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# Active Heating Infrared Thermography for Detection of Subsurface Bridge Deck Deterioration

Final Report for Highway IDEA Project 101

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TRANSPORTATION RESEARCH BOARD
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# NCHRP 101 – Active Infrared Thermography for Bridge Deck Evaluation

## FINAL REPORT

October 6, 2004


## EXECUTIVE SUMMARY

This project addresses the development and implementation of an accurate and reliable method for assessment of reinforced concrete bridge decks. The method, based on active infrared thermography, involves briefly heating the deck with high intensity pavement heaters, and then detecting the temperature differentials at delaminations using infrared thermography. Theoretical studies have been conducted showing that detectable differentials can be produced using the output of a standard pavement heater with 5 to 10 seconds of heating application. A 4 foot by 8 foot by 7.25 inch thick laboratory concrete test slab has been built with simulated delaminations incorporated at different locations and depths. Ten-second heating tests have been carried out on this slab using the same type of commercial heating equipment that would be used on a full-scale deck. The infrared data collected on the heated slab showed detectable temperature differentials at the delaminated locations. Thus, the technical feasibility of the active infrared system for bridge decks has been demonstrated. Based on a ten-second heating requirement, a cost analysis of the active infrared method has been carried out vs. conventional chain dragging. The results show that for a standard overpass bridge, active infrared is less than half the cost and occupies the structure for one tenth of the time. The reduced cost and significant impact of the reduced survey time on safety and road users makes this method attractive from and economic and safety perspective. It is recommended that this feasibility study proceed to field evaluation.


## 1. Introduction and Background

### 1.1 Motivation and Objectives

Repair and replacement of deteriorated bridge decks and elevated roadways represents a major expense to many state highway agencies. During the life of a typical bridge the deck is replaced once, and repaired frequently. Deck repair is expensive and highly disruptive to traffic. Bridge deck deterioration is primarily due to corrosion-induced delamination resulting from infiltration of chlorides introduced by winter road salting operations or by a saline environment. Corrosive conditions produce rust on the surface of the steel. This product takes up a greater volume than the original steel and eventually leads to radial cracks from the reinforcing steel that ultimately connects to form a planar "delamination". Growth of the delamination may be exaggerated by freeze-thaw action.

An accurate description of the extent and severity of deck deterioration is required by highway agencies in order to prioritizing and planning and maintenance and rehabilitation. Such a description has been difficult to obtain, since the mechanisms of deterioration occur below the surface, and their manifestations are not readily seen in visual inspections. The lack of reliable condition information has led to the replacement of good quality decks (their "soundness" was revealed during demolition), and to neglect of unsound decks until the resulting potholes and falling concrete require emergency response. Many of the bridge decks that were built during the construction of the interstate system in the 1960's, 70's, and 80's are rapidly reaching their limits, and it is important that highway and bridge agencies and authorities have information about the subsurface conditions of their bridge decks so they can repair or replace the right structure at the right time in the right way (Figure 1).

DELAMINATED BRIDGE DECK SECTION

DAMAGE DETECTED DURING REHABILITATION

Figure 1 – Bridge Deck Issues

Traditional methods for bridge deck assessment, including half-cell potential, chain drag and chloride content testing, are labor intensive and require significant traffic disruption. Newer methods, such as infrared thermography (IRT) and Ground penetrating radar (GPR) can be implemented at higher speeds without standing lane closures and significant traffic disruption.

The current implementation of infrared thermography uses solar radiation to generate thermal differentials between delaminated and sound areas of the deck. The solar radiation heats the deck, and the areas above the delamination are essentially insulated from the remainder of the deck. These delaminated areas heat up faster, and can develop surface temperatures from 1 to 3 °C higher than the surrounding areas when ambient conditions are favorable. These differentials can be detected by an infrared camera, and the detected areas are mapped and quantified.

In practice, solar heating has not proven to be a reliable means for generating the thermal differential required for detection of delaminations. There can be shadows from overhead signs, railings, trees and adjacent buildings. Reliance on solar heat makes data collection location, weather, and season dependent, and can cause delays and compromise data quality. The recently evaluated dual band infrared approach (Del Grande, et. al., 1996), while addressing surface emissivity variations, does not address the unreliability of solar heating.

The proposed active heating IRT method would be more reliable. Active heating would enable IRT surveys to be planned and conducted as scheduled, eliminating the delays and waiting for the right weather or the right time of year. Data collection could be carried out at night, thus eliminating reflected solar radiation and shadows which are a problem for IRT data evaluation. Night-time work would also minimize the impact of traffic control on the traveling public. Active heating would greatly add to the usefulness of the IRT method by making the technique reliable and independent of uncontrollable variables.

## 1.2 Background and Previous Work

Two recent applications of active infrared thermography to civil structures have yielded promising results. Starnes (2002, 2003) evaluated the delamination of fiber reinforced polymer (FRP) wraps on concrete columns and other structures. Due to the relatively small thickness of an FRP wrap (vs. the thickness of concrete cover on a bridge deck), the quantity of heating and the time to reach maximum temperature differentials are much smaller than the bridge deck application. However, the phenomenon is fundamentally the same, and we expect similar behavior with increased magnitudes of time and quantities of heat.

Starnes conducted both theoretical studies and supporting experiments. The reported work has demonstrated how the detectable temperature differentials vary with heating time for a given quantity of heat. The study also shows that after heating, the temperature differential grows to a maximum, and then tapers off. The time at which the temperature differential reaches the maximum also varies with the quantity of heating. An example of Starnes results is shown in Figure 2.

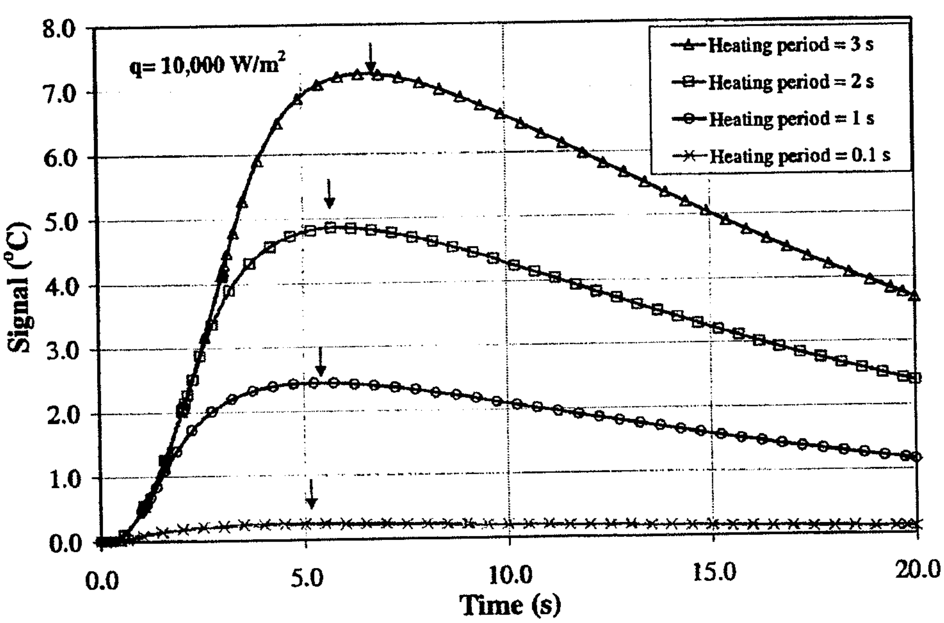



Figure 2 – Temperature Differential vs. Time for FRP Wraps (Sarnes 2002)

A second effort identified in this review is work conducted at Bündesanstalt für Materialforschung und Prüfung (BAM) in Berlin (Wedler, et. al, 2003). The BAM researchers have conducted both experimental and theoretical studies of the use of active infrared for identifying anomalies in concrete. Figure 3 shows the BAM experimental arrangement. The following components are identified in the figure: (1) heater; (2) vertical slab; (3) infrared camera mounted to tripod; and (4) pc and video monitor for data display and processing. For the BAM tests, the heater is moved slowly across the front of the slab at a set rate of motion. The results are observed qualitatively in the infrared image and quantitatively through a thermal analysis of the infrared image. Figure 4 (a) shows the results for a particular test after 8 minutes of heating. The bright spots in the image are associated with artificial voids of different size placed in the slab and at different depths from the surface. Figure 4 (b) shows quantitative measurements of temperature vs. time for one of the anomaly areas. The temperature differential (A-B) between the "hot" spot and the surrounding area is the basis for detection of the anomaly. The time variation of this differential is quite similar to that demonstrated by Sarnes for the FRP wraps. The BAM research also showed that deeper defects appear later in time, and developed a relationship between time of maximum temperature differential and depth.

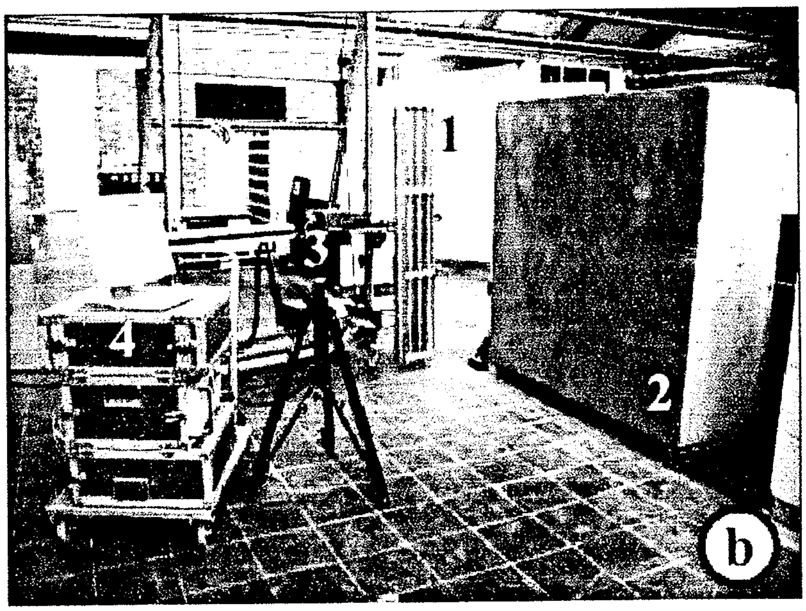
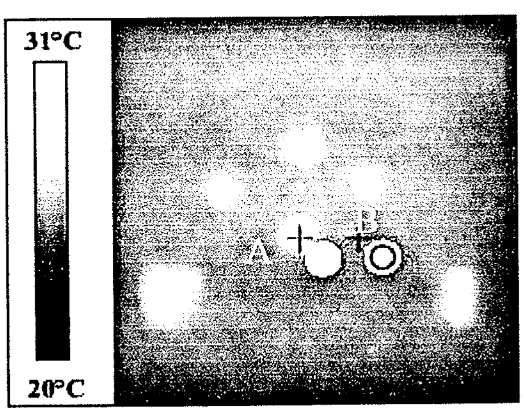



Figure 3 – Concrete Slab Active Heating Test at BAM



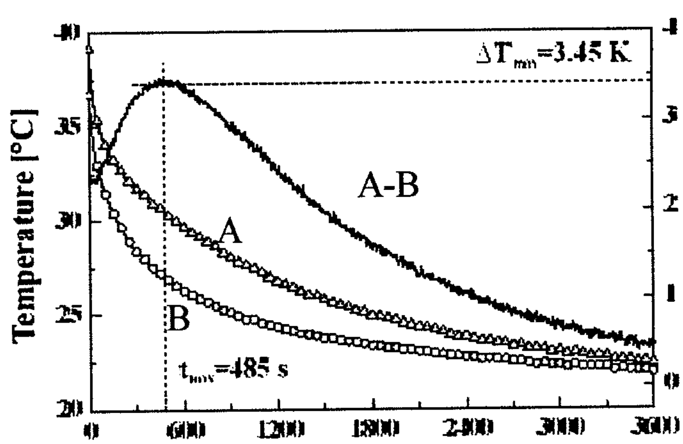




Fig. 4 (a) IR Image 8 Minutes After Heating

Fig. 4 (b) Temperature vs. Time

Figure 4 – Results of Infrared Heating Tests at BAM

Previous work (Maser and Roddis, 1990; Kazzi, 1988) investigated thermal patterns in concrete bridge decks subject to diurnal solar heating. These were one-dimensional transient heat transfer models implemented both with finite difference and finite element methods. These models confirmed that a 1 to 2 °C temperature differential will exist between delaminated and sound deck sections. They also showed the relationship between delamination depth and maximum temperature differential. The findings from these models have been confirmed in field experiments (Maser and Roddis, 1990).

## 1.3 Research Plan

Figure 5 is a schematic of the proposed active infrared bridge deck evaluation system. The system consists of two main units — the pavement heating unit and the infrared measuring unit. The heating unit has a width, w, and will travel at uniform speed, $V_h$ (ft/sec) with pavement heaters delivering heating Q (BTU/ft$^2$/hour) into the deck surface. At some period of time after heating, $\Delta t$ (sec), the measuring vehicle scans the deck surface at speed $V_m$ (ft/sec) with an infrared camera and records the thermal differentials associated with the delaminated concrete. A visual camera with artificial lighting would be included to enable surface stains and other emissivity anomalies to be distinguished from subsurface delamination. The data will be stored on magnetic tapes for processing purposes. To implement the active heating infrared method for bridge deck evaluation, it is necessary to establish the quantity of heating (Q), the rate of movement of the pavement heater ($V_h$) and the time after heating ($\Delta t$) to achieve optimal delamination detection with minimum survey time, and the required width (w) of the heating unit.

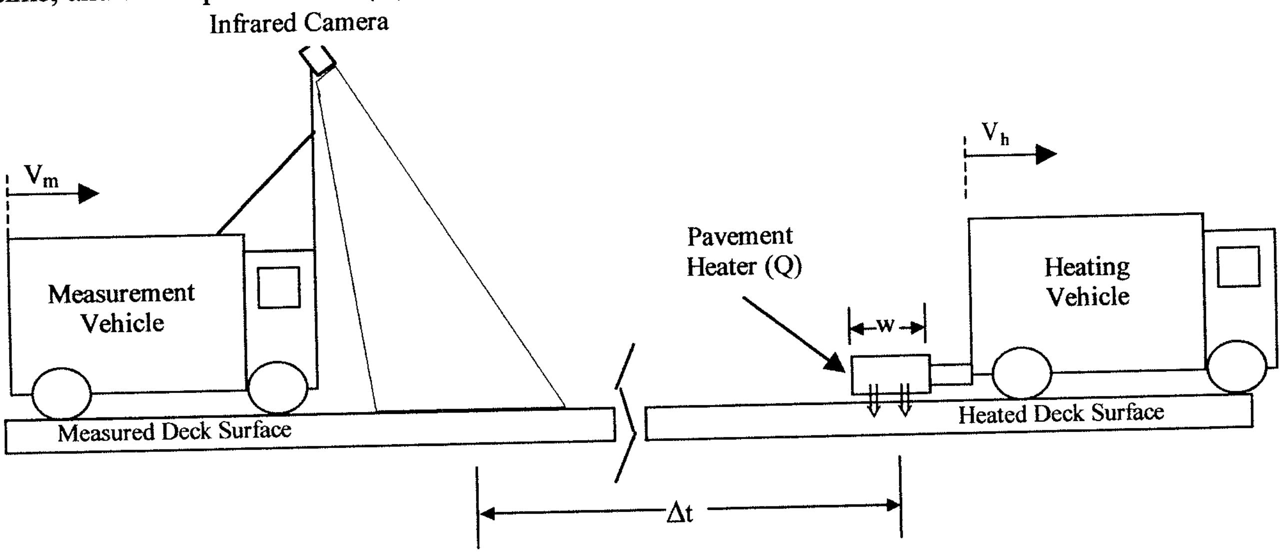



Figure 5 – Schematic of the Active Infrared Thermography Method

The first stage of the research has involved reviewing and evaluating pavement-heating equipment to determine their thermal characteristics and how they could be used on a bridge deck and a test slab. The second stage of the research has included both analytical and laboratory studies. We know that detection of a delamination using an infrared camera requires a temperature difference between the delaminated area and the sound area. One-dimensional thermal models have been set up to represent heat flow in both an intact deck and a delaminated deck. These models have generated data about the expected the surface temperature development and decay over time. These results have been used for order of magnitude estimates for the speed of the heater ($V_h$), to be used in laboratory studies.

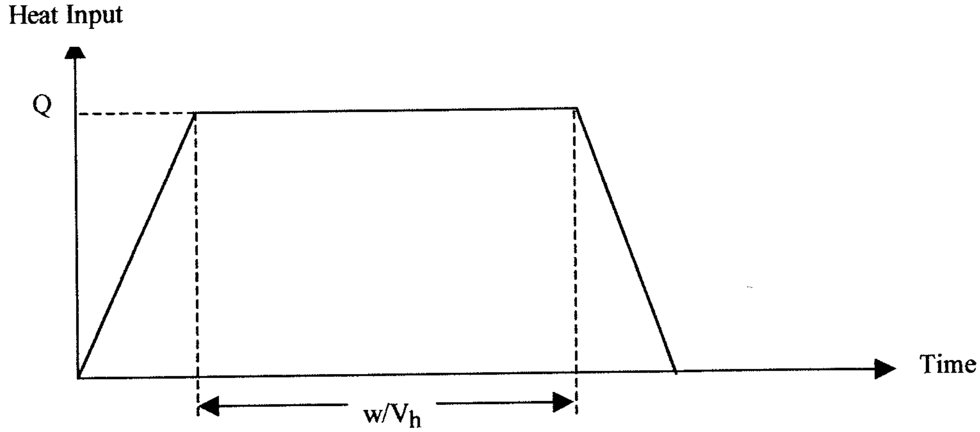



Figure 6 – Thermal Input Applied to Each Element of the Deck Surface

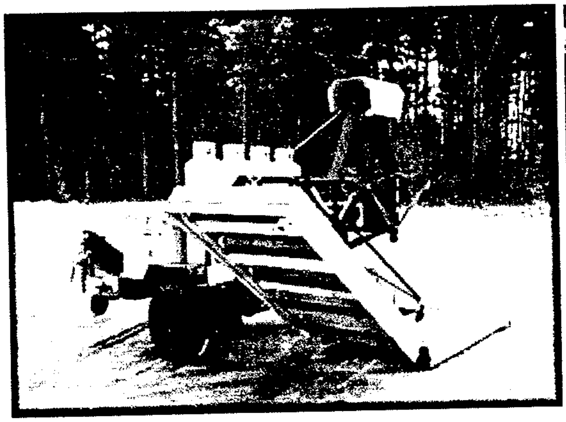
The laboratory studies have employed a concrete slab to simulate a section of a bridge deck. The pavement heater has been moved a fixed rate of speed ($V_h$) over the slab, and the infrared camera has been used to capture the evolution and decay of the thermal differential at the slab surface. The laboratory test slab has been instrumented with embedded thermisters to monitor the temperature change vs. depth as the external heating is applied, which provides more confirmation of the thermal properties of a concrete slab. In addition, the test slab has been tested using sounding methods to see how mechanical methods of delamination detection compare with infrared methods.

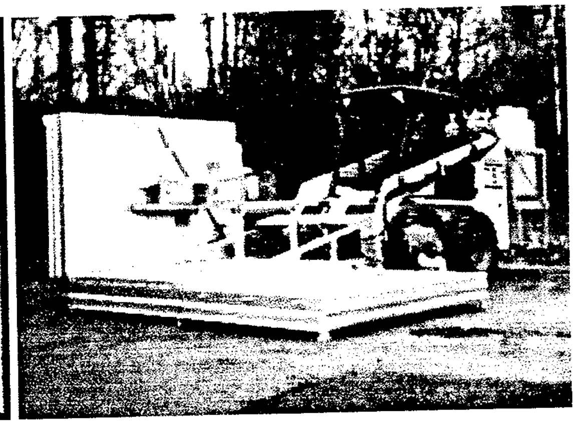
## 2. Review and Evaluation of Pavement Heating Equipment

A review of commercial highway heating equipment was conducted. Ray-Tech Infrared Corporation of Charlestown, NH was identified as having a line of pavement heaters that could potentially be utilized to heat bridge decks. Other manufacturers exist (eg., Kasi of Colts Neck, New Jersey), and their equipment is fundamentally similar.

The heat output for the pavement heaters is 9,000 BTU/sf hr. The amount of heat applied to the pavement can be controlled by the amount of time the pavement is exposed to the heater. In standard asphalt repair applications, asphalt temperatures will reach 300 °F after about 6-8 minutes exposure to these heaters. This is an increase in temperature of approximately 130 °C, which is more than is necessary for active infrared thermography. For the active infrared method, we anticipate a shorter exposure time, making it more economical.

The amount of heat applied can also be controlled by the element size (surface area) of the heaters. The ideal heater for bridge deck infrared thermograph work would heat an area 13 feet wide (or cover a lane), which is the same width covered by the infrared camera. The evolution of the temperature differential would be uniform across the lane, and the infrared camera could record the thermal differential with one pass per lane.





(a) 3 ft. x 13 ft. ("Tech-36") (b) 6 ft. x 13 ft. ("Triple-Tech 78")

Figure 7 – Pavement Heating Units

Two pavement heaters identified in the review meet the above criterion. The "Tech-36" shown in Figure 7a has two 3 ft x 6 ft 6 inch chambers that lower individually to the pavement joining at the center to form a single 3 ft x 13 ft heating area. Premixed gas and air are delivered under pressure to energy converters, where the IR radiation is created. Convection heat loss is minimized by the use of louvers around the perimeter. Fuel is delivered by four 100 lb propane cylinders mounted on unit and held in place by heavy-duty steel tank holders. The unit consumes 16 lbs of fuel per hour and can operate continuously for 25 hours. The heating chambers are attached to a single axle trailer that is designed to be towed.

The "Triple-Tech 78" (Figure 7b) also has a 13 ft wide heating area. It has three chambers 6 ft x 4 ft 4 inches and that form a 6 ft x 13 ft heating area. The heater is similar to the Tech 36 in its operation, associated fuel delivery and operating control systems, but has more heating elements. The heating chambers are attached to a skid-steer loader (such as a Bobcat®), which makes it more maneuverable.

The research team made a site visit to the Ray-Tech pavement heater manufacturing facility. During this visit, a heater with one 4 ft x 4 ft chamber (Figure 8) was demonstrated. Infrared images of the heated concrete floor of the RayTech facility were obtained and evaluated for temperature variation vs. time. The analytic study is described in Section 3.

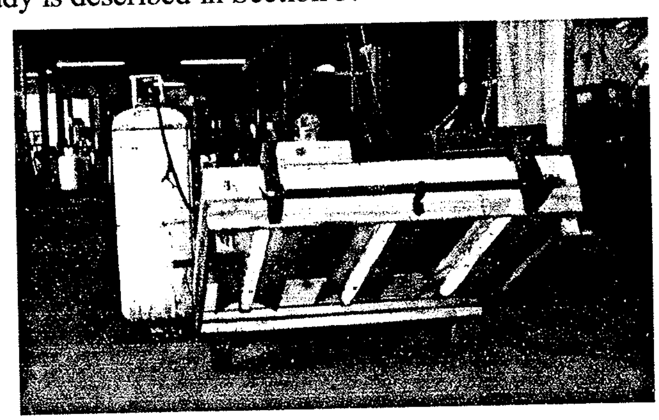


Figure 8 –"Mini-Tech" Heater Used for Laboratory Testing

## 3. Analytic Studies

Analytic heat conduction models for a heated concrete slab were developed. The thermal models described in this report are based on closed form solutions from Carslaw and Jaeger, *"Conduction of Heat in Solids"*, Second Edition. The model is of a one-dimensional concrete slab (wide enough in both directions that the only significant heat flow is in the thickness dimension). The surface temperature vs. time is calculated for an intact slab and a delaminated slab, and then the differences are calculated. This calculated difference is what would be detected with the infrared camera. The slab thickness, *l*, has been taken as 8 inches. The delamination has been modeled as a thin slab (*l* =2") where heat cannot be transmitted from the bottom (representing the insulating effect of the delamination). The effect of the pavement heater has been modeled as a short duration pulse of constant heating, Q. The value of Q, set at 9000 BTU/sf hr, is equal to the output of the pavement heaters. Other thermal parameters used in the analysis are shown in Appendix A.

The solution for both sound and delaminated slab has been developed from the superposition of two steps: (1) heating, and (2) cooling and conduction, as shown in Figure 9. The first solution is that for a slab heated by Q for $T_{heat}$ seconds. This can be found in Carslaw and Jaeger, Section 3.8, page 112, equation (3). The second part is the solution is for an unheated slab with an initial temperature distribution (defined by the solution of the first part). This solution can be found in the same reference, Section 3.10, page 120, equation (8). In the second part, heat transfer is allowed at the top surface but not at the bottom surface. This boundary condition is reasonable for an air filled delamination, since the air gap impedes the transfer of heat to the remainder of the slab. For the intact slab, this assumption is not really correct. However, the heat transfer boundary condition at the bottom of the intact slab is unlikely to have much of an effect, since there is negligible temperature rise at the slab bottom.

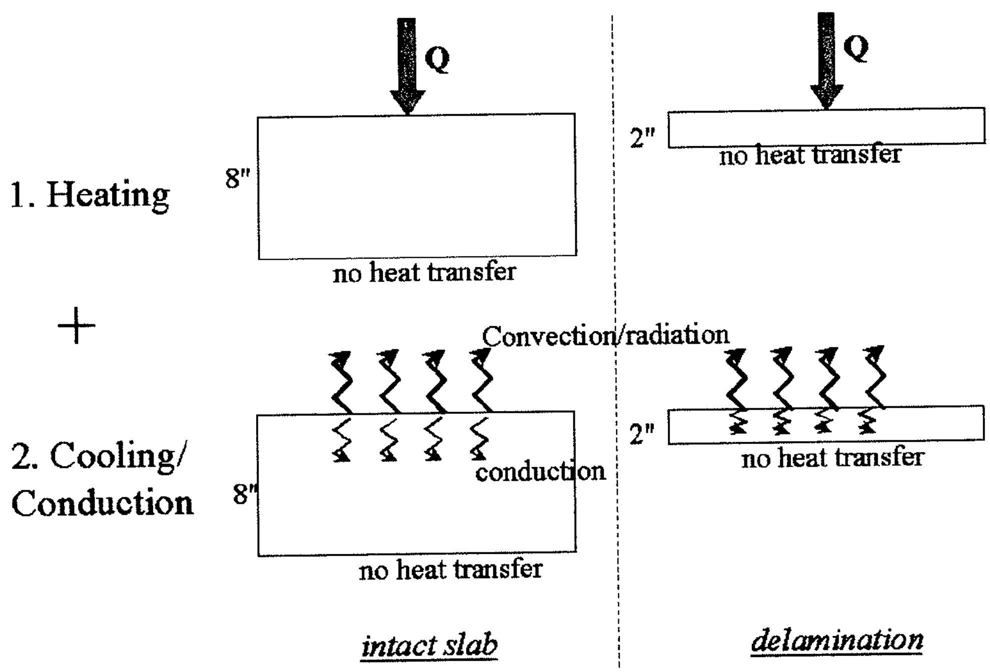



Figure 9 – Schematic of Analytic Model

A preliminary test of intact concrete was done to check the analytic results. At the Ray-Tech manufacturing facility, the Mini-Tech pavement was used to apply heat for 1 minute on their concrete floor slab. The results of the analysis for two different surface heat transfer coefficients (H) have been plotted along with data from the test (Figure 10). The values for H were selected from a table of values provided by Starnes and Carino (2003). The value of 5.54 appears to be a very good match for the experiment where the slab was covered for a period of time after heating. The higher value of 12.38 appears to be a good match for the experiment where the slab was exposed to the air immediately after heating. These comparisons verify that the model (and the thermal properties used) provides a good representation for the surface temperature vs. time for a slab heated uniformly for a short period.

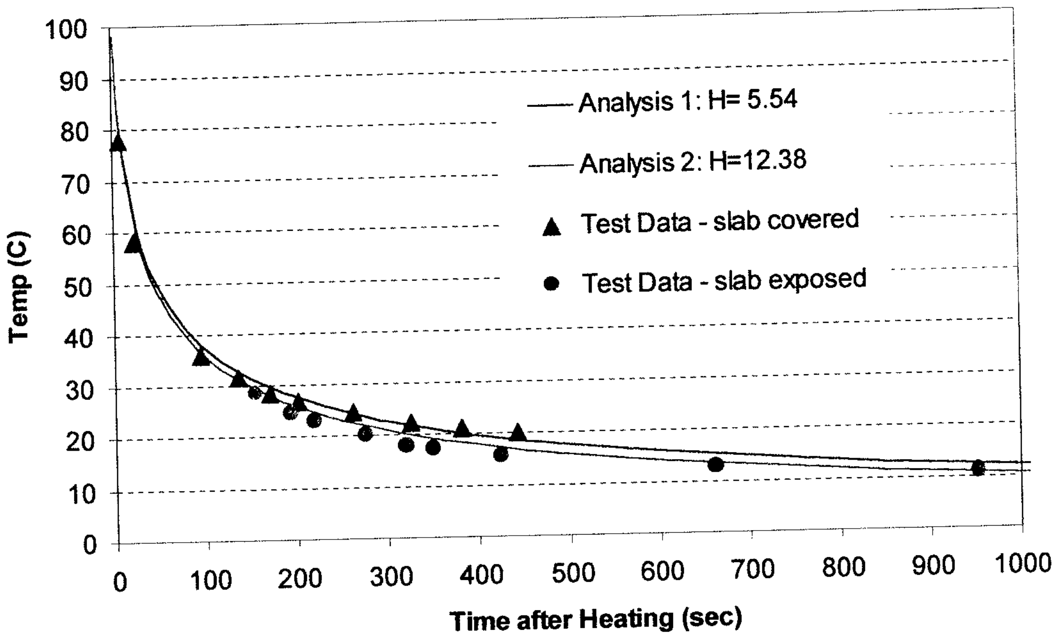
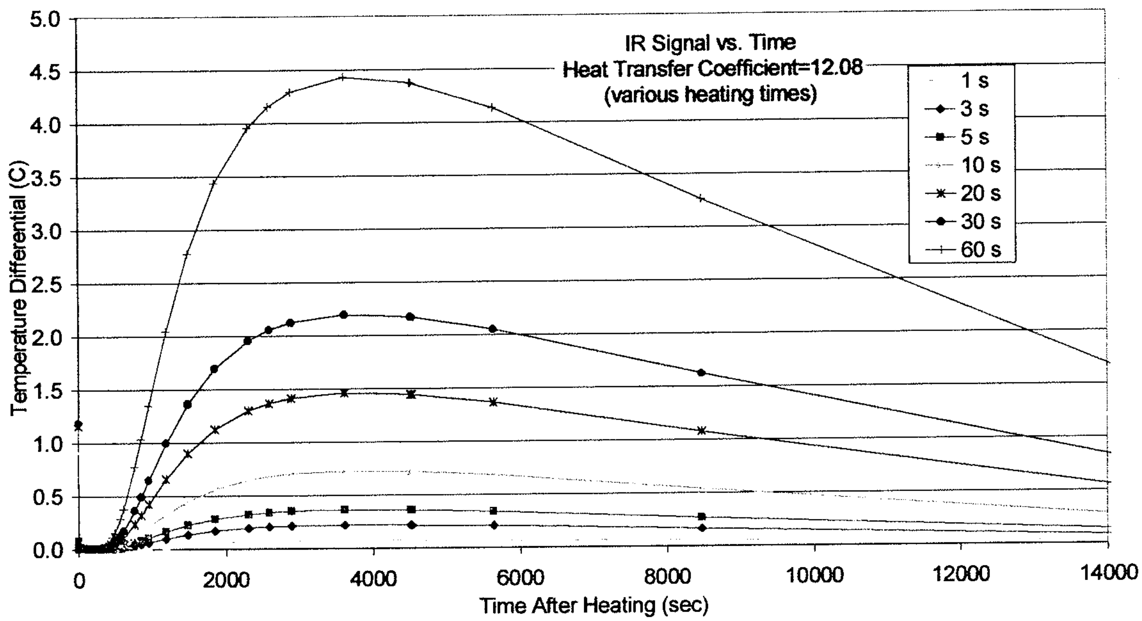



Figure 10 – Model vs. Experiment: Results for 60 Seconds of Heating

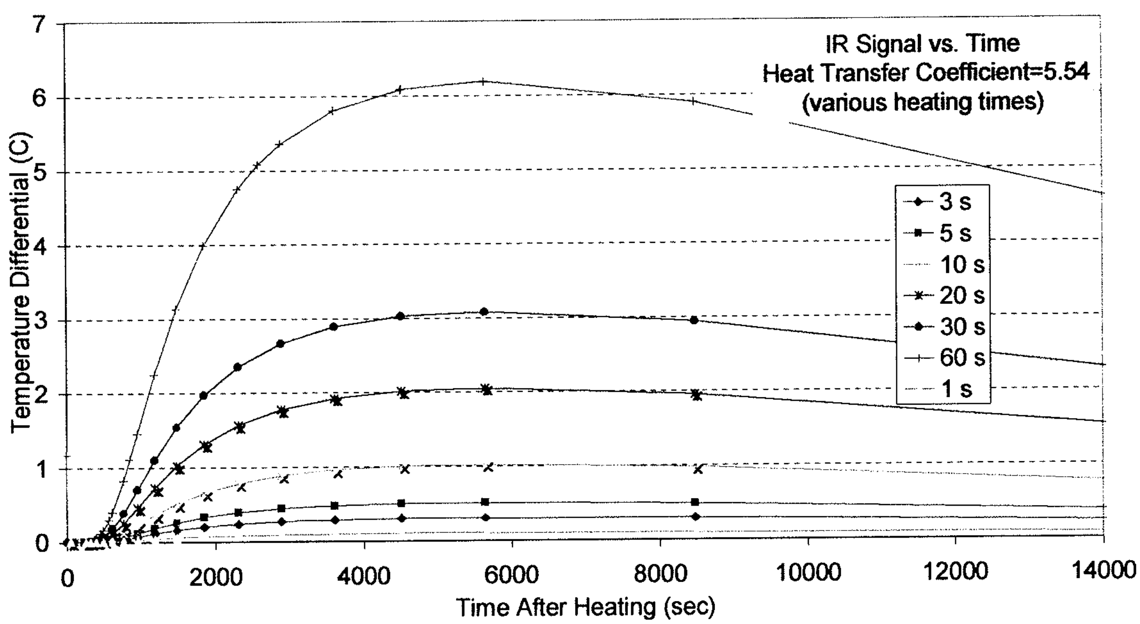
With this reality check on an intact slab, the analytical work continued to model a delaminated slab. The results of this analysis are presented as a temperature differential vs. time for sound vs. delaminated slabs. The temperature differential results for this calculation are shown in Figure 11. The calculation was conducted for various heating times ranging from 1 to 60 seconds, and for the two different heat transfer coefficients discussed above. Note that the differential rises to a maximum at time, $T_{max}$, and then slowly tapers off. Times close to $T_{max}$ would represent the best times to conduct the infrared survey.

The results of Figure 11 reveal a very similar pattern of behavior to the results obtained by previous researchers as described in Section 2. The temperature differential rises after the time of heating to a maximum value, and then tapers off slowly over time. The model results show that the time to reach the maximum temperature differential is approximately 3500 seconds, or almost 1 hour, regardless of the heating time. The maximum value increases with increasing time of heating, as would be expected.

The results of Figure 11 show that that heating times of 1 to 10 seconds produce temperature differentials ranging from 0.1 to 1.0 °C. These short heating times would allow the heaters to move across the deck at up to 1 ft/sec, and a 300 foot long, 4 lane deck can be surveyed in 1200 seconds, or 20 minutes. Note that the lower value of H (associated with decreasing the surface heat loss) increases the differential and extends the time to the maximum differential. The following section describes laboratory tests conducted to verify the above analytic observations.




(a) Results for H=12.38




(b) Results for H=5.54

Figure 11 – Temperature Differential vs. Time for Different Heating Times

# 4. Laboratory Tests

The objective of the laboratory tests was to verify that detectable temperature differentials could be generated on a realistically delaminated slab using the proposed heating equipment. A concrete slab was constructed to simulate a concrete bridge deck with delaminations. The testing involved moving the pavement heater across the slab, and monitoring the changes in surface and internal temperature over time. This experimental work was done at the Tufts University's Civil Engineering Materials Laboratory, Medford, MA.

## 4.1 Test Setup

The concrete test slab was designed to be, 4 ft x 8 ft x 7.25 inches thick, and was reinforced according the Massachusetts Highway Bridge Manual (#5 rebar @ 5 inch transverse; #4 rebar @ 8 inches longitudinal). The overall layout of the slab is shown in Figure 12. Delaminations in bridge decks are typically very thin, (the two piece of fractured concrete remain next to each other). In order to replicate this condition, 1/16 inch thick Cell-Aire® closed cell polyethylene foam sheets were used create defects (these foam sheets are commonly used as a packing material). This type of foam can be used to create a defect of known size in the concrete that is mostly air and behaves in many ways like a real delamination. The foam was placed on top of the reinforcing steel since delaminations typically occur at the level of the reinforcing steel. These defects were placed in the interior of the slab to minimize the slab edge effects.

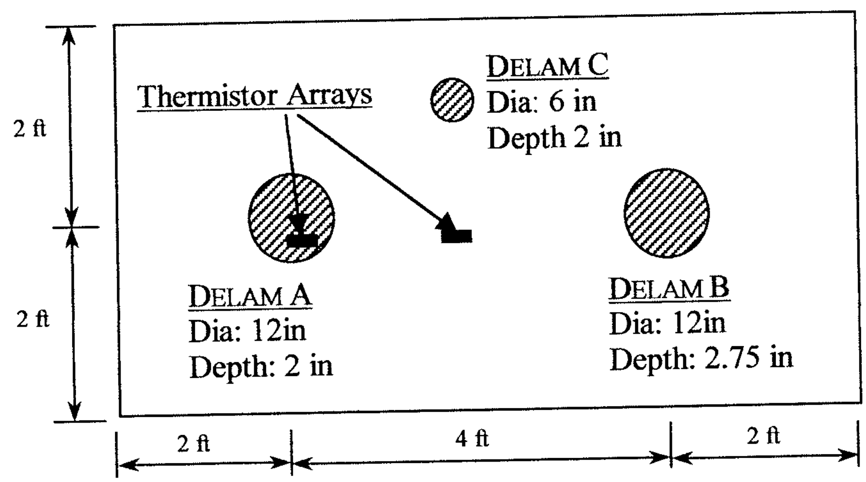



Figure 12 – Plan View of Test Slab

The slab was instrumented with thermistors with a range of -40 to +212 °F. The thermistors were oriented horizontally so that each thermistor would not experience a thermal gradient. Four thermistors were placed together in a vertical array. One array was placed where the slab was solid (in the center of the slab), and one array was placed at the location of a delamination (Figure 13) approximately 2 inches from its outer boundary.

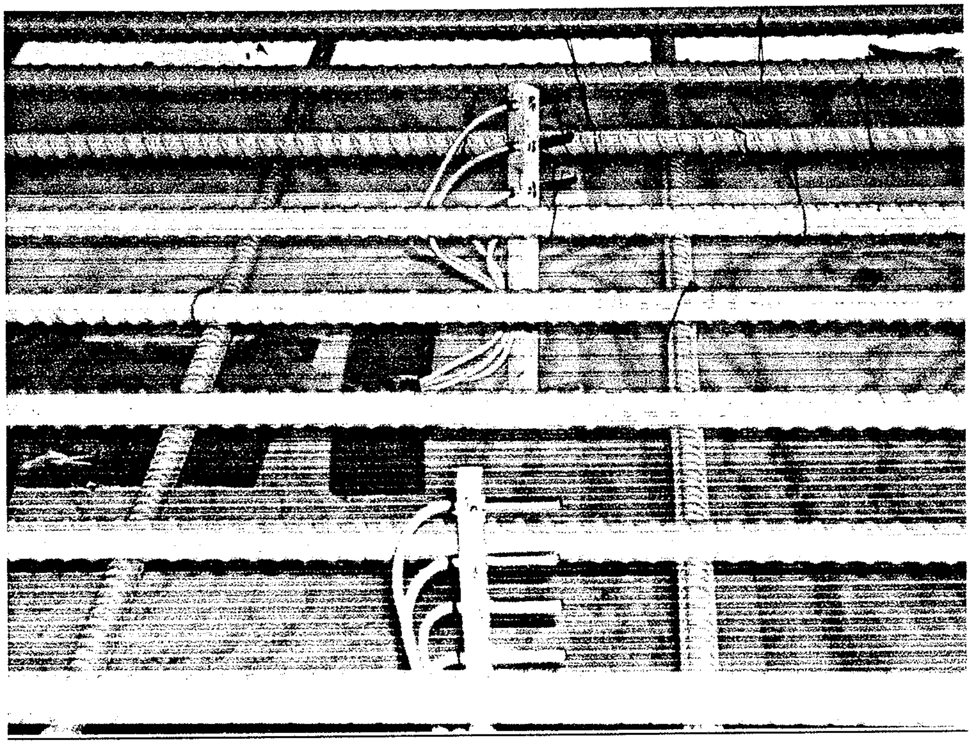


Figure 13 – Thermister Array for Internal Temperature Monitoring

Thermistor data was collected using two "HOBO" U12 4-channel data loggers and "Greenline" interface software loaded on a laptop personal computer. Onset Computing Corporation of Pocasset, MA supplied the loggers, software, and thermisters. The thermistor cables passed through the concrete at the base of the slab and exited through a sealed hole in the side of the form, where they were attached to the data loggers fastened to the outside of the forms. Data collection for each of the two loggers was initiated using a laptop computer and the interface software. The temperature data logged at 10-second intervals. Data collection continued automatically, and the laptop could be disconnected from the loggers while data collection continued. The laptop and interface software was used to view and plot the temperature data during a test, to terminate data collection, and to download and store the collected data.

Charles Ronchetti, Inc. of Lexington, MA, placed the concrete on April 8, 2004. Aggregate Industries, Saugus, MA supplied the Massachusetts Highway Bridge Mix (4,000 psi, ¾" stone, and 610 lbs cement per cubic yard and 4-6% entrained air). The concrete was transported from a ready-mix truck in wheelbarrows and shoveled into the form. The fresh concrete was consolidated using a hand held immersion vibrator.

During the casting of the slab, three circular pieces of the Cell-Aire® packing foam were placed in the fresh concrete (Figure 14) and tied into place to the rebar with wire to keep the delaminations at the level of the rebar. The careful placement of concrete was resumed until the form was filled with concrete. The excess concrete was struck off and the fresh concrete was floated. After the bleed water evaporated, the slab was finished with a steel trowel and a broom.

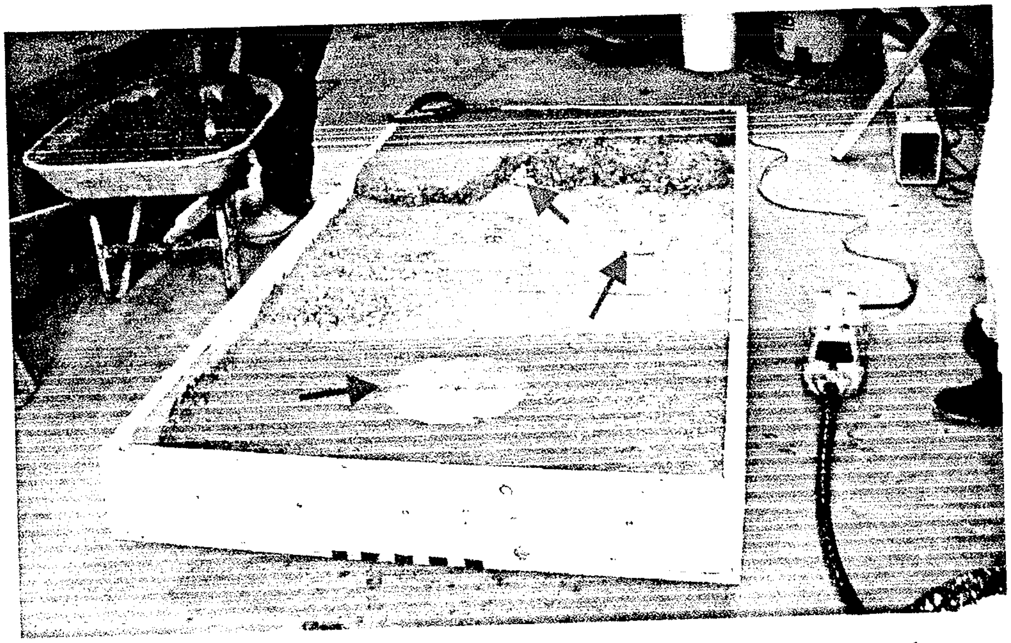


Figure 14 – Simulated Delaminations During Final Stage of Concrete Placement
(delaminations shown with red arrows)

The fresh concrete was tested for slump and air entrainment. The slump was measured to be 4.5 inches, and was considered to be within specification. The air content was measured at 2.5%, a value well below the specified amount of 4-6%. The air test was repeated, confirming the low reading. The concrete ready mix supplier explained that possibly the air was lost during transport. The movement of the small batch of concrete (~1 cu yd.) in the large transit mixer drum (~11 cu yd), knocked the air out of the concrete. This lack of air, although a problem for exterior concrete, was acceptable for this test slab, since it would not significantly affect the thermal properties.

Three cylinders were cast for compression testing. The three compression tests were done at 28 days, with breaks at 4,712 psi, 4,773 psi, and 5,260 psi, which met the strength specification. In addition to standard tests for fresh concrete, a test was conducted to evaluate how the simulated delamination material would interact with the concrete. A cylinder was cast with a circular piece of the Cell-Aire packing foam placed in the upper third. Figure 15 shows the edge view of the cylinder with the simulated delamination. The test showed that the foam did not disintegrate and possibly was compressed to thinner than the original 1/16 inch thickness.

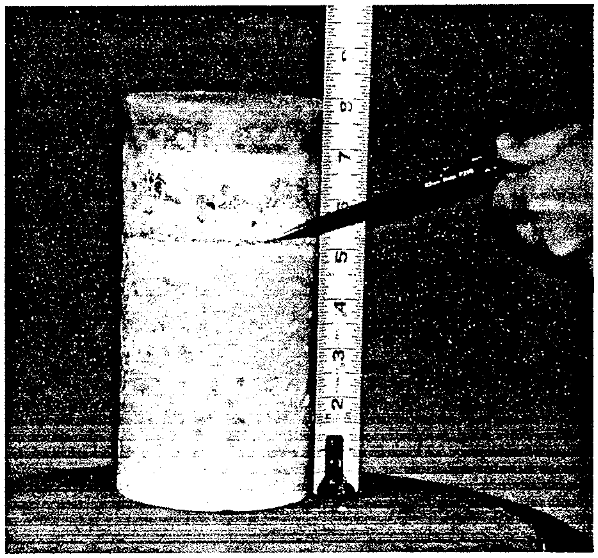


Figure 15 – Cylinder Showing Delamination

## 4.2 Conduct of Tests

The slab was allowed to cure indoors for 22 days. After curing, the slab was taken outdoors into the driveway just outside of the Tuft's lab. (The formwork had been set on pallets, prior to the concrete placement so that it could be moved with a combination of rollers and a pallet jack).

Platforms of cement blocks and a ramp were constructed so that heater could ride on and off the slab during the conduct of a test (see Figure 16). In this way, the heater could be moved at a uniform velocity and each point on the surface of the slab could be exposed to the heat for the same amount of time. For safety, prior to firing up the pavement heater, a fire extinguisher was placed near by.

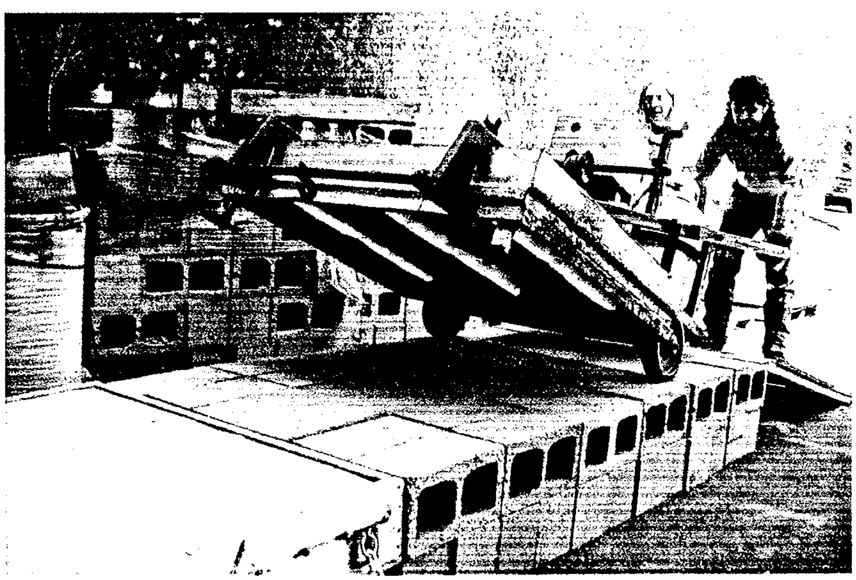


Figure 16 – The Ray-Tech Mini-Tech on Platform Prior to Testing

The heating tests were conducted by first firing up the heaters, letting them warm up, and then moving the heater at a controlled speed across the top of the slab. The movement of the heater during a test is shown in Figure 17. Heater movement began with the heater on the approach slab before the slab was exposed, and movement ended with the heater on the "leave" slab after completely clearing the concrete slab.

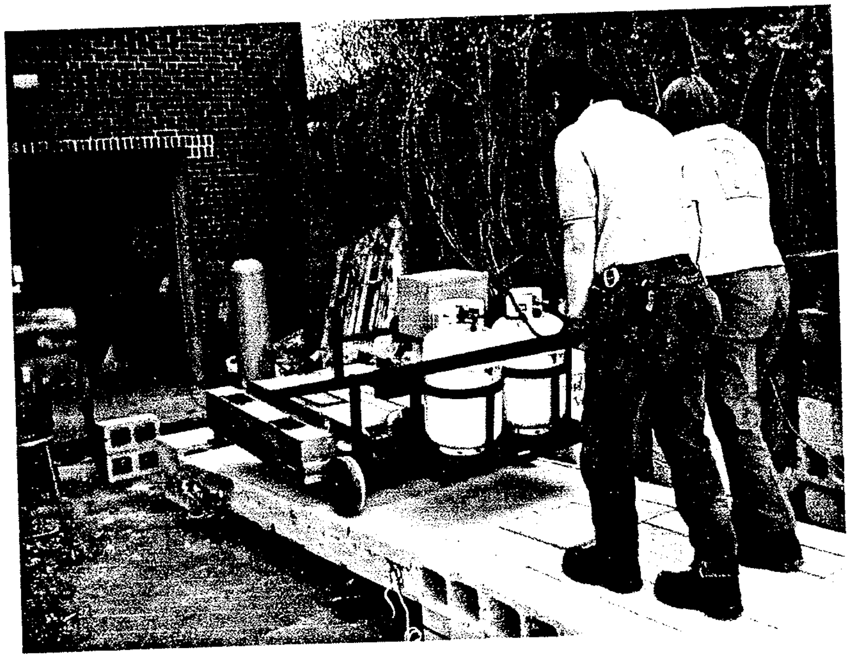


Figure 17 – Moving the Heater During a Test

Infrared images of the heated slab were obtained immediately after the heating of the slab, then repeated every 15 minutes. The images were taken from a ladder at one end of the setup (Figure 18). The elevation allowed for a clear image of the entire slab. The logging of the internal temperature of the slab was initiated prior to the beginning of each test, and the temperatures were logged at 10-second intervals throughout the duration of each test.

Figure 18 – Infrared Thermography Measurements in Progress

To counteract the adverse effects of wind on the development of temperature differentials, some tests employed a tarp to cover the slab for approximately 60 seconds after the heating. Covering a real bridge deck could be achieved by simply dragging a tarp behind the pavement heater. The time of covering would depend on the speed of the heater and the size of the tarp. For a heater moving at 0.33 ft/sec (3 ft heater with 10-second exposure), a 20 ft trailing tarp would cover each location on the slab for 60 seconds.

## 4.3 Results

Five tests were carried out during the period between April 30 and May 11 (Table 1). Due to environmental constraints and the required time to monitor temperatures, only one test per day could be performed. Heating times of 6 and 10 seconds were used, based on the findings from the analytic data. The heating time for each point on the surface was controlled by the rate of movement of the heater across the slab. The tests represented a range of ambient temperatures and wind conditions, and one test was conducted at night.

Table 1 – Test Summary

| TEST NO. | DATE | START TIME | HEATING TIME (SECONDS) | AMBIENT TEMP (DEG F) | WIND | COVERED AFTER |
|---|---|---|---|---|---|---|
| 1 | April 30, 2004 | 11:45 AM | 10 | 70 | calm | no |
| 2 | May 4, 2004 | 12:50 PM | 10 | 54 | windy | no |
| 3 | May 5, 2004 | 12:40 PM | 10 | 54 | breezy | yes |
| 4 | May 6, 2004 | 12:53 PM | 10 | 62 | calm | yes |
| 5 | May 11, 2004 | 08:20 PM | 10 | 70 | calm | no |

For each test, infrared images were taken immediately before and after each test, and then at 15-20 minute intervals afterwards. For each test, the delaminations began to appear in the infrared image at approximately 20 minutes after the heating took place, and continued to appear in the image until approximately 90 minutes after each test. Figure 19 shows an example of an infrared image showing higher temperature "bright spots" at the location of the delaminations. The scale on the side of the image shows the temperature levels assigned to each gray scale level. For the 10-second heating test, the temperature differential between the delaminated and the surrounding area reached 1 °F, as predicted in the theoretical model.

### 4.3.1 Temperature Analysis

For each infrared image, specialized image analysis software was used to determine the temperature differentials between the center of the delaminated areas and the center of the slab. Figure 20 shows all of the infrared temperature differential for delamination "B" plotted vs. time and vs. the theoretical predictions. A best fit curve through the data points shows a pattern that is reasonably similar to the predicted pattern for H = 12.38. The primary difference between measured and predicted differentials is the more rapid development of the temperature differential in the measured data. A similar fitted curve is shown for the differentials at delamination "A" (the individual points have been omitted for clarity).

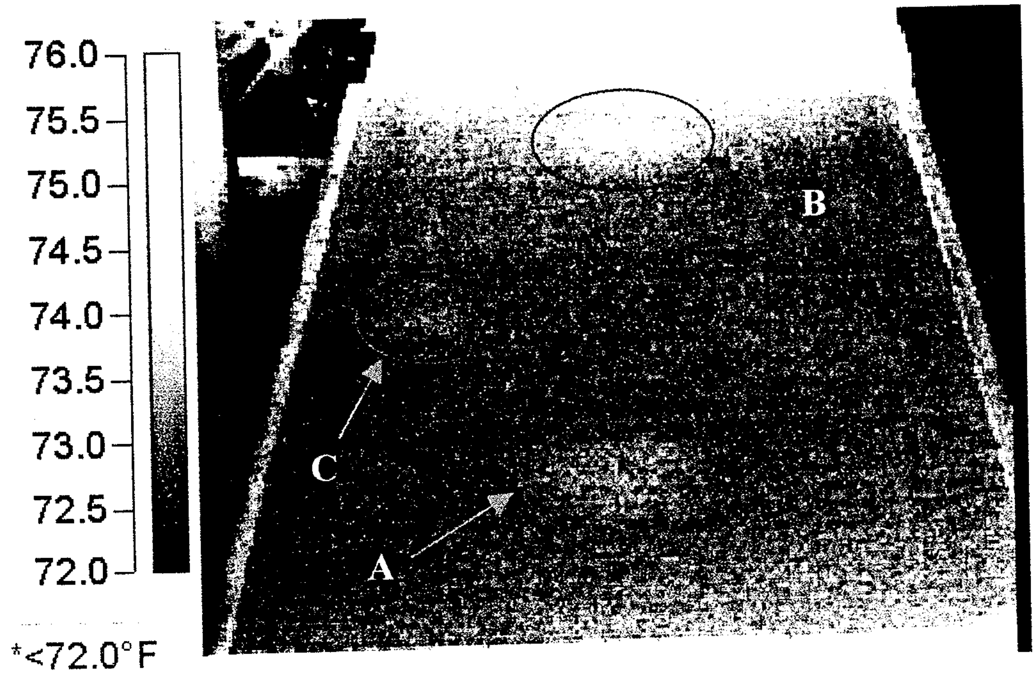



Figure 19 – Sample IR Image from 10 Second Heating Test
(arrows and circles show actual delamination locations)

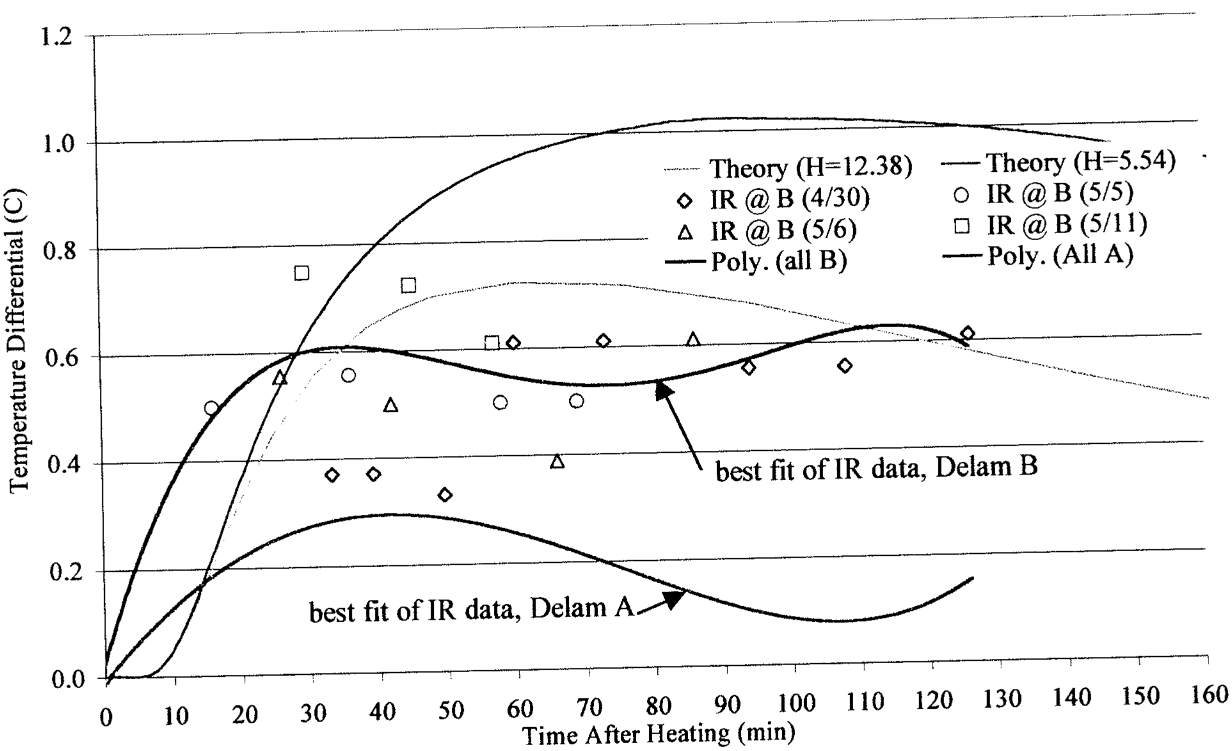



Figure 20 – Infrared Temperature Differentials for All Tests

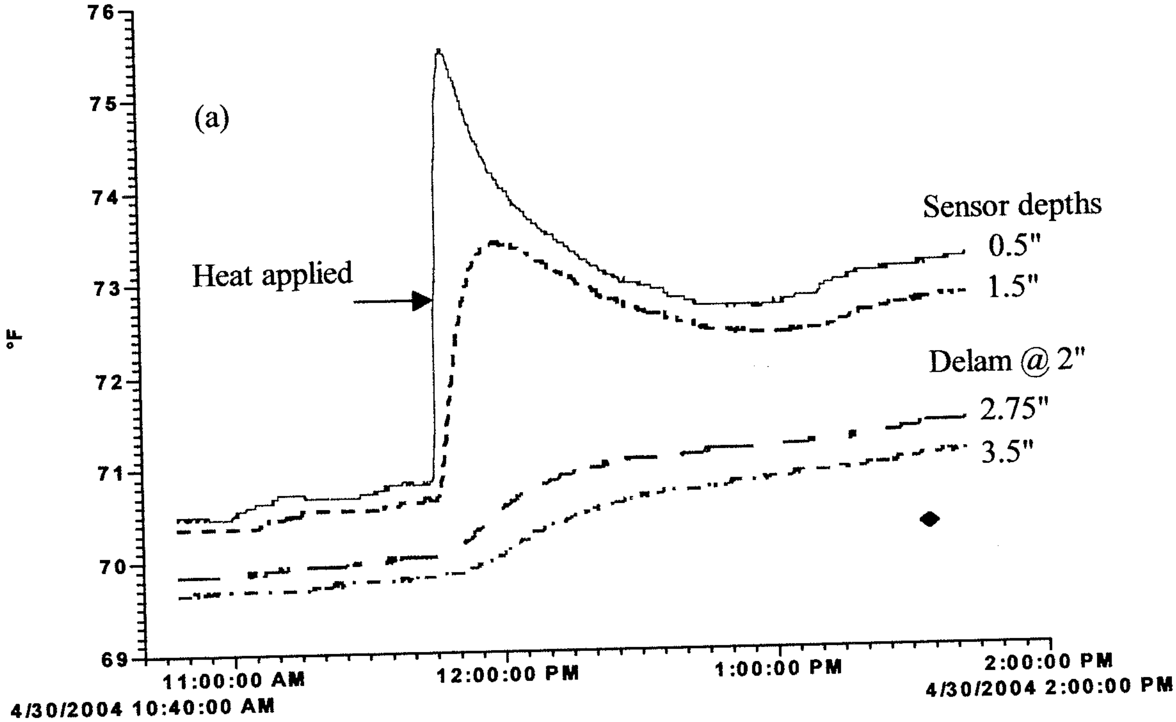
Figure 20 shows that the temperature differentials measured for delamination A were somewhat smaller than those measured for delamination B. This is unexpected, since A was closer to the surface than B. Most likely there was more heat applied to B due to the configuration of the heating arrangement. The lowest differentials were measured for delamination C. This is expected, since it is the smallest of the three delaminations.

In one of the 5 tests (May 4), the delaminations did not appear in the infrared image. This test was conducted on a windy day. The winds apparently accelerated the heat loss from the slab, and the heat flow into the slab was inadequate to create thermal differentials. Under such conditions the heating time would have to be increased to compensate for the heat loss.

The monitoring of the internal temperatures in the slab using thermisters provides insight into the development of the temperature differentials produced by the delamination. Figure 21 shows a sample of the internal temperatures of the slab at the delaminated vs. the sound locations. The effect of the delamination on the temperatures is clear in these graphs. The graphs show that the delamination creates a small temperature discontinuity before heating, which is then magnified after the heating occurs.

A more detailed analysis of this data is shown in Figure 22, where the temperature differential between the two near surface thermisters is plotted vs. time for a selected test. This plot shows the difference between the near surface (-0.5" depth) temperature at Delamination A vs. the near surface temperature in the center of the slab. What is interesting to note is that immediately after the test, the center of the slab became over 4 °C hotter. This difference lasts for over 10 minutes, after which the delaminated area becomes hotter as expected. This pattern was observed for all of the tests.

The initially higher temperature at the center of the slab (vs. the end where delamination "A" was located) suggests that the center of the slab is being heated more than the area around delamination A. The previous discussion of the temperature differentials at delamination A and B also indicated that the "B" end was being heated more than the "A" end. The test was conducted with the heater starting at the "B" end and moving towards the "A" end, moving at a constant rate. It is not clear why there is a non-uniformity in heating from one end of the slab to the other, it may be that the residual heat from the pavement heater that was placed at the "B" end of the slab caused this thermal gradient.



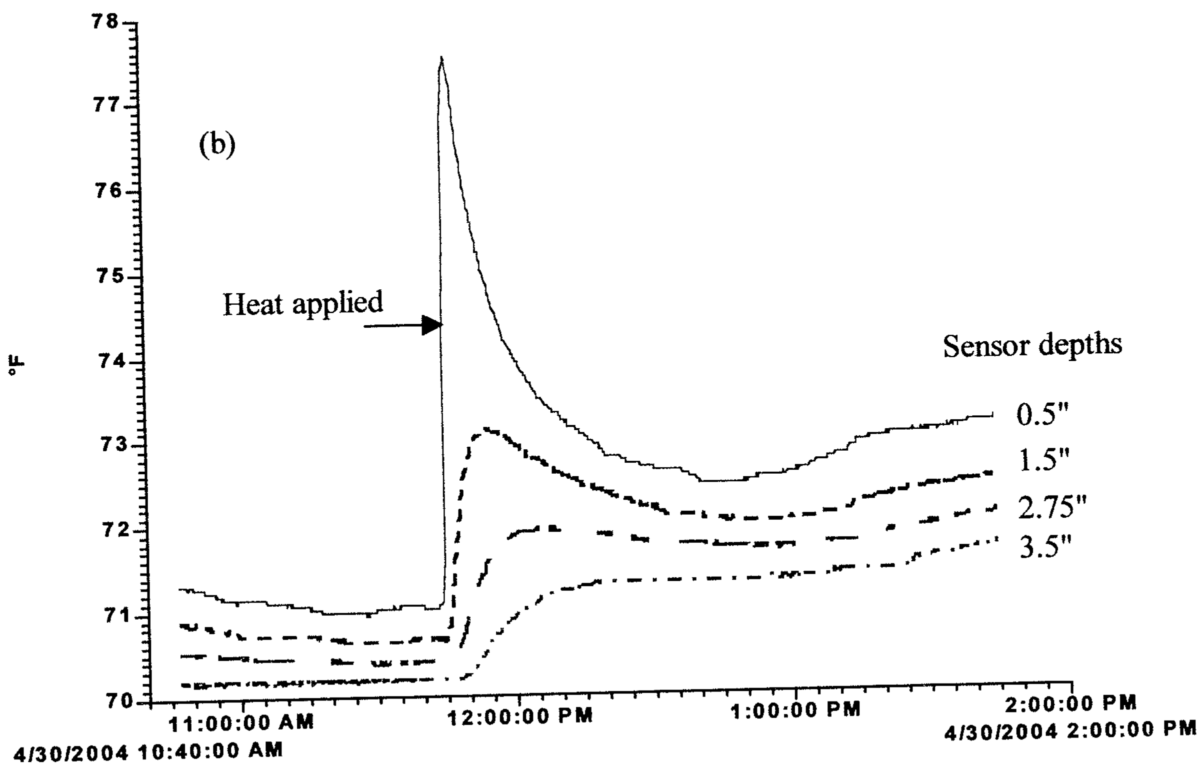




Figure 21 – Temperature Profiles: (a) at Delamination and (b) in Sound Area

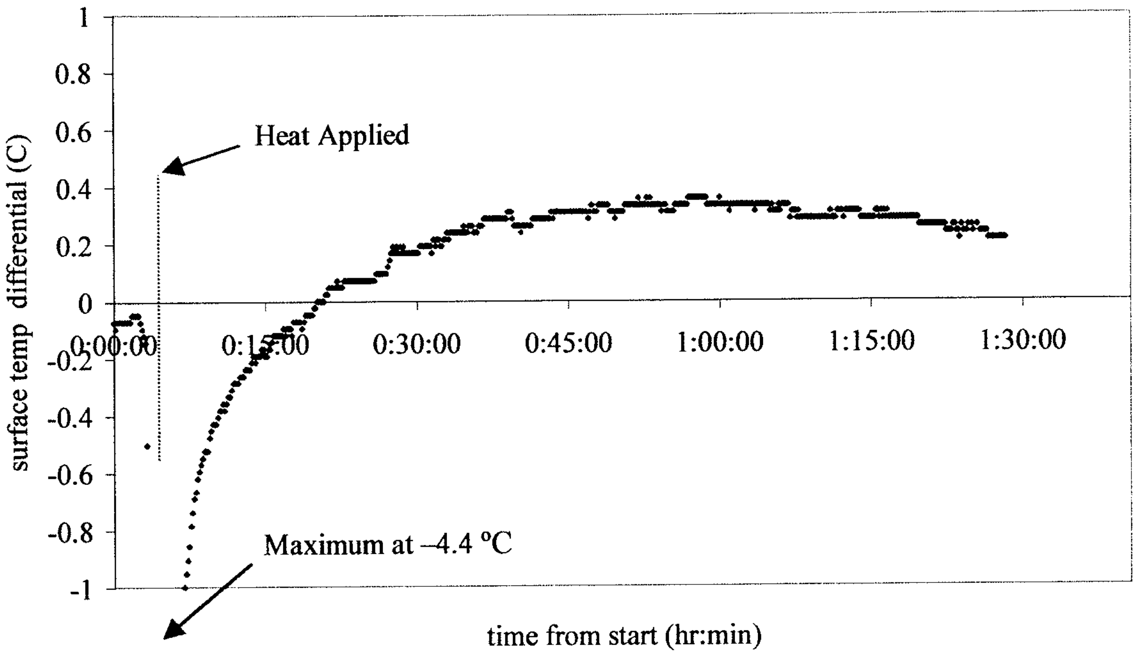



Figure 22 – Temperature Differential (Delamination A – Center of Slab)
(measured using near surface thermister – May 5 test)

### 4.3 2 Soundings

The test slab with its careful fabricated delaminations provided a unique opportunity to evaluate the detection of delamination using conventional sounding methods vs. the infrared method. To carry out this evaluation, arrangements were made with the Massachusetts Highway Department (MHD) to have an experienced Bridge Inspector sound the slab. On May 5, 2004, MHD sent an inspector to the Tufts University Lab to sound the slab. Using a chain, he quickly found the two large delaminations (see Figure 23). He then used a 16 oz. hammer to zero in on the delaminations and reported their estimated size (Table 2).

Table 2 – Sounding Results

| | Diameter (in) | |
|---|---|---|
| Delam | Actual | Estimated by Sounding |
| A | 12 | 6-8 |
| B | 12 | 3-4 |
| C | 6 | 0 |
| delam % | 5.5% | 1.0% |

From these results, it is clear that while sounding detected the larger delaminations, the method underestimated the extent of the delamination and missed the smaller delamations. It appears that the edge of a delamination does not sound as hollow as the center of the delamination and is below the detection limit for sounding. Delam A, 2 inches below the surface, showed up bigger than

Delam B that was at 2.75 inches. This indicates that the deeper the delamination is more difficult to detect.

Figure 23 – Chain Drag Survey of Test Slab

## 5. Discussion, Economic Analysis, and Conclusions

The analytic and experimental results obtained clearly show that the active infrared method for bridge deck evaluation is feasible, and that it can be implemented with available equipment. The results provide valuable information for determining the time and intensity of heating, and for accommodating the influence of weather conditions on the process.

To evaluate the economic feasibility of this Active Infrared method, the anticipated cost has been compared with those of the Chain Drag method for a representative bridge. The representative bridge in this analysis has two 12 foot wide lanes in each direction, and is 180 ft long. The details of the cost analysis are provided in Appendix B.

The active infrared method data collection would take a two-person crew an estimated 2 hours on the representative bridge. These figures are based on a 10 sec heating time, and a pavement heater that covers a 3 ft x 13 ft area moving at a velocity of 0.3 ft/s. At this speed, the entire bridge can be heated in 40 minutes. After the entire bridge is heated, the infrared thermography measurement would be conducted at a rate of 4.5 ft/s, traversing each lane in one minute. Allowing an additional 50 minutes for turning around, repositioning and other delays entire operation could be completed in two hours. The total cost of the work, including office data analysis, is estimated at $3,673. Details of the estimate are presented in Appendix B.

Chain dragging would take an estimated 21 hours and cost $7,227 on this representative bridge. This is based on production data indicating that a chain drag survey for a 30 ft span, one lane, 2-person crew, including pavement marking and location mapping, would take between 45 and 60 minutes (Mass Highway Data, Clang 2004). The 21-hour estimate was calculated using an average value of 52.5 minutes per 30 foot, 1 lane span.

The analysis above shows that for this type of bridge, the active infrared method is not only less that half the cost, but occupies the structure for one tenth of the time when compared to chain dragging. The reduced time on the structure for the active infrared method makes the method safer, and minimizes the cost to the road users. The primary advantage of the chain drag is that the results are available at the time of the survey, since office processing is not required.

Based on the technical and economic findings presented above, we recommend that the program proceed to Phase II field testing as originally proposed. A discussion of the proposed field testing is presented in the next section.

## 6. Recommended Phase II Field Testing

The objectives of the field evaluations are to verify the feasibility of the active infrared bridge deck evaluation system under realistic field conditions. These field tests will be carried out in cooperation with local state highway departments who have been represented in this project through participation in the Regional Expert Panel.

### Task 1—Selection of Candidate Decks

Infrasense will work with the agency representative to identify bridge(s) that are known from other tests and observations to have some level of deterioration. For simplicity, the decks to be considered for this testing will be ones with low traffic volume and easy access, and will be bare concrete decks without overlays. If possible, selected decks will be ones, which the agency plans to evaluate (or has evaluated) in detail for other purposes. One such deck, Route 66 over the Kinderhook Creek near Albany, NY, has already been the subject of a research study, and core and sounding data is already available. Candidate decks will be visited by the project team, the available data will be reviewed, and two to three different deck candidates will be selected for testing.

### Task 2—Conduct of the Tests

As indicated by the results generated thus far, the key variables for the field tests will be the heating time, the time after heating for the infrared data collection, and the environmental conditions such as wind and ambient temperatures. Data will be collected at night to provide the optimum heating and detection conditions. The following issues will be addressed as part of the field testing.

Variations in Heating Time – Variations in heating time will be evaluated by testing each bridge at least twice, each time with a different heating rate. We propose to conduct the initial test at the nominal 10-second heating rate used in the laboratory. If this rate appears to provide clear indication of the delaminations, the second test can explore a faster rate of heating. If not, a lower heating rate can be explored. During each test, the infrared observations will be periodically confirmed using direct sounding.

Timing for Infrared Evaluation – During each test, infrared observations will be made at different times after the heating has been applied. The clarity and extent of the observed defects will be evaluated as a function of time, and an optimum detection time window will be determined.

Environmental Conditions – Repeat tests will be conducted in an effort to assess the influence of environmental conditions. Although such conditions cannot be controlled, they will recorded through multiple tests and the influence of ambient wind and temperature will be assessed.

Traffic Control and Deck Heating – Decks in low traffic volume areas will be sought to minimize the cost of traffic control. Traffic control will be provided either by the agency, or by Infrasense using licensed traffic control personnel. Pavement heaters will be rented on a daily basis from Raytech, the supplier that participated in the initial feasibility study. The heater will be positioned in a fixed lane and slowly moved from one end of the deck to the other. The rate of speed will determine the heating time for each element of the deck.

Infrared Measurement Equipment – Infrasense will use its infrared data collection vehicle equipped with the FLIR Systems Model SC-1000 infrared camera and standard video camera to collect the infrared and visual data. Pavement surface lighting will be added for nighttime operation. The first round of data collection will begin as soon as the pavement heating has been completed.

### Task 3—Data Analysis and Confirmation

Following the survey, the IR and visual data will be taken back to the office, digitized, and analyzed using the infrared data analysis methods that Infrasense has developed for conventional infrared surveys. The delaminated areas will be mapped, and the decks will be revisited for confirmation. Confirmation data will be obtained by chain dragging and hammer sounding. The comparison between the infrared and confirmation measurements will seek to determine the percentage of the deck where delaminations have been successfully identified, as well as areas that were missed, and areas where false positive readings were obtained.

Where feasible, the confirmation data will be provided by the agency as part of its own evaluation process. Where this is not possible, Infrasense will take responsibility for obtaining this information through subcontract with qualified personnel.

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# APPENDIX A

## Thermal Parameters Used in the Analysis

Q = uniform heat input applied for time $T_{heat}$
$K_1$ = thermal conductivity of concrete
$\rho$ = density of concrete
c = specific heat of concrete
$\kappa$ = diffusivity of concrete
H = "coefficient of surface heat transfer"

$$Q := .6782 \frac{cal}{cm^2 \cdot sec} \qquad Q = 9001.129 \frac{BTU}{ft^2 \cdot hr}$$

$$K_1 := .005 \frac{cal}{cm \cdot sec \cdot K} \qquad K_1 = 2.093 \frac{W}{m \cdot K}$$

$$\rho := 2.5 \frac{gm}{cm^3} \qquad \rho = 2500 \frac{kg}{m^3}$$

$$c := 920 \frac{J}{kg \cdot K}$$

$$\kappa := \frac{K_1}{\rho \cdot c} \qquad \kappa = 0.009 \frac{cm^2}{s}$$

$$H := 12.38 \frac{W}{m^2 \cdot K}$$

$$h := \frac{H}{K_1} \qquad h = 5.914 \frac{1}{m}$$

# APPENDIX B

## Time/Cost Evaluation

### Active Infrared Thermography vs. Chain Drag

Representative Bridge Description:

| | |
|---|---|
| Number of Lanes | 4 |
| Length (ft) | 180 |
| Area (Lane-ft) | 720 |
| Lane width (ft) | 12 |
| Surface Area (sq ft) | 8640 |

Active Infrared Thermography Costs:

| | QUANTITY | $/UNIT | $ COST |
|---|---|---|---|
| Mobilization (ea) | 1 | 1,000.00 | 1,000.00 |
| Field technicians (hr) | 4 | 60.00 | 240.00 |
| Vehicle (hr) | 2 | 25.00 | 50.00 |
| Pavement Heater (hr) | 2 | 62.50 | 125.00 |
| IR Camera (hr) | 2 | 125.00 | 250.00 |
| Moving lane closure (hr) | 2 | 150.00 | 300.00 |
| Analysis (hr) | 16 | 80.00 | 1,280.00 |
| Police Detail (hr) | 1 | 128.00 | 128.00 |
| **Total** | | | **$3,673.00** |

Chain Drag Costs:

| | QUANTITY | $/UNIT | $ COST |
|---|---|---|---|
| Mobilization (ea) | 1 | 360.00 | 360.00 |
| Field technicians (hr) | 42 | 60.00 | 2,520.00 |
| Fixed lane closure (hr) | 21 | 87.50 | 3,675.00 |
| Police Detail (hr) | 21 | 32.00 | 672.00 |
| **Total** | | | **$7,227.00** |