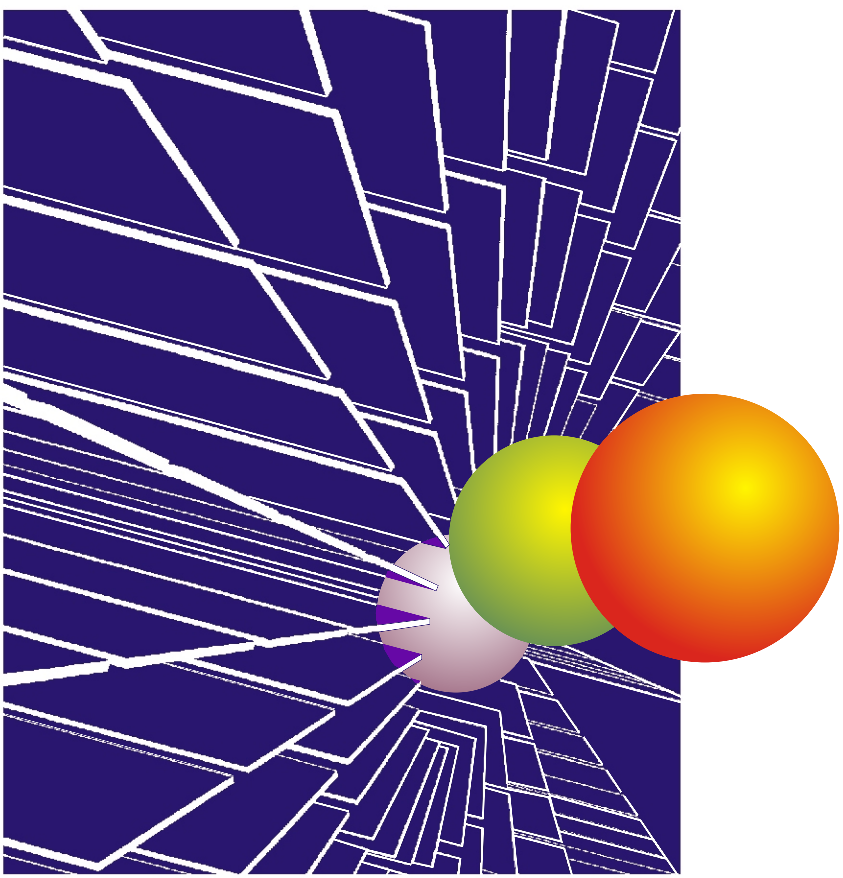
MoDOT

Research, Development and Technology

RDT 03-003

# Evaluation of Stainless Steel Reinforcement Construction Report

RI 00-027



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16. Abstract
Stainless steel reinforcement has greater corrosion resistance than that of the conventional reinforcement. In this project, bridge A6059, the first in Missouri utilizing stainless steel reinforcement in the deck, was constructed, along with bridge A6060, a control bridge using conventional rebars.

An evaluation of the performance of stainless steel reinforcement will be conducted and will focus primarily on the durability and field performance of the stainless steel reinforced deck in comparison to that of the epoxy coated steel reinforced deck. The bridges will be researched utilizing non-destructive tests to monitor salt application and chloride penetration in correlation to presence of (or lack of) corrosion. Fiber optic chloride sensors were incorporated into both bridge decks. Cylinders were taken and tested for chloride permeability, and chloride samples were taken from the cylinders to get a base line chloride content of the concrete. In addition, half-cell potentials were taken and will continue to be taken to determine any corrosion. Maintenance costs will be documented in an effort to determine and compare life-cycle costs.


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Research Investigation 00-27

# Evaluation Of Stainless Steel Reinforcement
# Construction Report

MISSOURI DEPARTMENT OF TRANSPORTATION
RESEARCH, DEVELOPMENT AND TECHNOLOGY BUSINESS UNIT

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# Executive Summary

MoDOT is using innovative materials to design longer lasting reinforced concrete bridge decks. Stainless steel reinforcement has greater corrosion resistance than that of the conventional reinforcement. In this project, bridge A6059, the first in Missouri utilizing stainless steel reinforcement in the deck, was constructed, along with bridge A6060, a control bridge using conventional rebars. Minimization of concrete cracking and spalling results in greater durability, less maintenance and repair, a longer service life, and lower life-cycle costs. The advantages of stainless steel reinforcement will be documented, and any early failure of the epoxy coated rebar will be monitored.

The control bridge A6060 has identical roadway width and girder spacing with bridge A6059, but has different span lengths and skew. The bridges are on the same route with bridge A6060 approximately 600 feet (180 meters) east of A6059. This will allow a good evaluation of the durability and performance of the subject bridge deck in comparison to the conventional deck. The advantages of stainless steel reinforcement will be documented using non-destructive fiber optic chloride sensors, permeability testing, half-cell potentials readings and visual inspection.

An evaluation of the constructability and performance of stainless steel reinforcement was conducted. The bridges will be researched utilizing non-destructive tests to monitor salt application and chloride penetration in correlation to presence of (or lack of) corrosion. Fiber optic chloride sensors were incorporated into both bridge decks, with ten sensors set on each bridge at different horizons.

Cylinders were taken to establish the compressive strength of the concrete for each bridge. Cylinders were also taken and tested for chloride permeability of both bridges according to AASHTO T277. Chloride samples were taken from the cylinders to get a base line chloride content of the concrete. In addition, half-cell potentials were taken and will continue to be taken to determine corrosion rates on the bridge containing stainless steel reinforcement.

Field observations and data collection concerning the condition and performance of each bridge deck will follow construction of the bridges. The fiber optic chloride sensors will be monitored every year for five years to verify any indications.

An interim report documenting current conditions will be prepared at the end of the first five years. Future monitoring and reports will follow as appropriate, with the eventual preparation of a final report discussing and comparing over-all performance and documenting project findings. Any maintenance or rehabilitation costs associated with either bridge deck will be documented throughout the service life of each structure, in an effort to determine and compare life-cycle costs.

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## Evaluation of Stainless Steel Reinforcement, RI00-27

## BACKGROUND

Missouri Department of Transportation, MoDOT, is using innovative materials to design longer lasting reinforced concrete bridge decks. Stainless steel reinforcement has greater corrosion resistance than that of the conventional reinforcement. In this project, bridge A6059, the first in Missouri utilizing stainless steel reinforcement in the deck, was constructed, along with bridge A6060, a control bridge using conventional rebars.

The advantages of stainless steel reinforcement will be documented using non-destructive fiber optic chloride sensors, permeability testing, half-cell potentials readings and visual inspection. The additional benefits of this project will be to test the epoxy coated rebar bridge using AC Impedance from time of construction and to test the use of non-destructive chloride testing. The objective is to monitor any early failure of the epoxy coated rebar. Stainless steel reinforcement has greater corrosion resistance than that of conventional epoxy coated rebar. Minimization of concrete cracking and spalling results in greater durability, less maintenance and repair, a longer service life, and lower life-cycle costs. Alternative methods of reinforcing decks will become more common in Missouri with increasing confidence in these methods.

The control bridge A6060 has identical roadway width and girder spacing with bridge A6059, but has different span lengths and skew. The bridges are on the same route with bridge A6060 approximately 600 feet (180 meters) east of A6059. This will allow a good evaluation of the durability and performance of the subject bridge deck in comparison to the conventional deck.

## BRIDGE DECK CONSTRUCTION

Bridge A6059 was built on MO 6 in Grundy County, about 100 miles northwest of Kansas City.  It was opened to traffic on June 25, 2001. It used a reinforced cast-in-place concrete slab by conventional forming. The control bridge, A6060, was built and opened at the same time. It used precast prestressed panels as permanent structural forms interacting with a reinforced cast-in-place concrete topping between its exterior girders. Conventional forming was used for the overhang of the exterior girders.

Costs for the rebar on this job were $ 1.40/Kg ($ 0.64/lb) for conventional black steel. $1.77/Kg ($ 0.80/lb) for epoxy coated steel (MoDOT's normal bridge deck rebar) and $5.63/Kg ($ 2.55/lb) for the solid stainless steel.  This price makes the cost of solid stainless about 3 times as expensive as Missouri's regular design with epoxy coated rebars and 4 times as expensive as black rebars.  This is well worth it, if it eliminates worry about corrosion problems and potholes caused by corrosion within the service life of the bridge deck (50-100 years). The manufacturer estimates the service life of stainless steel to be 100 years. Additionally the steel industry claims that less expensive alloys of stainless steel with comparable corrosion resistance are on the horizon which would bring the cost of the rebar down considerably from the 3-4 times extra cost.

The only difficulty in placing the stainless steel rebar was at splices to black rebar needed at the solid diaphragms, at the abutment and pier caps. Specifications called for using 1" plastic spacers so there would be no reaction between the two dissimilar metals. The rebar could not be firmly fastened in this way, and the contractor installed additional epoxy coated rebar so that both the black and stainless steel rebar could be attached to the epoxy without touching each other. This problem will be fixed in the next project, described below, in which all the conventional rebar spliced to stainless steel clad rebar will be designed to be epoxy coated.

MoDOT is contracting another bridge deck to be constructed with stainless steel clad rebar which is estimated to cost 1.5 – 1.7 times the cost of black steel. This bridge will be completed in the year 2002.

Figure 1. Stainless Steel Reinforcement of Bridge A6059

## BRIDGE DECK EVALUATION

An evaluation of the performance of stainless steel reinforcement will be conducted and will focus primarily on the durability and field performance of the stainless steel reinforced deck in comparison to that of the epoxy coated steel reinforced deck. The bridges will be researched utilizing non-destructive tests to monitor salt application and chloride penetration in correlation to presence of (or lack of) corrosion. This will require instrumentation of both bridge decks during construction.

Cylinders were taken to establish the compressive strength of the concrete for each bridge. Cylinders were also taken and tested for chloride permeability of both bridges according to AASHTO T277. Chloride samples were taken from the cylinders to get a base line chloride content of the concrete. Fiber optic chloride sensors were incorporated into both the experimental and control bridge decks. In addition, half-cell potentials were taken and will continue to be taken to determine corrosion rates on the bridge containing stainless steel reinforcement and AC Impedance testing on the bridge utilizing epoxy coated reinforcement.

### Installation Of Sensor Housings

In this project, non-destructive fiber optic chloride testing will be performed on both the experimental and control bridge decks. Fiber optic chloride sensors were incorporated into both bridge decks. 20 sensors were set on each bridge at different horizons. Before the sensors were put in, the sensor housings were installed during the deck construction. See Figure 2, 3 for the installation of sensor housings, and Figure 4, 5, 6 and 7 for their horizontal locations and depths. The most popular sensor openings are set at ½”, 1 ½” and 3” (rebar level) from the top of the deck. The sensor housings were literally nailed to the bottom formwork. On bridge A6060, the conventional construction using epoxy rebar, prestressed precast deck panels were used instead of forming. Holes had to be cored to allow installation of four (4) of the chloride sensor housings. After measuring to make sure none of the prestressing strands would be cut, 2" diameter holes were cored in the 4" thick panels. Epoxy glue was used to hold the sensor housings in place. The remaining six (6) sensor housings were set on each side of the bridge where they could be nailed into the conventional forming needed on the overhangs. After the concrete was cured, and formwork was removed, the nails sticking through the bottom PVC cap of the sensor housing protruded from the concrete. With the assistance of ladders to reach the deck bottom, these housing caps were unscrewed on June 28, 2001 to remove the steel and plastic bars which kept concrete out of the throat area of the housings. Since the old caps were damaged during the unscrewing, new caps were screwed back onto the housings.

Figure 2. Sensor Housing Attached to Forms of CIP Deck

Figure 3. Sensor Housing Glued into Deck Panel Core Hole

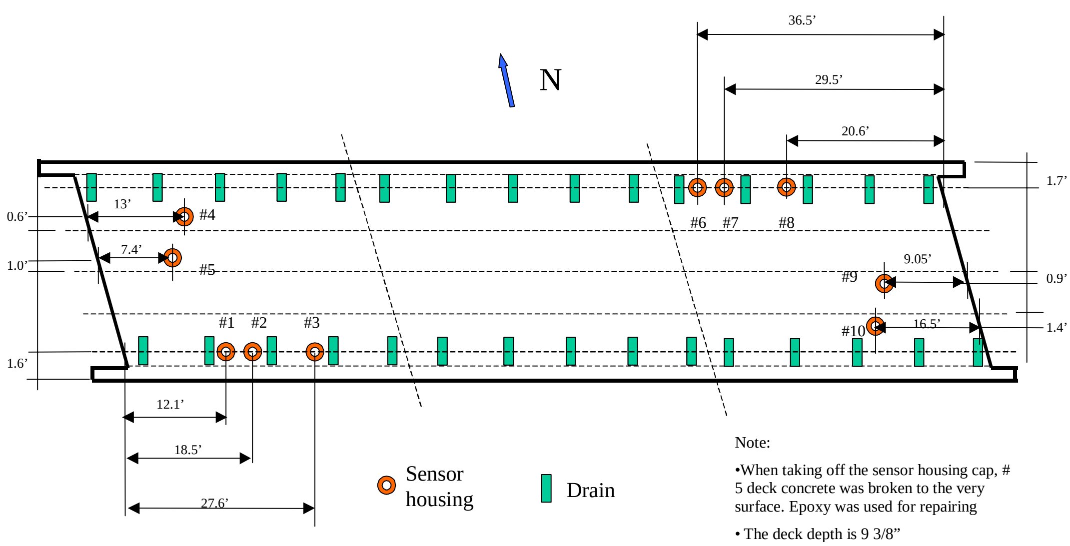


Figure 4. Locations of Sensor Housings of Stainless Steel Bridge A6059

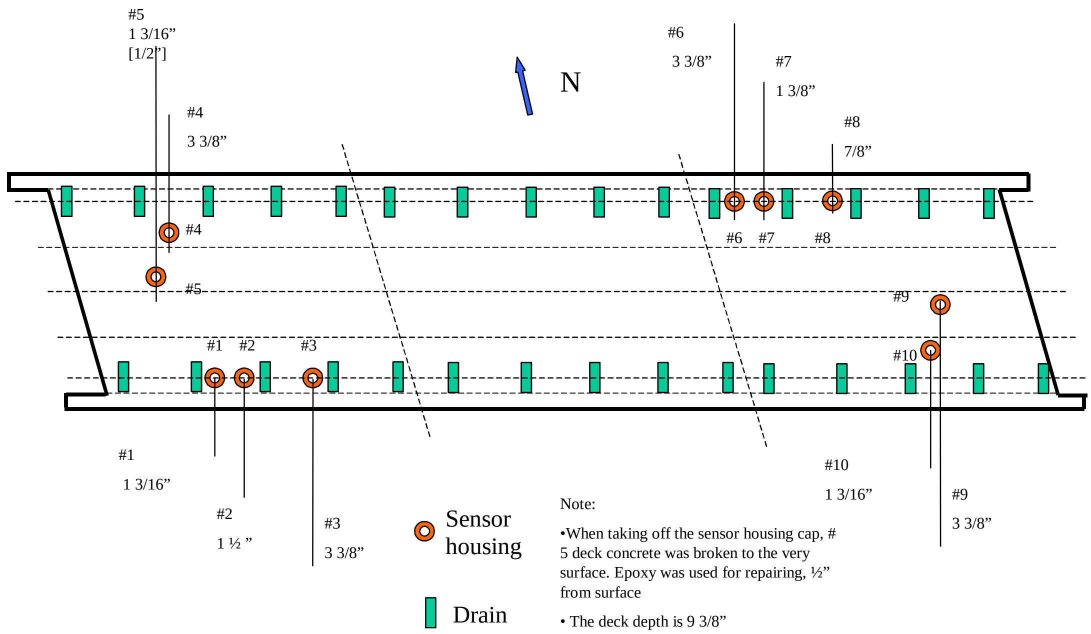


Figure 5. Depths of Sensor Housings of Stainless Steel Bridge A6059

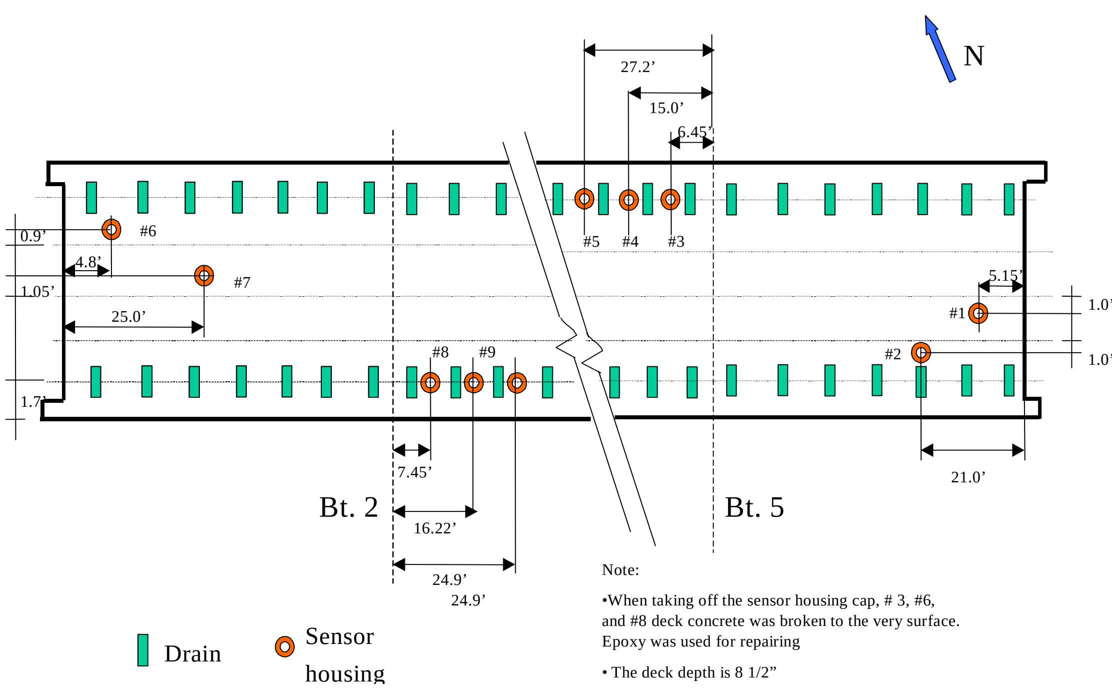


Figure 6. Locations of Sensor Housings of Epoxy Steel Bridge A6060

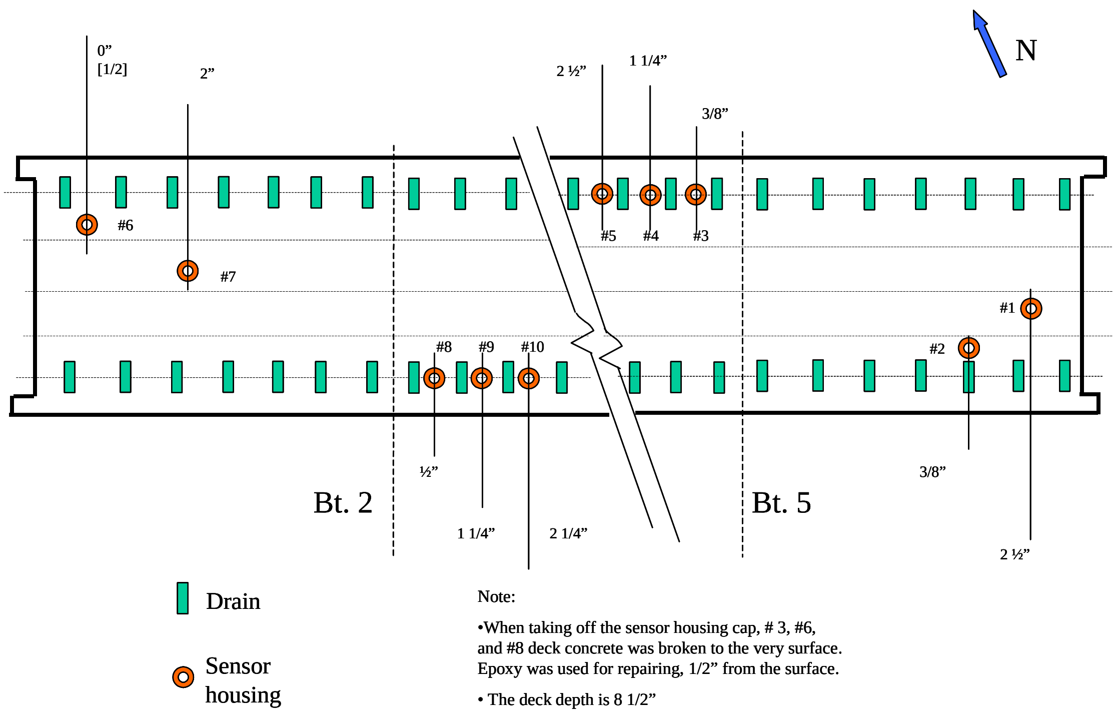


Figure 7. Sensor Housing Depths of Epoxy Bridge A6060

### Installation Of Sensors

The fiber optic chloride sensors are modular units that contain a chemical reagent. When chlorides react with this chemical, the color of a light signal sent through the fiber optic cable changes. This is a one-time reaction; so 20 sensors were set on each bridge at different horizons. The sensor elements are replaceable so the sensors can be revitalized for future readings.

On October 18 and 19, 2001, 20 sensors were installed. The procedure was rather straightforward. The contractor completed the installation with the assistance of RDT personnel. Basically, the sensor-housing cap was unscrewed, and then the chloride sensor was fitted into the module (cleaning the inwards before fitting the sensor if necessary). The sensors were tested to make sure they would function properly before they were coiled up and the sensor housings were resealed. The installation started from stainless steel bridge A6059 and moved to control bridge A6060, and was completed within 4 hours.

The only problem countered was when installing sensor #6 on bridge A6059, it was found out that light came though the top of that sensor housing. Later on a visual check was conducted on the bridge deck. The deck concrete was broken and repaired with epoxy when preparing sensor housings on June 28, 2001. The sand cover on the epoxy patch has been worn off. This spot was repaired on October 30, 2001 during the half-cell potential testing.

Attached as Appendix A for additional information, is Dr. Peter Furh's report on "Development, Testing, Installation of Embedded Fiber Optic Chloride Monitors for the State of Missouri Department of Transportation".

## Continuity Test

In order to use AC impedance testing on the epoxy coated reinforcement, a test grid was set up with 22 bars made electrically continuous and a bar at each end of the bridge left protruding from the side of the deck for an electrical connection. Continuity tests were done on August 17, 2000 before the deck pour and on October 3, 2000 after the deck pour. Resistance readings of each circuit are shown on Figure 6.

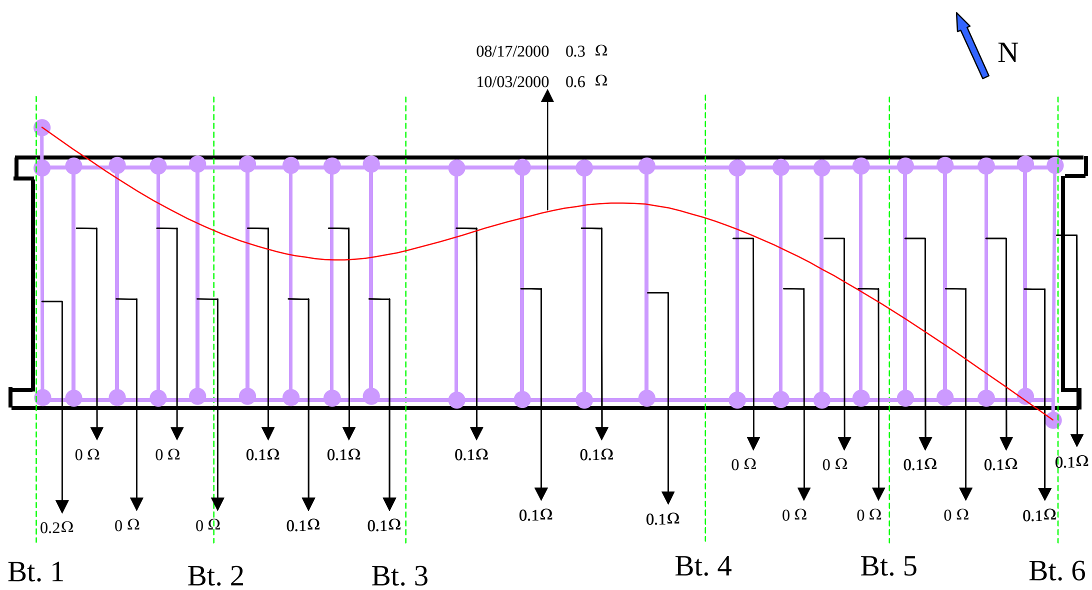


Figure 8. Continuity Test of Bridge A6060

It was decided that AC impedance testing done in the field was not reliable. This is because slight variations in temperature and moisture content of the concrete cannot be controlled closely enough in the field and are critical in the analysis to get meaningful data. As a substitute for AC impedance testing, after five (5) years, cores will be taken through the epoxy rebar. The rebar will be examined and any deterioration will be documented. Samples will be taken from these cores at different levels to determine the chloride content of the concrete.

## Strength, Chloride Content And Permeability Test

Cylinders were tested for chloride permeability of both bridges according to AASHTO T277. Chlorides samples were also taken from cylinders to get base line chloride content. See Table 1 for detailed information.

Table 1. Strength, Chloride Content Test

| Bridge No. | Compressive Strength (psi) | Chloride Content (%) | Chloride Content (Lbs./cy) | Permeability (Coulombs) |
|---|---|---|---|---|
| A6059 | 8,800 (1-year) | 0.005 | 0.2 | 1924 * (1 year) |
| A6060 | 5,556 (28-day) | 0.003 | 0.1 | 1403 * (1 year) |

* Original cylinders were transported quickly when concrete was still in plastic state, and gave erroneous results.

It is normal for new concrete to have up to 0.2 Lbs./cy of chloride content just from the sand and gravel used to make it. Corrosion of uncoated reinforcing steel will begin when the chloride content of the concrete surrounding it reaches 1.5 Lbs./cy. Chloride permeability of the concrete in both decks was found to be between 1000 – 2000 coulombs which is considered low permeability, typical of concrete with a low water-cement ratio (<0.4) such as dense concrete bridge overlay.

## Half-Cell Potential Test

The potential of a corroding metal is very useful in corrosion studies, and it can be readily measured under field conditions. The corrosion potential is measured by determining the voltage difference between a metal immersed in a corrosive environment and an appropriate reference electrode with the help of a voltmeter with a high input impedance. (ASTM C 876) If potentials over an area are more positive than –0.20 volts as compared to a Copper Sulfate Electrode (>-0.20V CSE), there is a greater than 90 % probability that no reinforcing steel corrosion is occurring in that area at the time of measurement. If potentials over an area are in the range of –0.20 to –0.35 V CSE, corrosion activity of the reinforcing steel in that area is uncertain. If potentials over an area are more negative than –0.35 V CSE, there is a greater than 90 % probability that reinforcing steel corrosion is occurring in that area at the time of measurement.

The reference electrode used in this half-cell potential measurement is CSE (Copper-Copper Sulfate Electrode). Measurements on the stainless steel bridge A6059 were taken on October 30, 2001 and the readings can be seen in Table 2 and Table 3. This test is based on regular milled steel reinforcing. The 9.1% tests more negative than –200mv were not expected, but may be because of the stainless alloy, AISI Type 316LN. If a correction factor for this alloy is found it will be added to the results, if not, these readings will still be good for comparison with future readings as they are.

(No half-cell potentials were taken on bridge A6060 since the Reinforcing steel is epoxy coated.)

Table 2. Summary of Half-cell Potential Test Readings - Bridge A6059

| Range | Amount | Percentage |
|---|---|---|
| <-350 mv | 1 | 1.3 |
| >-350 mv, <-200 mv | 6 | 7.8 |
| >-200 mv | 70 | 90.9 |
| No Readings | 3 | |
| Total Tests | 77 | |

Table 3. Half-cell Potential Test Readings (millivolts)

| **Bridge A6059, Survey Direction: W** | | | | |
|---|---|---|---|---|
| **Station (ft.)** | **Offset (ft.)** | | | |
| | 3 | 6 | 9 | 12 |
| 2 | -334 | | | |
| 6 | -255 | -218 | -327 | -371 |
| 10 | -138 | -134 | -232 | -236 |
| 14 | -151 | -147 | -129 | -150 |
| 18 | -114 | -123 | -147 | -104 |
| 22 | -116 | -114 | -96 | -113 |
| 26 | -77 | -108 | -89 | -103 |
| 30 | -84 | -78 | -63 | -91 |
| 34 | -94 | -101 | -79 | -106 |
| 38 | -71 | -76 | -56 | -79 |
| 42 | -62 | -115 | -82 | -73 |
| 46 | -113 | -100 | -67 | -45 |
| 50 | -101 | -158 | -100 | -79 |
| 54 | -76 | -117 | -107 | -126 |
| 58 | -86 | -92 | -106 | -108 |
| 62 | -119 | -114 | -119 | -100 |
| 66 | -79 | -69 | -60 | -85 |
| 70 | -45 | -95 | -46 | -62 |
| 74 | -90 | -83 | -77 | -77 |
| 78 | -105 | -109 | -104 | -94 |

## FUTURE EVALUATION AND MONITORING

Field observations and data collection concerning the condition and performance of each bridge deck will follow construction of the bridges. The fiber optic chloride sensors will be monitored every year for five years to verify any indications.

An interim report documenting current conditions will be prepared at the end of the first five years. Future monitoring and reports will follow as appropriate, with the eventual preparation of a final report discussing and comparing over-all performance and documenting project findings. Any maintenance or rehabilitation costs associated with either bridge deck should also be documented throughout the service life of each structure, in an effort to determine and compare life-cycle costs.

# Appendix A

# Development, Testing of Embedded Fiber Optic Chloride Monitors for the State of Missouri Department of Transportation

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Keywords: chloride sensing, health monitoring, bridges

**ABSTRACT**

Fiber optic sensors rugged enough to be embedded into concrete bridge decks and capable of measuring chloride ion concentrations within such structures have been developed, tested and installed in a pair of bridges in Missouri. When properly embedded into the bridge deck, these non-reversible chemical sensors provide a method of monitoring the gradual increase in chloride ion concentration caused by freeze/thaw cycling and overloaded conditions that may create cracks in the bridge deck surface through which the chloride ions may penetrate into the deck. While not a reversible process, the sensor housing has been designed such that components with different chloride concentration measurement ranges may be exchanged in a field setting once the unit has been embedded into the concrete structure. Details of the sensors, the installation process, and baseline measurements from these instrumented bridges are presented.

# Index

## Part 1. An Overview of Chloride Sensing

Seemingly for as long as there have been roads and ice, there has been an ongoing battle to reduce the dangerous impact that ice has played with vehicular traffic. The 1950's brought on the U.S. "clean roads" policy which led to millions of tons of salt being dumped on roadways and bridges to melt ice and snow (AASHTO, 1976). The salt lowers the melting point of ice, but some of the salt reacts with the water, which transports the chloride into cracks near metal. The rate of corrosion has been strongly linked to the amount of chlorides present (John et al 1992; Babaei and Hawkins 1992). This has led to a steady degradation of reinforced concrete structures exposed to these chlorides. Not everyone agrees on the chronological order of degradation. Some (e.g., Crane 1983) have suggested the following chain of events: (1). Chloride Penetration, (2) Corrosion, and (3) Cracking and spalling (where the expanding corroded rebar has exerted such a force as to dislodge some concrete).

Others (Vaysburd, 1993) have suggested a slightly different ordering: (1). Cracking occurs, (2) Chlorides are introduced via the cracks, (3). Corrosion occurs, causing more cracks...

Regardless of the sequence of events, the ramifications are high in terms of repair of the nation's infrastructure. For instance, in 1992 it was estimated, according to the National Association of Corrosion Engineers, that the total cost of corrosion in terms of structures being replaced, rehabilitation engineering, replacement inspection of structures and/or related efforts was $210,000,000,000 (Fuhr et al, 1995). Another estimate (Wranglen, 1985) is that the cost of metallic corrosion may be $2000-$3000 per person in highly industrialized countries. Some environments accelerate corrosion more than others. It has been widely observed that metals in marine environments corrode faster than metals in other environments (Chandler, 1985). Coastal areas, offshore oil drilling platforms and bridges all exhibit higher rates of corrosion than inland structures.

In addition to the mere economics, there is a safety concern regarding structures with reinforced concrete exposed to harsh, corrosive environments. In order to monitor the safety of structures, periodical inspections are often performed. The American Association of State Highway and Transportation Officials publishes a Manual for Maintenance Inspection of Bridges. Bridge decks, walkways, trusses and barriers are all targeted for corrosion inspection to help ensure the safety of the structure. Similarly, offshore structures such as oilrigs are inspected for corrosion. The corrosion of steel piping systems is susceptible to corrosive attacks that can thin the pipe walls, compromising the integrity of the structure. Because of the relationship between corrosion and safety, methods of monitoring corrosion have received considerable attention.

Nondestructive measurement of parameters within a structure has always proven to be difficult. In the case of chloride penetration of concrete bridge decks the current method of determining chloride concentration is to bore holes (take core samples) of the deck and then perform traditional methods of chemical concentration measurements. Such sampling has inherent limitations including: point sensing, expensive labor intensive, and quite simply being destructive. We have investigated a different approach to determining the level of chloride concentration within reinforced concrete structures. In this method, the virtues of embedded fiber optic sensing are used and married to fiber optic chemical sensing. Although always questionable to the onsite construction crews, fibers are robust, chemically inert and immune from electromagnetic interference (Adams and Henning, 1990). The fact that fibers are durable and chemically inert allows them to be placed in a multitude of environments such as fiberglass, concrete and composites. Within these environments, optical fiber sensors can measure such parameters as vibrations, temperature, strain and magnetic fields (Spirit and O'Mahoney, 1995). Because of the flexibility and durability of fibers, sensors can come in many of configurations and shapes, as the application requires.

In this case, however, it's chemical sensing that we're interested in - specifically detection of chloride ion penetration within the concrete structure. It is generally believed that the chlorides enter into the system (i.e., the bridge deck) through the following chain of events: deicing agents, typically road salts are applied to the surface (in 1995 it was estimated that approximately 7.6 million tons of salt were dumped on roadways and bridges to melt ice and snow (Fuhr et al, 1995)). The salt lowers the melting point of ice, but some of the salt reacts with the $H_2O$, which transports the chloride into cracks near metal. The rate of corrosion has been strongly linked to the amount of chlorides present (Udd, 1991; Vaysburd, 1993; Hime, 1994; Chung, 1994; Pauri et al, 1989) that, in turn, has lead to a steady degradation of reinforced concrete structures exposed to these chlorides.

Corrosion inspection methods typically are based on accelerated laboratory testing and Fick's second law for chloride penetration in concrete (Gareth et al, 1992; Babaei and Hawkins, 1992). Use of such a diffusion law of chloride into a semi-infinite homogenous medium allows the determination of effective diffusion coefficients that generally lie in the $10^{-5}$ $mm^2/s$ range. Analysis of concrete exposed to a "real" environment for extended periods (years) yield surface concentrations that are roughly 10-60 times larger than expected. But at the same time, the actual chloride transport in the concrete specimen is typically 10-60 times smaller (slower) than predicted by Fick's law. Perhaps it is self-healing, carbonation, or even hydration causing this decrease in the diffusion coefficient but whatever the means, it appears to be occurring with respect to the Fick model of chloride transport.

This most obviously does not mean that chloride ion penetration into the concrete does not occur. Rather, it implies that the modeling methods currently used to predict such diffusion are inaccurate.

In consort with the predictions of chloride penetration come established methods of determining resistivity to chloride ion penetration such as ASTM Standard 1202-94. As an alternative to the resistivity measurement techniques, the use of embedded fiber optic chloride sensors allows a nondestructive method of achieving the direct measurement of chloride penetration into the roadway surface.

The measurement technique that serves as the fundamental principle for this reported work is based on analytical chemistry as a means of modulating an optical signal that is transported to/from the sensing region via optical fibers. The fibers are embedded with structural ingress/egress occurring at a location, or locations, predetermined. Determination of the chloride ion level is based on the depth of intensity and/or wavelength variation of the input light signal.

## Part 2. Fiber Optic Chloride Sensors (for Embedding into Concrete)

Optical fibers have migrated from being strictly a research subject, to a practical technology with many new applications emerging. While fibers were initially developed for the communication industry, fiber optic sensor technology is rapidly growing. In fact, the fiber sensor industry has considerable influence in the current development of optical fibers. To date, more than 60 different parameters have been measured using various types of fiber optic sensors (Udd, 1991).

With so many sensing possibilities, attention turned to the development of fiber optic sensors that could be embedded into structures. Within recent years, embedded fiber optic sensors have gone from speculation, to laboratory study (Fuhr et al, 1992; Escobar, Gusmeroli and Martinelli, 1992; Kruschwitz, et al, 1992) to field applications in buildings, dams, and transmission lines [Barbachi and Caussignac, 1996; May, Claus and Murphy, 1992; Measures, 1994; Holst et al, 1992). Bridges, both railway and roadway, have been targeted for structural performance and health monitoring due to their innate susceptibility to large-scale failure.

Chemical fiber optic sensing was originally proposed as one of the candidate mechanisms for measuring corrosion. Within this task an extensive literature review of corrosion, the byproduct, its causes and other suggested solutions, was performed. Once again, while looking specifically for corrosion, what was found was that the presence of chloride seems to be the major predictor to the onset of corrosion. Therefore, if you could not measure corrosion directly, then a principle cause of corrosion should be monitored. This, logically, led to chloride being targeted as the chemical parameter to be sensed. The use of standard, chemical fiber optic sensing techniques was examined to determine if others had already encountered or developed a chloride sensor. While there are many other molecular species detectors, a chloride detector that used optical fibers was not found.

The elements of an extrinsic fiber optic sensors, where the fibers would deliver the light to/from the sensing region, and some form of light modulation would occur at the sensing region were to be coupled into the robust designs found in sensors which have been embedded into structures. In other words, the fibers would serve as light pipes thereby allowing chemical sensing to occur somewhere within the bridge deck.

### 2.A. Chloride Sensing

Chloride may exist in many different forms and, as such, is not easily targetable as a single species for detection. We performed laboratory measurements on different types of chloride detectors. The most promising turned out to be silver nitrate $AgNO_3$ and fluorescein. Aqueous state interactions of fluorescein and chloride were monitored. In this experimental configuration, it was observed that precipitants would fall out of this liquid solution. The precipitants have a very discernible red color associated with them that, once again, allows for standard spectroscopic measurements. This wavelength detection may be practical either as an indicator or as an overall measurement for the detection of chloride.

The net result of this particular facet of chemical fiber optic sensing relies on the fact that there also exists a method to encase this chlorisene into a gel configuration. This “solid” state material is used in a windowing region. In the sensing configuration, broadband light is injected into the fiber. If chloride, in a predetermined concentration, has penetrated through some surface and encountered the fluorescein, it will cause a wavelength shift or a color modulation of that broadband light signal to occur. The wavelength-encoded broadband light is then sensed by a detector, once again via standard spectroscopy. A simple threshold decision regarding the presence of a certain amount of chloride may be made based on the amount of wavelength modulation as well as the depth of intensity modulation of the input light signal.

While certain details of chloride chemical sensors have been reported elsewhere (McPadden, 1997), there arose two methods for optical chloride sensing which were investigated that show potential for eventual implementation in an optical sensor. The fluorescence-based method is the more attractive in that it is reversible. If the problems of immobilization of the chemical reagent could be overcome, it would form the basis of a useful real-time in-site chloride indicator.

The second, absorption-based, method has potential even though based on the irreversible development of a colored precipitate (it is this technique on which this reported sensor is based). A number of chemical sensors based on irreversible colorimetric indicators have been reported in the literature. These are normally based on renewable reagent delivery to a micro-reservoir situated at the tip of a pair of optical fibers. The reagents are normally separated from the measurement medium by a semi-permeable membrane.

### 2.A.1. Reagent Details

Based on the favorable solgel reagent results it becomes prudent to examining physical configurations of a fiber optic sensor to allow it to survive the harsh environment present at a roadway construction site.

Specifically, Fajans Method is a method for determining the amount of chlorine in an unknown sample via analytical chemistry. As the AgNO3 solution is titrated with a chlorine solution, the solution reaches an equivalence point where the number of chloride ions is equal to the number of silver ions. Beyond this point the addition of a small amount of silver nitrate solution allows the number of silver ions to exceed the chloride ions. Here the excess silver ions adsorb to the AgCl surface imparting a net positive charge, attracting the dichloroflouroscein dye. The adsorption of the dye to the silver chloride molecule changes the precipitate to a pink color. At the equivalence point, knowing the sample mass and the amount of silver nitrate solution required to titrate, determining the percentage of chloride ions in the test sample is a matter of calculation.

An embeddable fiber optic chloride sensor is then formed through the use of spectroscopy using fibers for delivery and reception of the light from the sensing unit and Fajans method of chloride analysis. The result is a fiber optic sensor that measures chloride concentration. Such a fiber optic sensor is based on the optical absorption of a broadband input signal through a silver nitrate solution. The sensor head consists of a Nalgene tee chamber into which an indicator solution is placed, a porous membrane on top, and fiber optic leads. Upon introducing this sensor to an aqueous environment containing chloride, the chloride will migrate through the porous membrane to the silver nitrate solution. The chloride ions bond with the silver ions to form silver chloride. There exists an excess of positive silver ions that adsorb onto the silver chloride molecule surface resulting in a net positive charge. Because the indicator, dichloroflouroscein, is an anionic dye, it is attracted to the precipitate resulting in a pink color. As observed in Figure 1, as more chloride passes through the membrane, eventually chloride ions outnumber the silver ions. Chloride ions adsorb onto the surface of the silver chloride molecule resulting in a net negative charge, repelling the dichloroflouroscein indicator. The precipitate, at this point, turns from pink to milky white. It is this shift in color from pink to white that indicates the concentration of chloride has exceeded the concentration of silver, which is known.

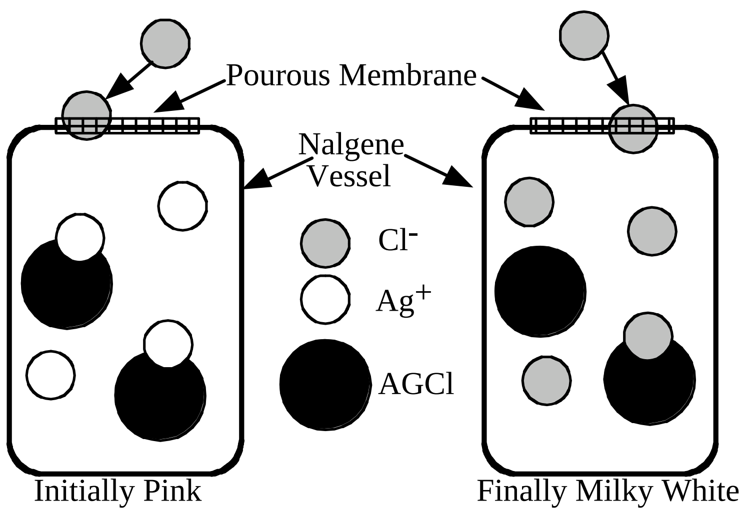


Figure 1. As the chloride ion concentration increases, the adsorption process causes a chemical reaction within the solution that results in a color variation.

<u>2.A.2. Initial Tests Of Chloride Sensing</u>

During the testing of this sensor, the silver chloride precipitate, being more dense than the surrounding solution, fell to the bottom of a Nalgene T-design. The density of the pink molecules was insufficient to alter the input light signal enough for the spectrometer to detect. The signal to noise ratio was too small to discern what was signal, and what was noise. However, while the precipitate did accumulate on the bottom of the sensor in significant amounts, the light signal was not targeting the bottom of the tee specifically.

With this in mind, a modification to this sensor was designed and built. The design objective was to configure the input and output fibers into an arrangement where more light would encounter the color changing molecules (for the chloride ions still migrate through a membrane and react with a silver nitrate solution inside a Nalgene cylinder). The precipitate falls to the bottom where it is illuminated by the input fiber, the reflected signal is sent to the spectrometer. This sensor has the ability to yield two important pieces of information. First, it can sense the simple presence of chloride. Secondly, it can be used as a threshold sensor, able to indicate when the chloride concentration has exceeded a predetermined critical value.

2.A.3. Design Improvements

This original opto-mechanical sensor design was modified in such a way that more light would encounter the color changing molecules. The Nalgene tee was replaced with a cylinder which was filled with a sample solution from a mixture of 6.0 ml of 0.1M $AgNO_3$, 0.2 ml dichloroflouroscein indicator and 0.1g of dextrin. A membrane was placed over the cylinder to keep foreign objects out, such as rocks, dirt and other elements from the concrete slurry mixture, while letting the aqueous chloride ions into the sensing cylinder.

While use of the change in color has proven to be the most reliable, a change in intensity (transmission level) in the reagent mixture also occurs as the chloride concentration threshold level is exceeded. It is possible therefore to simply monitor the throughput of the sensor to ascertain if a chloride induced reaction has occurred. Characteristic information is found by analyzing the intensity levels in terms of the classic Visibility (Imax-Imin/Imax+Imin). The change in reagent color, as recorded by the spectrometer, is a gradual process, not instantaneous.. The visibility for milky white molecules is 0.3447 - a value that is used as a reference point for the molecular reaction. Using this reference point allows the sensor to readily detect a color shift from pink to milky white. This means that the chloride concentration of the solution to which the sensor was introduced, was higher than the silver ion concentration inside the sensor. The silver concentration was 0.1Molar, meaning there was 0.1 Moles of silver per 1000 mL of water. The chloride concentration was saturation, far exceeding 0.1 Moles per 1000 mL of water. The sensor acted consistent with these concentrations.

While effective, and vastly superior to the earlier design, the second design suffered from a mechanical frailty associated with the input and output fibers undergoing a bend outside of a protective region. Therefore, while the chemistry and optical sensing aspects of this design worked well the fiber leads would shear off during construction (probably due to the local concrete aggregate's movement as the concrete mixture was stirred to remove bubbles).

2.A.4. The Final Design for a Robust Fiber Optic Chloride Sensor

Packaging of this "chemistry" has resulted in the field worthy fiber optic sensor shown in

Figure 2. The fibers, reagent chemistry cell, and micro-optics are cast in epoxy into a threaded section that allows this section to be literally screwed into the sensor housing in line with the porous throat's tube section. More details on the sensor design and motivations are presented in the following section.


Figure 2. The final design, suitable for bridge deck installation, is shown.

The components comprising this sensor include a number of custom-machined composite pieces. In certain instances, it has proven to be prudent to injection mold the pieces. The master for these pieces, which include the Nalgene chemical reservoirs, are shown in Figure 3.

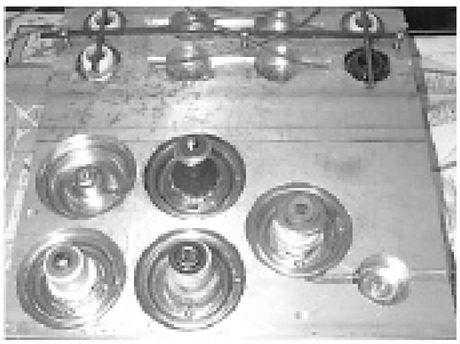


Figure 3. This machined master component allows for multiple chemical reservoirs to be fabricated simultaneously.

One motivation is the relative ease with which the sensors may be damaged or destroyed at the construction site. Field tests have shown that in the case where concrete with added accelerants, for rapid curing, is used, the construction site personnel acknowledge the noninvasive chemistry of PVC into the mixture. Therefore a PVC cylinder with female insert is used for the sensing region housing. Certain components are shown in Figure 4.

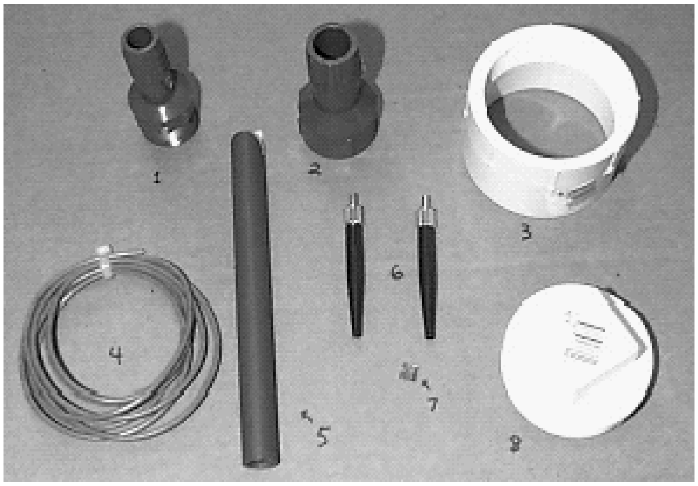



Figure 4. This photo shows a few of the components used in the embeddable sensor.

A detailed view of key aspects within the chloride sensor fabrication phase is shown in Figures 5 through 7.

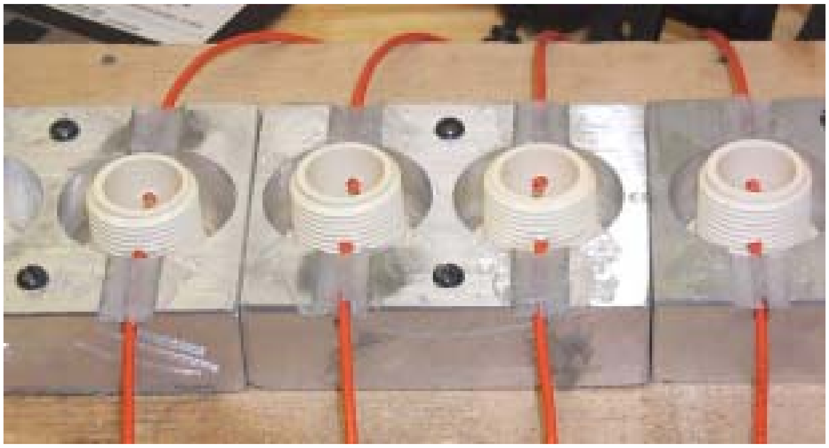


Figure 5. Optical fibers are glued into place and threaded through drilled holes in the PVC screw on cap.

Figure 6. Note that the cap and fiber have been cut. This was achieved using a diamond saw. Into this notch is placed the active chloride sensing element. The fibers act as transmit and receive light pipes.

Figure 7. The transmit/receive fibers coil into the base of the sensor unit.

Referring to Figure 7, the sensor housing, or case, is made of 2" stock PVC. A transparent plastic case top is epoxied to the PVC. Through this top extends a hard plastic tube whose length varies according to the placement requirements of the bridge deck (e.g., if the deck is relatively thin then this tube is shorter than if the deck is considerably thicker). The tube has holes drilled throughout it and a wire mesh covering the tube's top opening (to keep aggregate and other materials out of the sensor). Waterborne chloride enters the tube through any of the openings where it falls to the bottom of the tube. There it interacts with the sensor chloride-sensitive reagent. Once the chloride concentration reaches a certain predetermined level a change in the optical transmission characteristics will occur. For these particular bridges, this "minimum activation level" was chosen to be 1ppm of chloride. This sensitivity level is established prior to sensor installation, and may not be changed once installed, but the entire internal section of the sensor may be replaced with a different section with different chloride threshold sensitivity. Determination if the chloride concentration level has been reached (or exceeded) simply involves injecting broadband light into the fiber and registering the fiber’s output spectrum and overall intensity. If a significant spectral and intensity variation is detected then the chemical interaction of reagent and chloride has caused such a change. Therefore the chloride concentration has met, or exceeded, the predetermined sensor sensitivity level.

## 2.B. ASTM Testing

Testing of the sensors' performance after they were embedded into concrete was conducted following ASTM Standard 1202-94 (chloride ion penetration) and the American Association of State Highway and Transportation Officials “Manual for Maintenance Inspection of Bridges”. A representative chloride ponding test cylinder into which a fiber optic chloride sensor was embedded is shown in Figure 8. By replicating prior ASTM testing methods (McPadden, 1997), results indicated that the embedded fiber optic sensor was able to accurately establish the presence of chloride traveling within this test cylinder.

Figure 8. This test cylinder allows ponding of chloride ions in solution. The ions then propagate through the cylinder eventually reaching the fiber optic chloride sensor.

While details of the chemistry were paramount in developing a working sensor, the optomechanical design emphasized being able to rapidly fabricate reproducible robust sensing components. The proof of the field worthiness of the sensor design came from numerous laboratory based tests where fiber optic chloride sensors were embedded into reinforced concrete test specimens verified the efficacy of minimal impact on the structure while providing a rugged housing for the sensor components.

To reiterate: To date zero failures of these sensors have occurred while being embedded into concrete specimens in the lab or in the field.

## Part 3. The Missouri Bridges

Details of the two bridges located in north-central Missouri on State Highway 6 near Galt, Missouri are to be provided by Missouri Department of Transportation officials. A photograph of the bridges is shown in Figure 9.

Figure 9. View of the twin State Highway 6 bridges located near Galt, Missouri.

## Part 4. Sensor Installations

Fiber optic chloride sensors were embedded into two roadway bridges. The bridges were chosen by the Missouri Department of Transportation as representative bridges which having medium levels of deicing agents applied to them each year. The bridges, shown in Figures 10.a and 10.b, are sequential on State Highway 6 and span Medicine Creek and an adjoining field runoff stream near Galt, Missouri. Each structure was built during 2000 at which time the chloride sensor housings were embedded into the reinforced concrete deck.

Figure 10.a. Photograph of Bridge #1.

Figure 10.b.  Photograph of Bridge #2.

Ten (10) fiber optic chloride sensors, of the type shown in Figure 2, were embedded at various points along the bridge. Missouri Department of Transportation officials performed placement of the chloride sensors in 2000 with the sensor placement heavily influenced by where the drains would be placed on the bridge deck.  Their configuration is such that broadband light is injected into one fiber. At the chloride sensing location, the light must pass through a thin membrane whose transmission properties change with increasing chloride concentration.  The change in amplitude and wavelength for the modulated light is then measured from which the chloride concentration may be determined. Access to these sensors is from the bottom of the bridge deck.

The locations of the fiber optic chloride sensors that have been embedded into both bridges are shown in Figure 10.

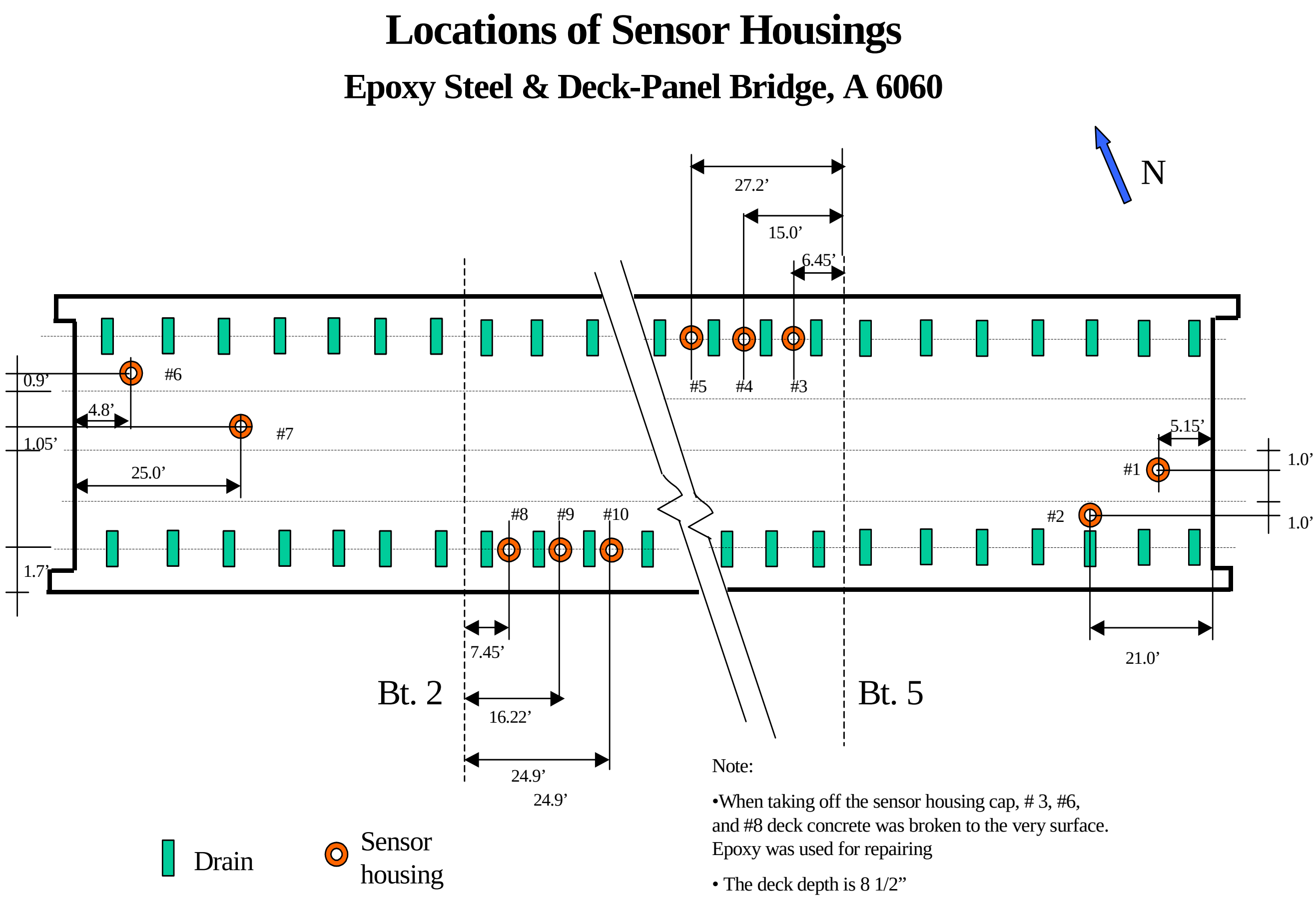



Figure 10.a. Placement of the fiber optic chloride sensors within bridge number A6060.

# Locations of Sensor Housings

## Stainless Steel, A 6059

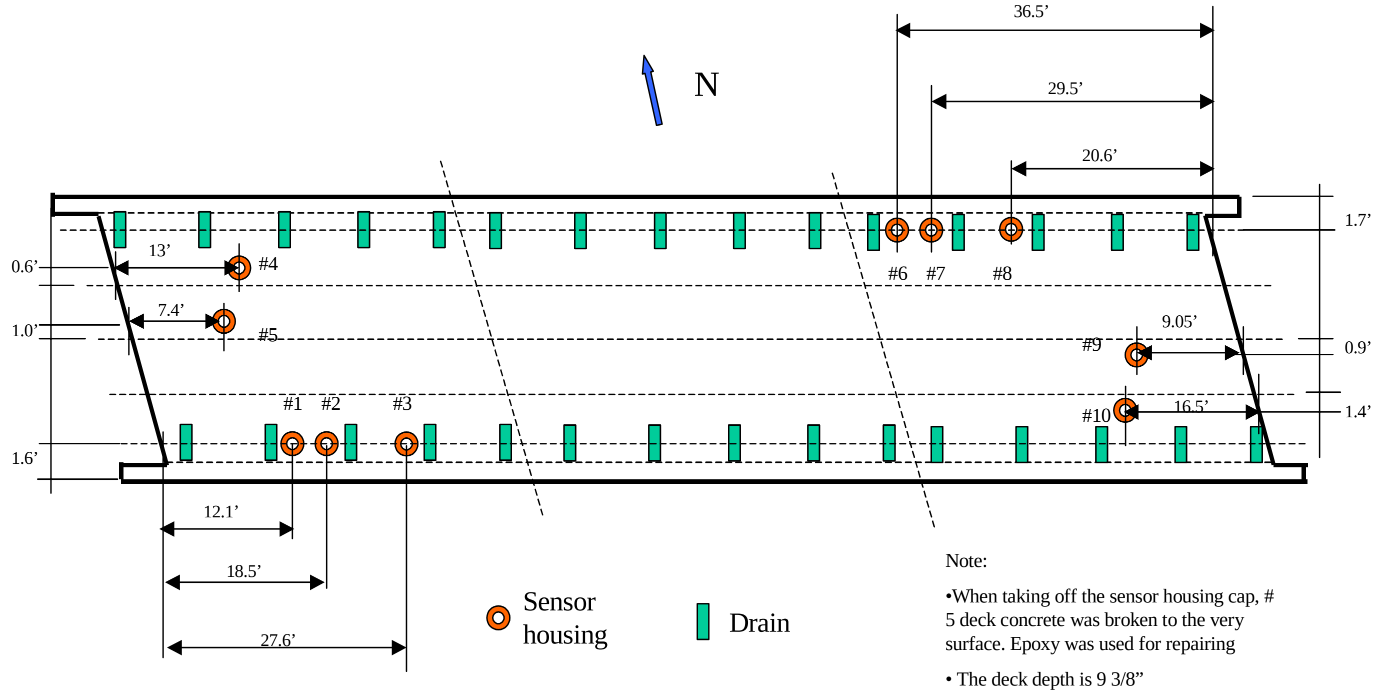
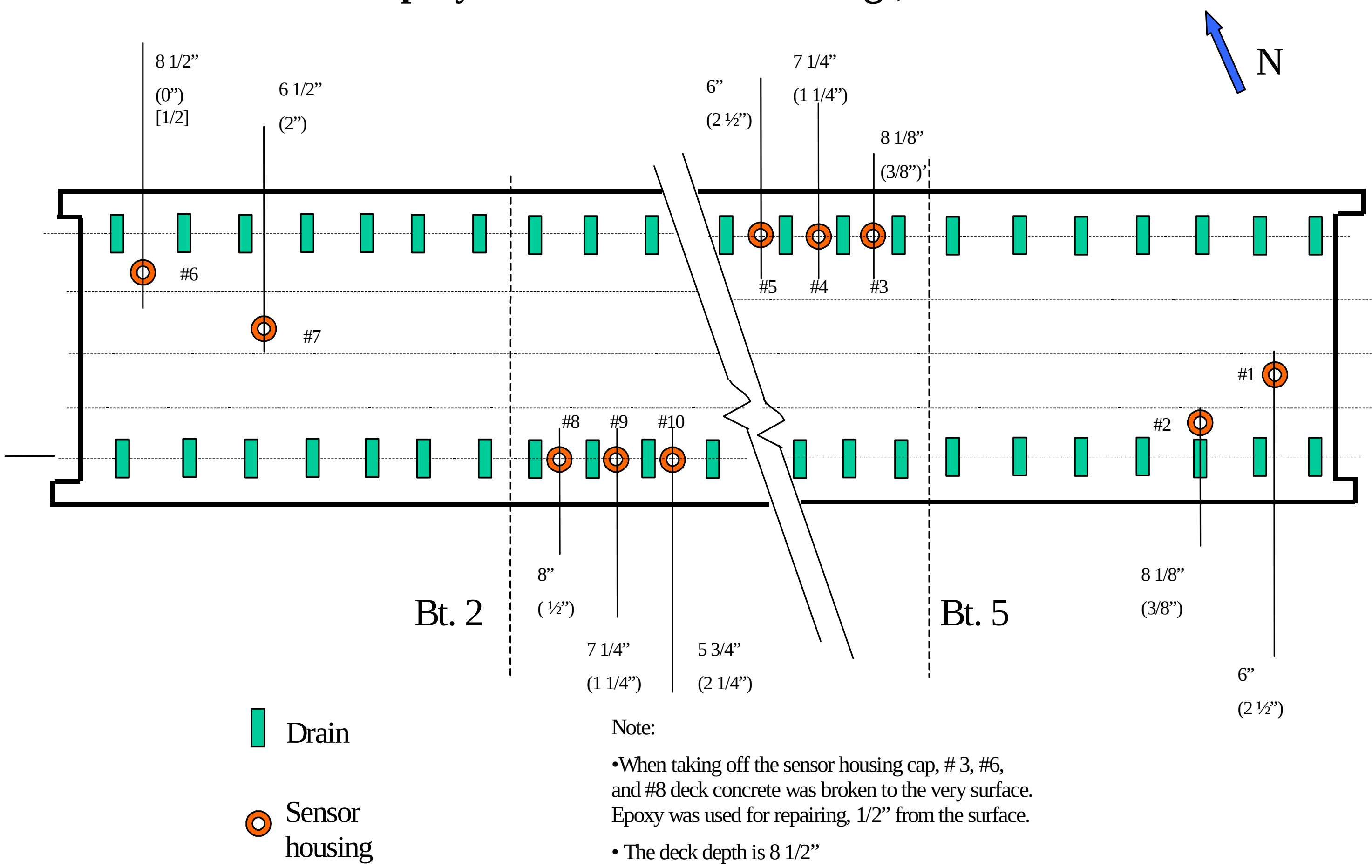



Figure 10.b. Placement of the fiber optic chloride sensors within bridge number A6059.

# Depths of Sensor Housings

## Epoxy Steel & Deck -Panel Bridge, A 6060




Note:

- When taking off the sensor housing cap, # 3, #6, and #8 deck concrete was broken to the very surface. Epoxy was used for repairing, 1/2” from the surface.
- The deck depth is 8 1/2”

Figure 10.c. The depth of each sensor housing throat is shown for bridge number A6060.

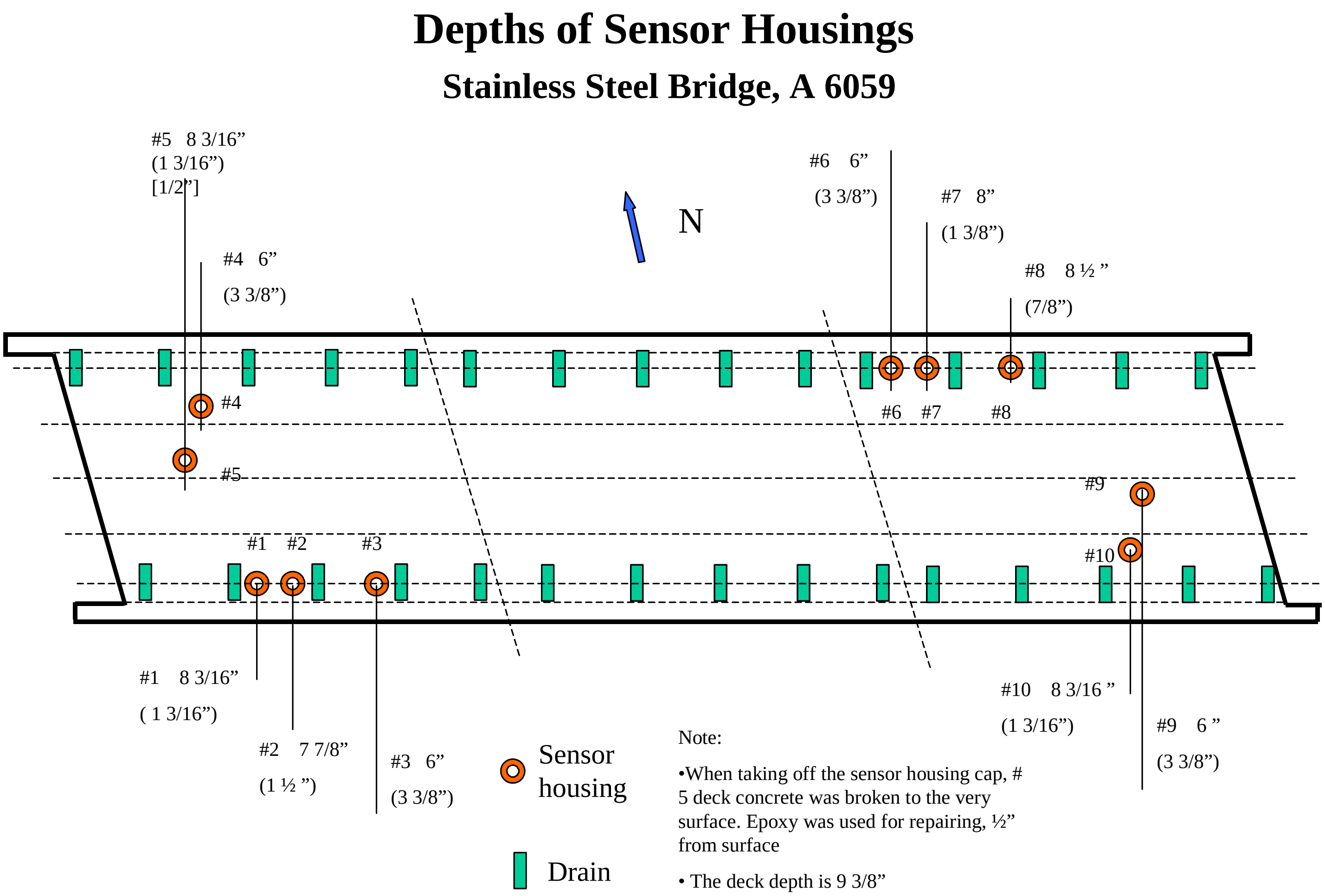



Figure 10.d. The depth of each sensor housing throat is shown for bridge number A6059.

To reiterate, Missouri Department of Transportation employees placed the sensor housings into the twin bridges. Details regarding the installation (e.g., ambient conditions, type of concrete, deck work details, etc) must be obtained from MoDOT. It is envisioned that the sensor housings that were embedded are similar to those shown in Figure 11.

Figure 11.  The length of the sensor housing's throat may be modified.

As previously mentioned, the sensor housings were embedded into the twin bridge decks in 2000.  The actual sensing "inserts" were designed, fabricated and tested during the summer-early Fall of 2001.  As opposed to earlier efforts in fiber optic chloride sensing within concrete structures, the sensors used in these bridges had a true analog varying chloride measurement insert, shown in Figure 12.

Figure 12.  Close-up view of the chloride sensing insert.

Polymer optical fibers, 960 μm diameter, each being 25cm in length had ST fiber optic connectors placed onto their ends (as shown in Figure 13) and served as the ingress/egress to the chloride sensing insert. These fibers were shown in a laboratory setting to have excellent mechanical properties while providing ample light to the sensor insert for an adequate signal-to-noise ratio for chloride sensing.

Figure 13. Multimode 960mm diameter polymer optical fiber with ST connectors is used.

Installation of the chloride sensor inserts was a relatively easy process since access to the housings was achieved via a ladder.

Figure 14. Ladders provided access to the sensor housings.

In most cases, the embedded sensor housing was in a nearly pristine condition (see Figure 15) thereby providing an excellent conduit for the waterborne chloride ions to reach the sensing insert.

Figure 15. View of an exposed sensor housing located in bridge#1.

The view of a sensor insert that has been installed into the sensor housing within the concrete deck of Bridge #1 is shown in Figure 16. The fiber optic leads were then coiled and placed into the housing with a PVC cap screwed onto the housing. This leaves an embedded sensor that is relatively unobtrusive and hopefully not of "interest" to anyone who may wander under either bridge.

Figure 16. A modular design allows for the sensor insert to be simply screwed into the housing.

# Part 5. Measurement Procedure & Baseline Readings

Waterborne chloride enters the tube through any of the openings where it falls to the bottom of the tube. There it interacts with the sensor chloride-sensitive reagent. Once the chloride concentration reaches a certain predetermined level a change in the optical transmission characteristics will occur. For these particular bridges, this "minimum activation level" was chosen to be 1ppm of chloride. This sensitivity level is established prior to sensor installation, and may not be changed once installed, but the entire internal section of the sensor MAY be replaced with a different section with different chloride threshold sensitivity. Determination if the chloride concentration level has been reached (or exceeded) simply involves injecting broadband light into the fiber and registering the fiber's output spectrum and overall intensity. If a significant spectral and intensity variation is detected then the chemical interaction of reagent and chloride has caused such a change. Therefore the chloride concentration has met, or exceeded, the predetermined sensor sensitivity level.

The two types of chloride sensing chemicals used lie within the fluorescent dye family: Lucigenin; 9,9´-Bis(N-methylacridinium nitrate), $C_{28}H_{22}N_4O_6$, MW 510.51 (chemical diagram shown in Figure 17); and, N-(3-sulfopropyl)acridinium, inner salt (SPA), $C_{16}H_{15}NO_3S$, MW 301.36 (chemical diagram shown in Figure 18). These two reagents provide two different sensitivity levels for minimum activation chloride ion concentration.

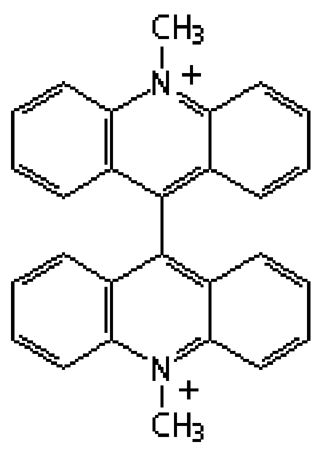



Figure 17. Chemical "schematic" diagram of Lucigenin; 9,9´-Bis(N-methylacridinium nitrate).

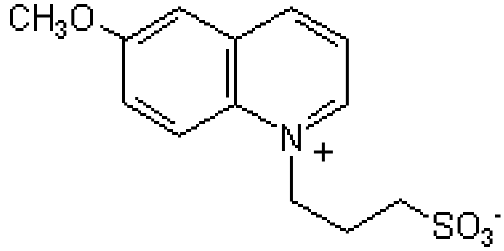


Figure 18. Chemical "schematic" diagram of N-(3-sulfopropyl)acridinium, inner salt (SPA).

The chloride sensor relies on a chemical interaction between the water-transported chloride ions and the reagent that is positioned between input-output fibers (the classic extrinsic fiber optic sensor configuration). When the amount of chloride ions present at the fiber optic sensor reaches a predetermined concentration level, the film’s transmission characteristics will change in terms of color (from milky white to pink to purple) and transmissivity (from 92% to 64%). The chloride concentration sensitivity levels for the sensors embedded into the bridge decks range from ~ 20 mg $Cl^-$/l to over 3000 $Cl^-$/l (activation at approximately 1ppm).

There are immediate and direct limitations in this detector. For instance, the detector collects all of the chloride ions which have reached the extrinsic fiber area. This is not necessarily the same ion concentration as that found in the region surrounding the rebar or even in other positions in the concrete around the sensor. The implications of having a point detector placed within a bridge deck also imply that there are most certainly instances where a crack may provide a direct path for ions to propagate into the deck but completely miss the sensor's "collection region". While in general the size of the porous membrane covering the sensor's throat should be chosen to reject most aggregate from falling into the sensing region, in this project the membrane porosity was not recorded. However, inspection of the sensor housings, just prior to placing the sensor insert in, showed that in approximately 71% of the housings, little foreign matter was present within the internal throat region. In those sensor housings that were epoxied in place (anecdotal information provided by MoDOT personnel), the overall porosity of the installation was not determined (i.e., it was not specifically determined if the epoxy sealed the sensor housing throat region).

**5.A. Measurement Procedure:**

Some of these limitations are accounted for in the sensor calibration process. Following the ASTM measurement guidelines, chloride ion sensing paper, similar to pH indicator paper, was placed at various depths within the ponding test cylinders. In that way the sensing paper would show it's measurement of the ion concentration, with the results compared to those obtained for the fiber optic sensor. Comparison of the two measurements showed agreement to better than 1% across the concentration range of 90 to 2400 mg $Cl^-$/l (which is less than the sensor's dynamic range measured in a direct laboratory setting). In order to achieve these highest concentration levels at depths within the test cylinder, certain cylinders were purposefully cracked.

To reiterate, the measurement procedure entails initially measuring the throughput optical intensity for each sensor. If the level exceeds 0.004μW then there is enough signal to proceed to the spectral analysis. If the optical intensity does not meet this minimum requirement, then the optical test source and detector should be first checked. If the power measurement components are functioning adequately/correctly then the sensor insert should be unscrewed from the housing and visually inspected to see if some piece of the bridge deck (aggregate, dirt) has fallen into the sensor insert. If so, then clean it and reinstall the insert. Spectral measurements involve simply using a broadband spectral source with output wavelengths spanning the visible range from 700nm to 350nm. Specifically, the variation in chloride concentration is a linear relation ranging from 390nm to 450nm. A spectral reading of 390nm implies a chloride concentration of 1ppm; a spectral reading of 450 nm indicates a chloride concentration of 2000ppm. A more detailed description of this transfer function will be provided to MoDOT personnel upon request.

### 5.B. Baseline Readings:

Baseline readings taken during the sensor insert installation were based strictly on intensity. A FOTEC optical source (λ=822nm) and an associated Si photo detector power meter (ST connector adaptor) were connected to the input and output fiber optic leads. The received intensity for identical launched power configurations were recorded. While the actual chloride concentration levels are measured spectroscopically, the spectrometer must have a minimum amount of received optical power. The power transmitted through the twenty (20) installed sensors varied from 0.018μW (min) to 2.881 μW (max). A diagram of each bridge's sensor baseline transmitted power readings is presented as Figure 19a and b. The detection process requires a signal level of at least 0.004μW, thus each sensor passed the minimum power requirements.

Baseline Power Readings for Sensors Embedded into Bridge A6059

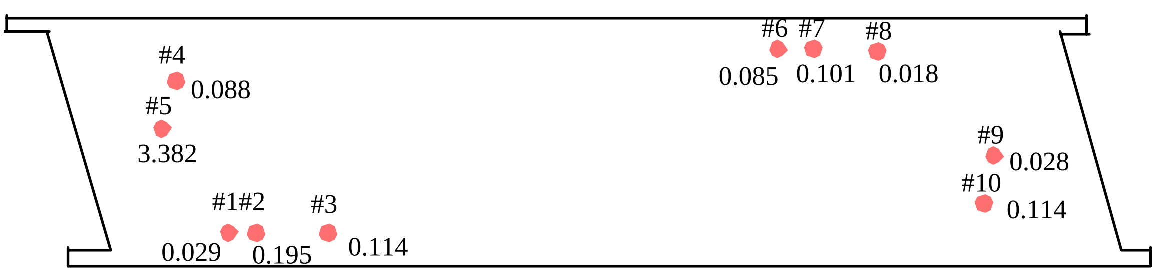



Figure 19.a. Baseline power readings for sensors within bridge A6059.

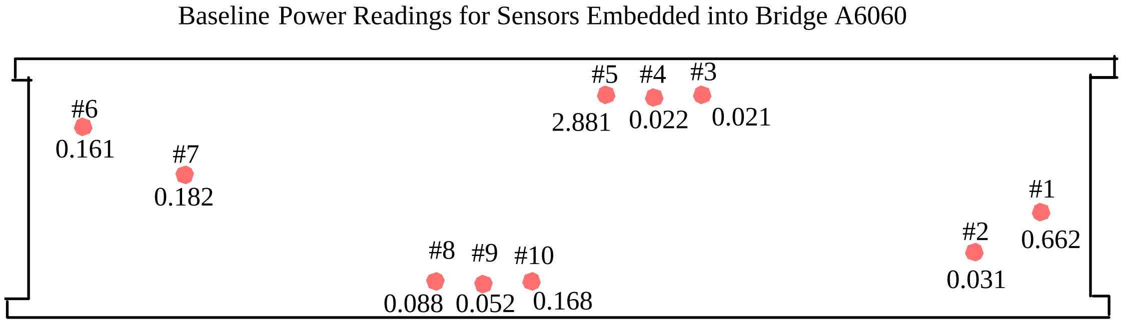



Figure 19.b. Baseline power readings for sensors within bridge A6060.

# Part 6. Summary

Fiber optic chloride sensors were developed, tested, modified, and tested again to achieve the measuring of varying levels of chloride ion concentration. Using chloride sensing chemicals listed in Part 5 as the principle indicating agent, it is possible to measure chloride ion concentrations ranging from 0-500 mg $Cl^-$/l to >3000 mg $Cl^-$/l. The reagent chemistry previously described results in the associated precipitant and color change. These color changes can only occur when the chloride ion concentration has exceeded the “desired” level. This type of sensor is not reusable unless it is disassembled and the active chloride sensing agent, shown in Figure 3, is replaced. The modular design allows for such "sensing caps" with different sensitivity levels to be easily exchanged within the modular unit that has been embedded into the concrete structure.

Interrogation of the sensor is performed spectrally. Therefore the sensing unit must provide and inject broadband light into one arm of the chloride sensor's optical fiber . The light is modulated by the reagent, coupled into the other arm of the fiber and presented to the sensing unit for spectroscopic analysis. While a high resolution (~ 1nm) scanning monochromator (Jarrell-Ash MP3400) has been used in the laboratory, results show that the use of a spectrometer, or color discerning photodiode set (e.g., Sharp PD153 photodiode) capable of discerning 25nm changes in received light is quite adequate to detect threshold changes in the reagent. The 25nm spectral increment in turn has meant that the detector's chloride ion concentration resolution limit is 1% variation (of 3000 $Cl^-$/l).

With this coarser spectral analysis level, it is possible to use less expensive, and portable, spectrometers. A suitable field unit uses an S1000 (Ocean Optics) spectrometer that is connected to a laptop microcomputer (Dell Latitude). The sensing unit's light source is a Broadband White Light Source (Ando Corp.) that is fitted with ST connectors to allow easy connections with the embedded fiber optic sensors. Once access to the sensors has been made (working on the underside of a bridge in mid-January poses special logistical difficulties), it takes approximately 2 minutes to interrogate each chloride sensor and an additional 5 minutes to repack and reseal the sensor housing. As with all longitudinal studies, it is recommended that the sensor readings be time-tagged and recorded for comparison with prior and future readings.

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# Appendix B

# Work Plan
RI00-027

## EVALUATION OF STAINLESS STEEL REINFORCEMENT

July 2000

***Research Agency:***

Bridge, Construction and Research, Development, and Technology (RDT)

***Principal Investigators:***

John Wenzlick, Research and Development Engineer, RDT-*Principal Investigator*
Anika Careaga, Research and Development Assistant, RDT-*Assist Principal Investigator*
Chris Criswell, Structural Special Assignments Engineer, Bridge-*Design Bridge*

***Objective:***

The advantages of stainless steel reinforcement will be documented using non-destructive fiber optic chloride sensors and permeability, half-cell potentials and visual inspections. The additional benefits of this project will be to test the epoxy coated rebar bridge using AC Impedance from time of construction forward and to test the use of non-destructive chloride testing. The objective is to monitor any early failure of the epoxy coating. Stainless steel reinforcement has greater corrosion resistance than that of conventional epoxy-coated rebar. Minimization of concrete cracking and spalling results in greater durability, less maintenance and repair, a longer service life, and lower life cycle costs. Alternative methods of reinforcing decks will become more common in Missouri with increasing confidence in these methods.

***Background and Significance of Work:***

This project will entail the evaluation of a cast-in-place bridge deck using stainless steel reinforcement versus one using conventional epoxy-coated steel reinforcement. Chloride level testing using non-destructive fiber optic chloride sensors will be performed on both the experimental and control bridge decks. This bridge is the first in Missouri to utilize stainless steel reinforcement in the deck, and thus will serve as indication of how alternative methods of reinforcing bridge decks might perform. A similar (identical roadway width and girder spacing but different span lengths and skew) bridge structure using conventional epoxy-coated steel reinforcement in the deck will also be constructed within this project on the same route approximately 180 meters east of the stainless steel reinforced structure. This will allow a good evaluation of the durability and performance of the subject bridge deck in comparison to the conventional deck.

***Action Plan:***

An evaluation of the performance of stainless steel reinforcement will be conducted by RDT and will focus primarily on the durability and field performance of the stainless steel reinforced deck in comparison to that of the epoxy-coated steel reinforced deck. The bridges will be researched utilizing non-destructive tests to monitor salt application and chloride penetration in correlation to presence of (or lack of) corrosion. This will require instrumentation of both bridge decks during construction. Field observations and data collection concerning the condition and performance of each bridge deck will follow construction of the bridges. The fiber optic chloride sensors will be monitored every year for five years to verify any indications.

An initial report will be prepared discussing the construction, including costs, and instrumentation aspects of the bridge decks. An interim report documenting current conditions will be prepared at the end of the first five years. Future monitoring and reports will follow as appropriate, with the eventual preparation of a final report discussing and comparing over-all performance and documenting project findings. Any maintenance or rehabilitation costs associated with either bridge deck should also be documented throughout the service life of each structure, in an effort to determine and compare life-cycle costs.

***Literature Search:***

MoDOT currently has specifications for epoxy-coated reinforcement. A literature and Internet search was also conducted on stainless steel reinforcement and non-destructive fiber optic chloride sensors including research conducted by Peter Fuhr at the University of Vermont, College of Engineering.

***Method of Implementation:***

The results of the evaluation will be included in a final evaluation report as stated in the action plan. This final evaluation report will be prepared after the completion date of the project by the RDT staff engineer responsible for the evaluation. RDT, Bridge and Construction personnel will determine the approval or disapproval of the use of stainless steel reinforcement and non-destructive fiber optic chloride sensors. If stainless steel reinforcement is approved, the bridge design manual will be altered to allow for design using stainless steel reinforcement and the standard construction manual will reflect the change. If the fiber optic chloride sensors are successful, they may be considered as an option for chloride testing when economically feasible.

***Anticipated Benefits:***

Because the stainless steel reinforcement has greater corrosion resistance than that of the conventional reinforcement, concrete cracking and spalling should be minimized. The bridge deck should require less maintenance and repair over a longer service life, producing overall lower life-cycle costs. This bridge is the first in Missouri to utilize stainless steel reinforcement in the deck, and thus will serve as indication of how alternative methods of reinforcing bridge decks might perform.

***Evaluation Period:***

An initial report will be prepared discussing the construction, including costs, and instrumentation aspects of the bridge decks. An interim report documenting current conditions will be prepared at the end of the first five years. Future monitoring and reports will follow as appropriate, with the eventual preparation of a final report discussing and comparing over-all performance and documenting project findings. Any maintenance or rehabilitation costs associated with either bridge deck should also be documented throughout the service life of each structure, in an effort to determine and compare life-cycle costs.

***Potential Funding:***

MoDOT will fund the cost of staffing and the cost of the fiber optic chloride sensors.

***Procedure:***

The stainless steel reinforcement will be evaluated on bridge A6059 and the control bridge using epoxy coated reinforcement will be A6060. The bridges are both on Route 6, Grundy County, Job No. J2P0394 let in December 1999. The prime contractor is Emery Sapp & Sons of Poplar Bluff, Missouri. The resident engineer for this project is James Gillespie.

This project will entail the evaluation of a cast-in-place bridge deck using stainless steel reinforcement versus one using conventional epoxy-coated steel reinforcement. Non-destructive fiber optic chloride testing will be performed on both the experimental and control bridge decks after two years and five years. Fiber optic chloride sensors will be incorporated into both the experimental and control bridge decks. The fiber optic chloride sensors are modular units that contain a chemical reagent. When chlorides react with this chemical, the color of a light signal sent through the fiber optic cable changes. This is a one time reaction so 20 sensors will be set on each bridge at different horizons. The openings of the sensor will be set at either ½ ", 1 ½" or 3" (rebar level) from the top of the deck. The sensor elements are replaceable so the sensors can be revitalized for future readings. Chloride tests using AASHTO T260 will be made to verify the fiber optic chloride sensor indications.

In addition, half-cell potentials will be taken to determine corrosion rates on the bridge containing stainless steel reinforcement and AC Impedance testing on the bridge utilizing epoxy coated reinforcement. In order to use AC impedance testing on the epoxy coated reinforcement, a test grid will be set up with 10 bars made electrically continuous and a bar at each end of the bridge left for an electrical connection. A change order will be needed to set up this grid pattern. Cylinders will be tested for chloride permeability of both bridges according to AASHTO T259. Chloride samples will also be taken from the cylinders to get a base line chloride content.

The field installation, evaluation and cost records will be coordinated with the Construction Division. Peter Fuhr as directed by the engineer will perform installation of the fiber optic chloride sensors. The installation procedure for the fiber optic chloride sensors will be according to the manufacturer's recommendations as agreed to by the engineer. The field-testing will be performed according to approved testing methods as agreed to by the engineer. RDT staff will be present for the installation and document the installation and evaluate results.

***Staffing:***

The anticipated staffing for this project will consist of a construction inspector and two or more RDT personnel. Repair cost records and qualities of salt application for the bridges will be monitored with help from District 2 maintenance.

***Equipment:***

The equipment needed is a half-cell tester, corrosion meter, AC impedance (Wenner soil test meter), drill truck and twenty fiber optic chloride sensors.

***Budget:***

The estimated cost for RDT was determined by using the monthly salary, plus a benefit factor and inflation, of one grade 20 for 2 days, one grade 18 employee for 7 days, one grade 12 employee for 9 days and a bridge crew for 4 days. In addition, the estimated cost of lodging, food and equipment expenses were calculated. The total budget for staffing will be $25,320.44 for testing and reporting.