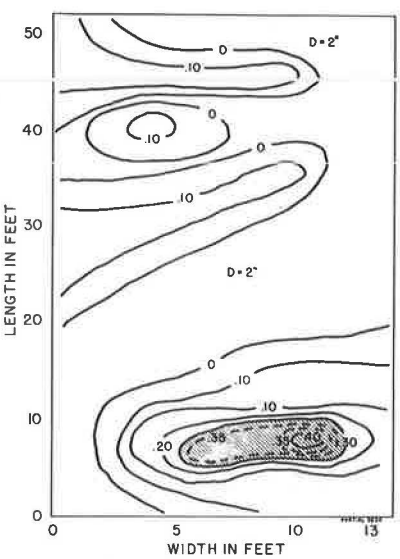
Cover variable
Active area 94%
Chloride Ions - 2#/cu. yd. at level of steel

Figure 4. Bridge deck condition classification 2.



Cover variable
Active area 24%
Chloride Ions varies-1#/cu. yd. at level of steel

Figure 5. Bridge deck condition classification 3.



Cover adequate for present day design
Active area 5.0%
Chloride Ions - Trace

2. The cover is adequate for current design.
3. Deck core samples indicate a minor amount of chloride at isolated hot spots.

A deck in this classification is recommended for a more elaborate patching procedure. All concrete should be removed to a 0.3-V reading or to clean steel and to a depth below the steel, which is adequate to accommodate the maximum aggregate size. The concrete must be replaced with a chloride-free mix. The old concrete and the exposed steel should be coated as explained previously. We believe a membrane can be placed on this deck with satisfactory results. An example of a deck in this classification is shown in Figure 5.

At this time, it is standard practice to do little or no work on a deck in the type 3 classification. Generally, the deck condition is good, few if any spalls are evident, and usually there is no physical evidence of a major problem. However, it is this type of deck where proper patching and a protective membrane may greatly contribute to extending the service life. Most repair efforts are devoted to decks in the type 1 and type 2 categories. In general terms, the patching techniques recommended for categories 2 and 3 are being used for category 1 with unsatisfactory results. The combination of patching and placing a membrane may prove successful, but we do not believe this can be done with bridges in an advanced stage of deterioration.

No repair methods are considered to be foolproof and therefore should be tested under local conditions. For example, removing all concrete down to the 0.3-V level is an approximation of passive steel. Because of the complicated mechanism of the corrosion cell, no exact number will perfectly define the specific location.

In summary, the highway engineer is challenged to provide a transportation facility 24 hours per day, 365 days per year. De-icing salts have proved to be an effective maintenance tool in meeting this challenge. We are now challenged to find an economic solution to what appears to be a costly secondary effect. Bridge deck spalling is not a local problem. All indications are that the affected geographical area will increase in size with a corresponding increase in cost. We are hopeful that research can find preventive techniques.

ACKNOWLEDGMENT

Special recognition is given to James Hall and R. J. Zimmerman, Federal Highway Administration, and R. Stratful, California Division of Highways, for their time and special efforts in the preparation of this report.

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DISCUSSION

S. M. Cardone, Michigan Department of State Highways

The author has given us some excellent guidelines for the repair of spalling bridge decks, which are based primarily on the use of a detection device that in turn is based on the assumption that "deterioration results primarily from corrosion forces that radiate from the embedded steel."

The author is quick to caution, "The background support is admittedly weak, but we think the concept is sound and lays a good foundation to build on." We heartily agree with this statement and want to add that when sufficient empirical data are accumulated the corrosion detecting device can become an excellent tool to assist us in the repair of spalling bridge decks.

However, we should place the importance of this tool in proper perspective. We should realize that the tool merely allows us to predetermine the quantities of concrete that should be removed, which is of value for estimating purposes. It removes the guess in the estimating process for a repair project, but it does nothing to eliminate the causes.

The common practice at the present time is to program the removal of an estimated amount of concrete, with past experience as a guide, and then by mechanical and visual means remove and replace all concrete that appears to be unsound at the time. This is usually followed by the addition of either a water barrier or subseal with a flexible wearing course or a rigid impervious overlayment. This serves to protect both the old and new concrete from further attack.

We have used this technique as a standard procedure for the past 5 or 6 years with remarkable success. As a matter of fact, this procedure got its beginning in Michigan some 15 years ago. We used a structurally bonded overlayment of latex-modified portland cement mortar. This project (6) is in excellent condition to the present day.

I should like to comment on another point given prominence throughout the paper, that the real cause of deck deterioration is de-icing chemicals. Now, no one will deny that chlorides accelerate the corrosive action. But, when the writer states that, "if moisture, oxygen and chlorides (in sufficient quantities) are present at the level of the steel, corrosion will take place," does the writer mean to say that, if only moisture and oxygen are present, corrosion will not take place?

Further, in November 1967 a large bridge, 135 ft wide and 8,770 ft long, consisting of 27 acres of deck was opened to traffic in Detroit. In the nearly 3 years that the deck was under construction, extensive cracking occurred and spalling commenced within the first year of service. This spalling has been progressing at such an accelerated rate in the past 4 years that an extensive repair and overlayment project is being planned for this year estimated to cost in excess of $2 million. An overlayment of latex-modified mortar, which is the system that has given us by far the longest performance, will be used.

Several observations can be made from this special case: Was the spalling that started in less than a year of service due entirely to the action of salt, or did the corrosion start during the construction period when no salt was applied? One might also ask where does the salt come from to rust my garden hoe or the farmer's plow between periods of usage.

At times we are prone to conveniently single out chlorides as the villain in all our deck problems and at the same time assign a lesser role to important items such as water-cement ratio, cement factor, curing, finishing, placement technique, and use of concrete in tension.

In summary, I believe that we have the scientific knowledge today to produce an indestructible concrete bridge deck, but actually very little progress has been made in this direction in the past 15 to 20 years. The author seems to be carried away with his enthusiasm for the steel corrosion detection device, which is nothing more than a maintenance tool.

When we consider the expensive problem described on the Detroit project, it can scarcely be said that a solution to deck spalling is at hand.

Let's get to the heart of the problem. We know that steel rusts even without the presence of salt. We can build bridge decks to keep saltwater and air from hitting the steel. Why this is not done and why bridge steel continues to rust is not the fault of maintenance men or nature; it is the fault of the designers and builders.

Reference

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AUTHOR'S CLOSURE

Cardone has presented a large number of interesting questions about the theory of corrosion and offers several solutions to the spalling problem. I will first address myself to the questions that relate to the theory of corrosion and second to his proposed solutions.

One general statement should be clarified and put into proper perspective. I have made no assumptions about the theory of corrosion or the effects of chlorides on embedded steel. In those cases where spalling is properly identified, research (supported by field conditions) has associated chlorides with corrosion and in turn corrosion with spalling.

The answer is yes in reply to the question "does the writer mean to say that, if only moisture and oxygen are present, corrosion will not take place?" Both field experience and laboratory work show that steel will normally not corrode in concrete unless chloride ions are present. The basic theory is that concrete provides a film of calcium hydroxide that protects the steel from corrosion. This protection is destroyed in the presence of chloride ions. Although this theory is only briefly described in my paper, it is supported by much research and discussed in detail in various publications.

This condition is also closely related to the question, "Where does the salt come from to rust my garden hoe or the farmer's plow between period of usage?"

It is normal to find metals, particularly steel, corroding in air. This supports the fact that the plow and hoe will corrode in the atmosphere because they do not have the protection film provided by cement. In atmospheric corrosion, the cells are microscopically spaced and the corrosion appears as a continuous film. In chloride contaminated concrete, the steel corrodes in a manner that is commonly referred to as macroscopic corrosion, where the corroding area may be spaced several feet from the cathode or noncorroding area.

I am not inferring that steel exposed at a crack is protected by concrete. If cracks or honeycombing are present in the concrete, the atmosphere can penetrate to the exposed steel and normal atmospheric corrosion will occur. In this situation, corrosion will in all probability occur regardless of concrete chloride content. However, if chlorides are present, the corrosion rate loss is considerably higher.

The corrosion detection equipment is principally an application of the galvanic cell. The theory of the galvanic cell is not new, although application of this principle to bridge deck corrosion is relatively new. We now believe that research work has adequately verified the concept of the corrosion detection equipment, and on this basis we demonstrated its potential merit throughout the United States.

I agree that the corrosion cell is a complicated phenomenon. However, after reviewing some 422 bridge decks in 46 states, correlating salting practices with deck conditions, comparing actual deck chloride contents with deck conditions, correlating these facts with readings taken with the detection device, I am convinced that readings obtained with the corrosion detection do indicate the condition of spalling decks and see no merit in collecting additional data to support this conclusion.

I agree that the corrosion detection device does nothing to eliminate the cause of corrosion, and after another review of the paper I cannot visualize drawing that conclusion. It does, as was stated, permit predetermination of concrete quantities to be removed by evaluating both sound and deteriorated areas. It, therefore, follows that the entire deck condition can be evaluated. It is the value of this information that is not recognized in Cardone's discussion.

Comments on the solutions as proposed in Cardone's discussion are given below.

The commercial product referred to in the discussion can and will extend the service life of a deteriorating bridge deck. However, tests of this and numerous other products have resulted in the following observations.

1. Modified latex mortars are not impermeable as indicated in Cardone's discussion. Available information indicates that the performance of these mixes largely parallels the high cement and low water mixes. Laboratory tests now under way support this conclusion. In addition, we have tested nine modified latex mortar field installations in six states. Seven of these decks had active areas of steel corrosion as

indicated by the steel corrosion detection device. This means that sufficient chlorides have penetrated the latex mortar and activated the steel or that the initial cause was not eliminated and corrosion is continuing.

2. Many thin mortar treatments are now applied to scaling decks. Scaling does not result from corrosion. Therefore, we can expect that a good bonding overlay will perform satisfactorily with this type of deterioration.

3. The states of Iowa and Kansas, which use high cement contents in their overlays, are having good success. To date, these overlays have performed somewhat similarly to the latex mortars. This supports my earlier statement that cement is an excellent inhibitor of corrosion.

I interpret the article (6) Cardone discusses as referring to a scaling deck. Perhaps this is the key to his success. Scaling, as you know, is a surface mortar deterioration, commonly found in decks constructed with non-air-entrained concrete, and is not associated with the corrosion of steel. By removing the scaled surface and replacing it with good bonding overlay, the cause of deterioration has largely been eliminated, and the correction should prove successful.

Spalling decks, however, are not as easily corrected. The cause of the problem is the chloride content in the concrete at the depth of the steel, and, unless the concrete is removed to this depth, there is little chance for any overlay to perform satisfactorily.

Cardone also states that the problem with deck deterioration is poor design and construction and that bridges can be built to keep saltwater and air from hitting the steel. I cannot agree with this concept because to date, under the best controlled laboratory conditions, we have not been able to produce impermeable concrete. It is, therefore, impractical to expect that the quality of concrete will be better in construction projects than can be produced in the laboratory. We have, however, identified factors that will extend the time for chlorides to penetrate to the reinforcement. Low water-cement ratios and high cement contents decrease absorption of the concrete. When low-absorption concrete is combined with adequate cover and controls over the indiscriminate use of de-icing chemicals, the service life of a deck should be extended. In fact, in some cases, these extensions can be quite significant; however, oxygen, moisture, and chlorides will eventually penetrate even good-quality concrete. We are, therefore, confronted with time to corrosion, and, because of the many variables, the time factor has not been defined. As in many engineering designs and studies, we may never be able to assign a definite time.

In view of the preceding, it is recommended that our efforts be concentrated in areas where they can be of significant benefit. The following are examples of this type of approach.

1. Recognize construction tolerances; if the deck is located in a heavily salted area, spalling will occur. If the quality of construction is within reasonable limits, additional requirements may only be an exercise in human and equipment capabilities.

2. Recognize the importance of quality materials, mix design, and design cover. These factors may contribute significantly to an extension of service life.

3. Recognize that controls over the indiscriminate use of salt can extend the service life of a deck.

4. Correlate these factors, including salt usage, with the need for deck membranes.