A PAVEMENT CRACK CLEANING AND HEATING SYSTEM FOR AUTOMATED SEALING MACHINERY

Interim Report of

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ABSTRACT

Each year in California, the State Department of Transportation (CalTrans) spends over $100 million maintaining approximately 33,000 lane-miles of flexible pavement (Asphalt Concrete - AC) and 13,000 lane-miles of rigid pavement (Portland Cement Concrete - PCC). A portion of these maintenance activities involves the sealing and filling of cracks (approximately $10 million per year) which, when properly performed, can help retain the structural integrity of the roadway and considerably extend the mean time between major rehabilitations. A typical operation to seal meandering cracks in AC pavement involves a crew of about eight individuals which can seal between one and two lane miles per day. The associated costs are approximately $1800 per mile with 66% attributed to labor, 22% to equipment and 12% to materials.

Proper maintenance of pavement cracks involves the periodic application of a bituminous hot-pour sealant to cracks that have been thoroughly rid of debris and moisture. As is currently the case however, there are few quality standards common throughout the various State departments of transportation regarding crack cleanliness and dryness prior to sealant application.

Currently, research is underway at the Mechanical Engineering Department of the University of California, Davis to develop prototype automated machinery that will sense, prepare, and seal (or fill) cracks and joints on pavement. As part of this overall project, this research reports on the design, testing and implementation of an automated pavement surface preparation unit that best meets crack sealing project goals in terms of feasibility, effectiveness, and efficiency. Specifically, means to improve upon and automate current crack cleaning and heating techniques are presented.

First, a feasibility study and literature search was performed to examine practical means of automating methods of crack cleaning and heating. Since the automated crack

sealing machine being developed is a possible prototype for future commercialization, a heating system that will allow for traveling speeds faster than walking was necessary.

To best determine the relative differences between convective and radiant heating *and* to develop a design tool that could help in evaluating the pavement heating performance of available commercial equipment, finite difference heat transfer models were constructed using basic principles of classical heat transfer and experimentally formed hypotheses from literature. Verification of the accuracy of the models was then proven through comparisons with other authors' experimental data and through testing of a commercial heater. Simulations using the developed models were then run resulting in the choice to discard radiant heating as a viable heating alternative since the lengthy heater that proved necessary would be difficult to articulate through turns.

After tests were conducted, formal design constraints were assembled and trade-off issues concerning the system to be selected for the crack sealing project were presented. Among these, general overall project goals, mechanical compatibility with the concept vehicle, performance of the heater, ability to integrate, and debris removal procurement and compatibility were identified as the important issues for design. Formalized specifications based on these criteria were then developed for purchasing and vendors with possible products meeting these specifications were contacted. The advantages and disadvantages of the available equipment were then discussed.

Finally, the cleaning and heating system components selected for procurement and integration with the automated crack sealing machine were chosen, followed by recommendations for commercialization.

CHAPTER 1 - INTRODUCTION

1.1 - Problem Description

Worldwide, a tremendous amount of resources are expended annually maintaining highway pavement. In California alone, the State Department of Transportation (CalTrans) spends about $100 million per year maintaining approximately 33,000 lane-miles of flexible pavement (Asphalt Concrete - AC) and 13,000 lane-miles of rigid pavement (Portland Cement Concrete - PCC). A portion of these maintenance activities involves the sealing and filling of cracks (approximately $10 million per year) which, when properly performed, can help retain the structural integrity of the roadway and considerably extend the mean time between major rehabilitations.

Proper maintenance of pavement cracks involves the periodic application of a bituminous hot-pour sealant to cracks that have been thoroughly rid of debris and moisture. As is currently the case however, there are few quality standards common throughout the various State departments of transportation regarding crack cleanliness and dryness prior to sealant application. All the more, recent studies have shown that through proper preparation, AC pavement life can be extended perhaps 3-6 years between major rehabilitations. The most critical task in crack sealing therefore is often times, not the sealing itself, but rather the preparation of the crack involved prior to sealing.

Having to clean, dry (or heat), and seal thereby makes the sealing and filling of cracks a very tedious, labor-intensive operation. A typical operation to seal meandering cracks in AC pavement involves a crew of eight individuals which can seal between one and two lane miles per day. The associated costs are approximately $1800 per mile with 66% attributed to labor, 22% to equipment and 12% to materials. Furthermore, the crack sealing work team is exposed to a great deal of danger from moving traffic in adjacent lanes.

1.2 - The Need for Automated Crack Sealing/Filling Technology

In order to improve on the *average* crack seal, and thereby extend the life of road surfaces, an automated means to affect the quality of roadway surface seals must be developed. By doing so, long term crack sealing costs can be minimized through a reduced labor force, mean pavement life can be extended by an improved quality seal, and worker safety can be increased. And, as can be inferred from above, a *critical* aspect to the success of automated crack sealing/filling machinery is the development of an improved method of cleaning and drying (or heating) pavement cracks prior to sealing.

Currently, research is underway at the Mechanical Engineering Department of the University of California, Davis to develop prototype automated machinery that will sense, prepare, and seal (or fill) cracks and joints on pavement. The primary objectives of the project are to design machinery for the sealing and filling of joints and cracks in pavement in order to:

- Increase the cost-effectiveness of these operations,
- Increase the quality, consistency, and life of the resultant seals and fills,
- Increase the safety of workers and highway users, and
- Increase the use of remote operation and control of equipment to attain the above.

Machinery that satisfies these objectives will additionally reduce lane and highway closures and thus, will play a significant role in reducing traffic congestion, an area of considerable concern in the major urban regions around the world.

1.3 - Purpose of this Research

In support of the above stated objectives, the purpose of this research is to report on the design, testing and implementation of an automated pavement surface preparation unit that best meets the goals of the overall crack sealing project in terms of feasibility, effectiveness, and efficiency. Specifically, means to improve upon and automate current crack cleaning and heating techniques will be examined. Each chapter of this report therefore, discusses steps taken in the development of such a system.

In Chapter 2, computational heat transfer models are developed and verified that will help in evaluating pavement crack heating abilities of available commercial equipment. In Chapter 3, actual tests are performed to determine the surface heating abilities of available equipment. Chapter 4 discusses design requirements and trade-off issues concerning the system to be selected for the crack sealing project. And finally, cleaning and heating system component selection and recommendations for commercialization are presented in Chapter 5. First though, some basic background information on current crack cleaning/heating technology is presented followed by a literature search and feasibility study into the possible means of achieving the said goals.

1.4 - Current Cleaning/Heating Methods

In order to develop automated crack sealing machinery, it is necessary to determine a method of efficiently and effectively cleaning and heating road surface cracks automatically prior to sealant application. The current manual method of choice, the hot compressed air (HCA) lance used for cleaning and heating road surfaces, is discussed below.

Rossman, et al. (1990) conducted a survey of States to determine current methods of crack preparation and found that the principle equipment used is the hand held hot compressed air (HCA) lance or compressed air jet alone. This does not mean that either of these methods is necessarily effective. However, it can be inferred from this survey that automated crack sealing machinery which uses a form of HCA lance to heat and clean the road surface would probably be accepted by the majority of end users.

The typical HCA lance resembles a high pressure, 30" long, hand held car wash jet with a wide burner chamber at the nozzle end. The main transfer of heat from a hot compressed air heat lance occurs via the main burner chamber. The chamber is fed with liquid propane (LP) gas at approximately 25 PSI. Air is also fed into the burner chamber at approximately 80 PSI. The two are mixed and combusted. The exhaust is then ejected from a 2 1/2" diameter stainless steel tube onto the crack to be heated. In doing so, the moisture formed in the chemical reaction that takes place during combustion is driven into the pavement. The lance portion of the HCA lance or "air knife" is mounted tangentially on the inside of the most aft part of the burner tube. It is assumed that the combustion heat is transferred to the compressed air passing through the exhaust tube thereby heating this new "hot dry air". This new dry air is then ejected out a nozzle onto the pavement. The user directs the small air knife portion of the lance into the crack in order to utilize the force of the rapidly expanding air from the small nozzle while heating the crack at the same time. The hot dry air impinging on the pavement after the combustion exhaust has already passed by does not force the moisture into the pavement but helps to evaporates it - the extent of which remains to be determined. In discussions with vendors it seems that the temperature rise inside of the hot dry air portion may only be on the order of 100°F. This implies that virtually no heat transfer will take place via the lance portion of the HCA lance at vehicle speeds on the order of 5 MPH. Also, it is doubtful that the heating tube portion of the HCA lance, in absence of the high pressure air knife portion, would actually remove significant debris from the road surface since the heating tube alone would not provide enough force to remove debris, which is generally composed of inert materials that do not burn (Davidson and Callahan, 1987).

Rossman, et al. (1990) nevertheless, recommend the hand held HCA lance as the preferred tool of highway crews for crack cleaning since it is capable of producing exhaust temperatures as high as 3,000°F (1650°C) with operating exit air lance velocities of approximately 3,000 ft/s (800 meters/second) at the small nozzle orifice. In general, these devices can remove loose debris and dust from cracks, as well as dry out and remove excess moisture before sealing which can aid in extending the sealing season in cold or damp weather (Chehovits and Manning, 1984; Rossman, et al., 1990). However, the ability of current HCA lances to transfer enough heat at speeds desirable in automation, remains to be addressed. Workers typically determines the amount of heat to be applied to a crack (loiter time) by the changing color it exhibits. When AC pavement turns a dark gray/black or begins to smoke, the worker moves forward. In an automated machine though, this is unacceptable. Better standards are necessary.

Furthermore, Schultheis and Velinsky (1991) determined that with a crack eccentricity greater than 1/2", compressed air jetting, in effect the air knife portion of an HCA lance, becomes ineffective at speeds greater than 5 MPH. This appears to be significant since, accuracy to within 1/2" places extreme demands on vehicle sensing and positioning systems. Alternative methods of cleaning/heating must therefore be examined to ensure proper crack preparation.

1.5 - Feasibility Study and Literature Search

It is widely accepted that cleanliness of the crack and the local road surface is very important to ensure that effective sealant adhesion to the road surface is achieved (Chehovits and Manning, 1984; Peterson, 1982; Rossman, et al., 1980; Belangie, 1989). These references, in addition to numerous others on this subject, unequivocally note that the crack must be free of moisture, dust, loose aggregate, and other contaminants for best sealant adhesion and life.

Therefore, to ensure the best seal from an automated crack sealing machine, the roadway should be heated prior to crack sealant dispensing to insure that the pavement is dry and to allow ample time for the 425°F hot-pour sealant to flow into the crack before cooling. As mentioned above, it is generally accepted that an off-the-shelf HCA lance is the preferred method of crack cleaning and heating among the labor crews today. However, typical existing HCA lances were built guided by different design criteria. They were designed to be hand held, to be simple to operate at slower than walking speeds, and to utilize a readily available air compressor as a means of supplying air to blow out the crack. These design criteria differ significantly from those of an automated crack sealing machine. Since the machine is to be designed for speeds greater than the current walking speeds, the heat output must be appropriately adjusted. A control package must also be implemented which will provide for automatic start-up and shut-down, and related safety features currently not available on HCA lances. Also, the air flow must be powerful enough to blow out a crack and/or its routed path given the inevitable errors associated with automatic sensing, robotic path planned motion, and vehicle positioning. For these reasons this section presents the finding from the feasibility study on various alternate methods of crack cleaning and heating and provides recommendations for the machine component design. Since both cleaning and heating need not be completed simultaneously, i.e., it is possible to use a simple air knife coupled with a radiant heat source to perform the given cleaning and heating tasks, cleaning is first briefly examined followed by an examination into viable heating methods.

1.5.1 - Crack Cleaning Methods

An in depth examination into possible pavement crack cleaning methods is not presented here. Instead, the interested reader is referred to Schultheis and Velinsky (1991) for a thorough investigation into automated pavement crack cleaning methods. Schultheis and Velinsky (1991) determined that abrasive vacuum blasting performs best in removing most forms of crack debris and road surface film. However, equipment costs, speed of operation, and power requirements proved significant and it was discarded as a viable method. As was pointed out though, centrifugal blowers may prove to be an effective method.

There has been a recent trend in the street sweeping industry. Cities across the nation are gradually shifting towards the purchasing "recirculating air sweepers" rather than the traditional mechanical sweeper. Roughly 60% of the market in 1987 was composed of mechanical sweepers as compared to 95% in 1977 (Layman, 1987). The shift is seen as a trend towards more reliable, simpler, and environmentally better equipment. Since dust and sound are major design issues in building a street sweeper, the recirculating air sweepers are well received in communities.

Typically, a street sweeper generates a velocity of approximately 200 MPH through the use of a 12,000 CFM blower (Novak, 1988). This volume and velocity produces enough sucking and blowing action to clean widths three times that of older mechanical sweepers. For details see Palmiter and Chermak (1974), Layman (1987), Toynton (1986), Best (1975), and Neise and Koopmann (1984).

This use of blowers on recirculating air street sweepers prompted an investigation into using blower air rather than compressed air to clean out cracks as well. Typically compressed air is ejected out of a nozzle at approximately 80 PSI and 75 CFM. This air expands very rapidly after leaving the nozzle and thereby does not have a long, wide "reach." This can best be visualized by holding the compressed air line from a gas station 4 feet off the ground and comparing its blowing effect to that of a garden leaf blower.

Compressed air cleaning is currently used in highway heating operations because compressors are readily available and crack eccentricity is not a major concern when using a hand held HCA lance. Nor is speed of much concern. However, on a crack sealing machine traveling much faster, a given robot end-effector can perform best by allowing the most tolerance, i.e., by rounding corners. And, as mentioned earlier, an existing HCA lance's compressed air knife does not effectively remove debris outside of an approximate 1" wide strip (+-1/2") and at speeds greater than 5 MPH (Schultheis and Velinsky, 1991). On the other hand, a high pressure centrifugal blower (relative to a low pressure 0-1 PSI blower) operates at roughly 2-4 PSI and therefore is able to clean a wider band since the air does not expand significantly after leaving the exit. Thus, a blower may be the best choice for crack cleaning.

The space savings by using a blower would be significant. A large 185 CFM compressor requires much power and roughly 72 ft^3 of space, whereas a hydraulic blower, which can tie into existing hydraulics used to power other subsystems, requires only about 2 ft^3 of space. Furthermore, the blower intake is available to be used as a vacuum source, possibly to catch and suck up dust and router debris (A router is a unit used by crews to cut a uniform rectangular cross-sectional reservoir before sealing, similar in principle to a woodworker's router. This cutting, in theory, minimizes stress concentrations present in a jagged edged unrouted crack that could lead to seal failure. It is planned that a router will used on crack sealing machinery under development at UC Davis). Since the router propels debris away from the blade at a high velocity, a "catcher" with a vacuum line could be attached in such a way to capture most of the debris. The vacuum line could then be plumbed through a dust collector where the pavement chunks and road dust could be removed prior to entering the blower face for recirculation.

Therefore, by using an off-the-shelf centrifugal blower as a means to clean the pavement prior to sealant application, cost can be minimized, travel speed can be enhanced (over the HCA lance) given the larger permissible crack eccentricity, a wider routed band can be cleaned, and the suction side of the blower can be used in a manner similar to a modern street sweeper.

1.5.2 - Crack Heating Methods

There are primarily two available methods of pavement heating, those being radiant and convective, and an extensive literature search has been conducted to gather information regarding each of these two pavement heating techniques. Radiant heating is currently being used in asphalt recycling and reworking operations and convective heating can be seen in use on the HCA lance. As mentioned, it is desirable to examine the feasibility of *both* heating methods since the conditions upon which the HCA lance was designed for are no longer accurate for the automated crack sealing machine. Also, one of the primary goals of the crack sealing project is to use existing off-the-shelf technology when possible to facilitate quick, reliable development of components and subsystems. Therefore, in order to best move forward in designing a useful heating system, it was decided to develop heat transfer models for both radiant and convective heating to not only determine the relative differences between the two heating methods but to determine the heating capabilities of currently available commercial heaters.

These models can be developed to output the temperature of the asphalt surface as a function of exposure time (or vehicle velocity), source temperature, and exit velocity (convective model only). The analytical development of such models is presented in Chapter 2, followed by testing of available commercial heaters in Chapter 3. Findings from literature are presented here first.

1.5.2.1 - Radiant Heating

There is a large body of literature available concerning radiant heat transfer to AC pavement. While none located relates directly to the rapid heating of pavement surfaces necessary for this project, much has been done in predicting temperature distributions within pavement relating to daily heating cycles, climatic variations, new construction paving, and AC pavement recycling.

Dickinson (1978) presents an in depth analysis of the 24 hour cyclic heating pavement undergoes using a finite difference computer model. The author is able to predict the temperature of a given sample of asphalt with known initial conditions to within 3°C. Marek and Dempsey (1972) examine the stresses and deflections in pavement systems through implementation of a similar finite difference model.

A two dimensional finite difference study to determine the average bulk temperature of windrows of hot-mix Asphalt Concrete under various environmental conditions was conducted by Fishback and Dickson (1973). A table of thermal diffusivity, thermal conductivity, and density of Asphalt Concrete (AC) at various temperatures was constructed by Highter and Wall (1983). The thermal properties for AC here were assumed to be those of aggregate, which is the common employed assumption since AC is made up of approximately 95% aggregate by weight (Carmichael et al., 1972). It should be noted however, that the thermal properties of a non-homogeneous material such as AC is at best an approximation and is subject to error.

Asphalt recycling operations provide the most applicable use of radiant heating technology to pavement crack sealing. Highway crews currently use radiant heaters to soften asphalt before scarifying and recycling. A number of papers have been written on the use of radiant heaters during these pavement recycling operations. Many discuss the implementation of a classical thermodynamic finite difference computer model applicable to the radiant heating of any homogeneous substance in order to produce temperature-depth history of the pavement. As noted, it is generally assumed that asphalt behaves as a homogeneous substance with properties of the aggregate. Carmichael, et al. (1972) developed a computer program that models the temperature distribution history within AC pavement subject to a radiant heating source. The program and its results are presented, but the model was *not* verified experimentally. Corlew and Dickson (1971) developed a similar computer model employing both radiant and convective boundary conditions but base it on a constant heat flux rather than the constant temperature source of Carmichael, et al. Both experimental and computational results are presented. Neither of these papers have considered cooling of the pavement surface as both were concerned only with heating in pavement recycling operations.

1.5.2.2 - Convective Heating

As cited previously, a recent value engineering study surveyed Departments of Transportation from 23 States and concluded that an HCA lance is the "most effective preparation tool for the majority of conditions encountered" (Rossman, et al., 1990). While it is generally accepted that using a hand held HCA lance to heat and clean pavement is effective in lengthening the life span of pavement, there is no available analysis that estimates the local heat transfer coefficient at the pavement surface which could lead toward the optimization of the heater exit velocity, temperature, and loiter time. Such information is necessary to examine the feasibility of using existing HCA lances at significantly higher travel speeds (perhaps as high as 10 MPH), the effects of modifications to such devices, and for the possible design of new generation heating systems.

However, the transfer of energy via an HCA lance combustion chamber, or any burner system chamber, strongly resembles the classical thermodynamic case of a turbulent axisymmetric jet impinging normally on a flat plate (as long as the flame is not impinging on the surface). Results of the numerous studies that examine this problem typically present the heat transfer coefficient in non-dimensional form as a function of the Nusselt number as:

$$Nu_D = \frac{h_{conv} D}{k} \tag{1.1}$$

where h_{conv} is the local heat transfer coefficient, k is the thermal conductivity of the exit gas evaluated at the average film temperature, and D is the diameter of the hot gas exit.

Many recent studies have been conducted concerning optimization of heat transfer between an impinging jet on a flat surface. Baughn and Shimizu (1989) present results of experiments using liquid crystals to measure heat transfer from a fully-developed jet impinging on a flat plate. The two significant factors that affect the heat transfer, the height of the jet exit above the material, Z/D, and the lateral distance from the stagnation point along the surface of the material, r/D, were studied. The authors showed that maximum heat transfer occurs for a jet-to-plate distance of approximately 6 and, that for a height greater than Z/D of 6, entrainment effects of the surrounding air start to become significant. Additionally, they showed that at a Reynolds number, Re_D, of 23,750, the Nusselt number generally decreases from Nu_D=160 at r/D=0 (the stagnation point) to Nu_D=30 at r/D=14, where r/D is the number of diameters down stream from the stagnation point parallel to the surface. (The Reynolds number is a non dimensional measure of the degree of turbulence a fluid flow exhibits. It is expressed as: $Re_D=DV/v$ where D is the pipe or nozzle diameter, V is the exit velocity, and v is kinematic viscosity of the exit gas.) An HCA lance operating at maximum heat, based on manufacturers specifications, has an approximate burner tube Reynolds number of 3,000.

Hrycak (1983) studied flow impinging on a flat plate with Reynolds numbers ranging from 14,000 to 67,000. Like the previous study, he concluded that the maximum heat transfer at the stagnation point occurs at $6 < Z/D < 7$. Hrycak's testing at Reynolds numbers of 56,000 produced a maximum Nusselt number of approximately 260 at stagnation. Non-dimensional curve fit equations of the experimental Nusselt number data were derived from two samples made of materials with differing roughness. The results differed greatly and Hrycak (1983) concluded that surface roughness definitely plays a role in forced convective heat transfer. However, he offers no solution as to how to model the Nusselt number, Nu_D, as a function of surface roughness.

The effects of entrainment of the surrounding air was investigated by Hollworth and Gero (1985). The authors found that for modest temperature differences between the jet and the surface of the sample, ΔT=60°C (140°F), the effective heat transfer is significantly decreased, the extent of which is not explained. The study also provided more evidence showing the increase in heat transfer with increasing Reynolds numbers. An experimental setup simulating jet motion across the surface of a substance, similar to the motion an HCA lance exhibits as it passes over the pavement, was constructed. Plots show Nusselt number/radial distance trends similar to those presented by Baughn and Shimizu (1989). The authors state though, that for large temperature differences, on the order of those sought by use of an HCA lance, density changes of the air may play a large role in affecting the energy transfer.

Goldstein and Behbahani (1982) measured the effects of cross flows on heat transfer performance. Reynolds numbers as high as 121,000 were examined with cross flow velocities of 8.5 m/s and 16.5 m/s. Results indicate that, given a cross flow, axisymmetric jet symmetry is lost and the location of the maximum Nusselt number is pushed downstream radially. Plots of the Nusselt number are presented at jet-to-plate distances of 6 and 12 diameters as a function of radial distances as high as 50 diameters. Based on experimental data, a regression analysis was performed to solve for the mean Nusselt number. For Z/D=6 this equation was found to be:

$$\overline{Nu} = \frac{Re_D^{.6}}{3.329 + 0.273(r/D)^{1.3}}. \tag{1.2}$$

This finding appears to be significant as it compares well to much of the literature cited. Also, it is valid for any turbulent Reynolds number.

The equations and methodology outlined above form the basis for the heat transfer models developed in the next chapter.

CHAPTER 2 - HEAT TRANSFER MODEL DEVELOPMENT

2.1 - Introduction

Based on initial automated crack sealing machinery goals, an approximate relative speed between the heater and pavement of 2 MPH is desired. So, given any reasonably sized heater, this means that only a few seconds of heat are available for crack heating, rather than the longer exposure times typically available during pavement recycling and current manual crack sealing operations. This short heat exposure and thereby shallow heat penetration coupled with the non-homogeneous, rough surface of pavement, make the accurate prediction of pavement surface temperature difficult. Therefore, any tool that can help to estimate the performance of commercially available heaters to be used in, to date, an untested application, is a welcome instrument that will aid in the designing of automated crack heating equipment. This chapter discusses the development of such tools, computational heat transfer models, based on the literature discussed in Chapter 1. These tools will then be used in developing an automated means of cleaning and heating pavement cracks prior to sealant application.

2.2 - Radiant Model Development

When sealing cracks it is only of interest to heat the *surface* of the roadway as this aids in the formation of the bond between the sealant and the pavement and forces the evaporation of any latent moisture. Any excess heat which penetrates down into the pavement is incidental. During recycling operations however, it is important to heat the pavement to a significant depth and much research has been presented as to how this heat penetration can be enhanced.

Typically, recycling crews are interested in heating the asphalt from 1.5" to 3" in depth to a temperature of approximately 175°F. In order to prevent combustion of the asphalt during this radiant heating process, the surface temperature must be limited to 350°F (Highter and Wall, 1983). Therefore, to maximize the effectiveness of the "rework", i.e., to heat the Asphalt Concrete (AC) to a reasonable depth for recycling, the pavement must be heated slowly to prevent overheating of the surface while still allowing the heat to "soak in". A heating time of approximately 2-5 minutes is normally required for such a recycling operation (Osborne, 1988). During crack sealing operations however, the conditions for the heat transfer drastically differ.

As discussed in the previous chapter, Corlew and Dickson (1971) presented experimental and theoretical radiant heating data based on a constant heat flux model and Carmichael, et al. (1972) presented an *unverified* simulation model for radiant heating based on a constant temperature source. The approach taken in this report for developing a useful model includes the modification of this Carmichael, et al. model to reflect the types of heaters that can be used for crack sealing operations. The predictions from this modified model are then compared with Corlew and Dickson's experimental data to verify its accuracy. The model is then used, in Chapter 3, to evaluate available commercial heaters of interest for use on the crack sealing project.

Carmichael, et al. (1972) models AC pavement as a semi-infinite solid initially at ambient temperature. The temperature above the surface is then suddenly changed to maintain a source temperature T_S. The program uses the finite difference numerical method to solve for the temperature of each incremental depth, *dz* after an incremental time step, *dt*. Conductive heat transfer effects at the surface are neglected as well as convection effects within the asphalt. The exact asphalt temperature distribution is represented by:

$$\frac{\delta T}{\delta t} = \alpha \frac{\delta^2 T}{\delta z^2} \tag{2.1}$$

or incrementally as:

$$T_i^{j+1} = T_i^j + \alpha \frac{dt}{dz^2}(T_{i+1}^j + T_{i-1}^j + 2T_i^j) \tag{2.2}$$

where i is the depth increment, j is the time increment, and α is the thermal diffusivity of the asphalt, 6.314 x 10^{-6} ft^2/s (Highter and Wall, 1983). The surface boundary condition is represented as:

$$\frac{T_i^{j+1} - T_{i-1}^{j}}{dz} = \frac{T_i^{j+1} - T_S}{\left(\frac{k}{h}\right)} \tag{2.3}$$

where i=1 at the surface, k is the thermal conductivity of the asphalt (.7 BTU/hr•ft•°F) and h is the total heat transfer coefficient at the surface made up of a radiant part, h_{rad} and a convective part, h_{conv}. Incrementally the boundary condition is represented as:

$$T_1^{j+1} = \frac{dbx(T_2^j) + dx(T_S)}{dbx + dx} \tag{2.4}$$

where $dbx=k/h$. The radiant heat transfer coefficient, h_{rad}, is determined by arranging the equation for radiation between two flat plates of equal area in a form similar to the convection equation $Q=hA\Delta T$ as follows:

$$Q = \frac{\sigma\left(T_1^3 + T_1^2 T_2 + T_1 T_2^2 + T_2^3\right)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F} + \frac{1-\varepsilon_2}{\varepsilon_2}} A\left(T_1 - T_2\right). \tag{2.5}$$

The large product on the right side of Eqn. (2.5) represents the effective radiant heat transfer coefficient, h_{rad}. Carmichael, et al. (1972) give h_{conv}=1.4 BTU/hr•ft^2•°F for air at 7.5 MPH. This value is acceptable for heating at crack sealing vehicle speeds. The total heat transfer coefficient h_{tot} is then represented as the sum, $h_{rad}+h_{conv}$. The author, nevertheless, chose to neglect the convective contribution, h_{conv}, since the radiant, h_{rad}, was found to be approximately 20-30 BTU/hr•ft2•°F. In Eqn. (2.5) above, the authors take T_1 and T_2 to represent the temperature of the surface of the heater and asphalt, respectively. ε_1 and ε_2, the heater and asphalt emissivity, are taken to be .9 and .95, respectively, and F, the shape factor, is taken to be 0.9. Boltzman's constant is 1.7121 x 10^{-9} and is shown as σ.

In order to meet project needs, this model was first modified to account for the free convective heating coefficient, h_{conv}. Second, a calculation for the rectangular shape factor consistent with typical radiant heaters (as opposed to an estimation) was added. The following equation provides the three-dimensional shape factor F for two rectangular parallel plates of length L and width W separated by a distance D (White, 1988):

$$F = \frac{2}{\pi XY}\left[\ln\left[\frac{(1+X^2)(1+Y^2)}{1+X^2+Y^2}\right]^{1/2} + Y\sqrt{1+X^2}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + X\sqrt{1+Y^2}\tan^{-1}\frac{X}{\sqrt{1+Y^2}} - X\tan^{-1}X - Y\tan^{-1}Y \right] \tag{2.6}$$

where $X=W/D$ and $Y=L/D$. It should be noted that this shape factor is given for two plates that are stationary with respect to each other. During an actual crack sealing operation, the heater moves over the road surface thereby constantly changing the actual local shape factor from 0, when the heater is infinitely far down the road, to approximately 1, when it is just above the point of interest, then back to 0 as it passes. Eqn. (2.6) does however, provide an estimate of the relative magnitude of heat exchange that takes place when compared to other heater sizes, speeds and fly heights, D.

Lastly, the model was altered to account for the cooling of the pavement. Accurate modeling of the road surface temperature as it cools provides a means for determining the maximum distance between the sealant applicator head and heater surface in order to promote optimal adhesion. During cooling, both convective and radiant effects are significant and are accounted for in the following equation of the cooling process:

$$\Delta x \rho C_v \frac{\delta T}{\delta t} = k\frac{\delta T}{\delta t} - \varepsilon_2 \sigma T_2^4 - h_{conv}(T_2 - T_{amb}) \tag{2.7}$$

The resulting finite difference FORTRAN model is presented in Appendix A. However, it remains unverified and therefore, its performance must be validated in order to correctly rely on its performance predictions of commercially available heaters.

2.3 - Radiant Model Verification

There are two possible ways of verifying the radiant model developed above. The first requires an experimental set-up designed to measure the temperatures at various depths in a pavement sample as radiant heat is passed over it. The second method requires altering the developed model in such a way as to accommodate for the experimental conditions Corlew and Dickson had in their verification tests. In this case, if the developed model, with its slight alterations, could give temperature profiles which match those measured by Corlew and Dickson, it could reasonably be assumed that it would serve as a useful tool in evaluating commercial equipment. In the interest of time, the second method was selected.

For their experiment, Corlew and Dickson used a simple direct-fired propane heater to heat a 4" diameter asphalt core insulated on its sides, as shown in Figure 2.1 below. Temperatures at various depths were measured using thermocouples. White (1988) gives the following equation for the three-dimensional shape factor F for two circular parallel plates of radius R_1 and R_2 separated by a distance D:

$$F = 0.5\left[X - \left(X^2 - 4Z_2^2 / Z_1^2\right)^{1/2}\right] \tag{2.8}$$

where $X = 1 + \left(1 + Z_2^2\right) / Z_1^2$ and $Z_1 = R_1 / D$ and $Z_2 = R_2 / D$. Since data was not provided as to the distance D below the heater that the nozzle was placed nor the nozzle radius R_1, nominal values were chosen for verification testing to be 2" and 1/2", respectively. R_2 was set equal to 2" (1/2 the 4" core diameter).

Also, since the Corlew and Dickson experiments were based on a constant heat flux rather than a constant temperature source, it was necessary to use their experimental information that was provided to solve for the equivalent heat source temperature. This temperature could then be used as input into the developed model. Corlew and Dickson stated that their propane burner provided a heater release rate of 75,000 BTU/hr•ft^2 with a thermal efficiency of 60%. To solve for the equivalent heater source temperature for this condition, iterative computer runs using the developed model were made at various input source temperatures, T_1. During these runs the radiant heat transfer coefficient h_{rad} was plotted with each time step and the average value was then multiplied by the average temperature difference between the heater surface and pavement surface temperature (T_1-T_2) to obtain the average heat flux. Iterations of the source temperature T_1 were made until the average heat flux was found to be 45,000 BTU/hr•ft^2 (60% of 75,000 BTU/hr•ft^2). This method resulted in the determination of an average source temperature of 1813°F which corresponds well with the typical value of 1800°F of a propane heater (Carmichael, et al., 1972).

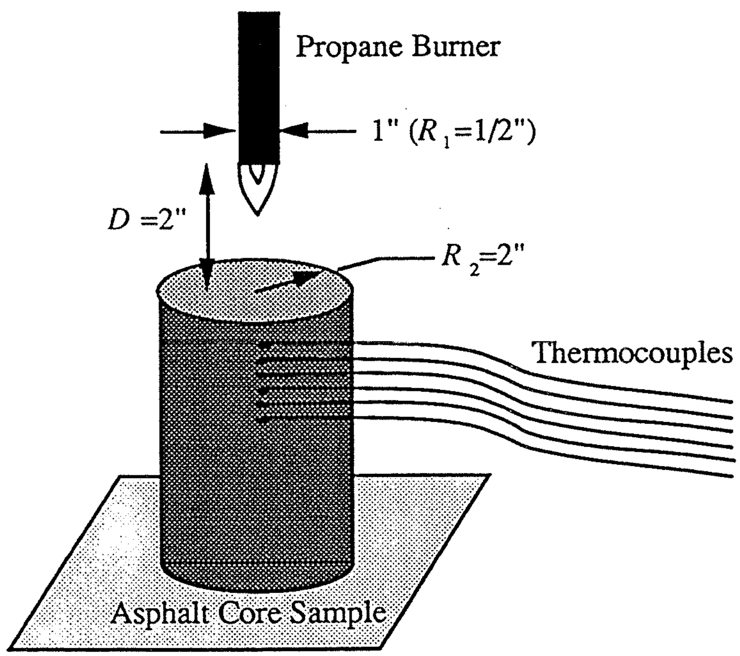


Figure 2.1 - *Corlew and Dickson's experimental set-up. For illustration purposes, the insulation sleeve outside the core sample is not shown.*

As an additional check, the new constant temperature source model was then altered to behave as a constant heat flux model. This required changing the method by which the surface temperature was calculated with each time step. Both the average value of h_{rad}

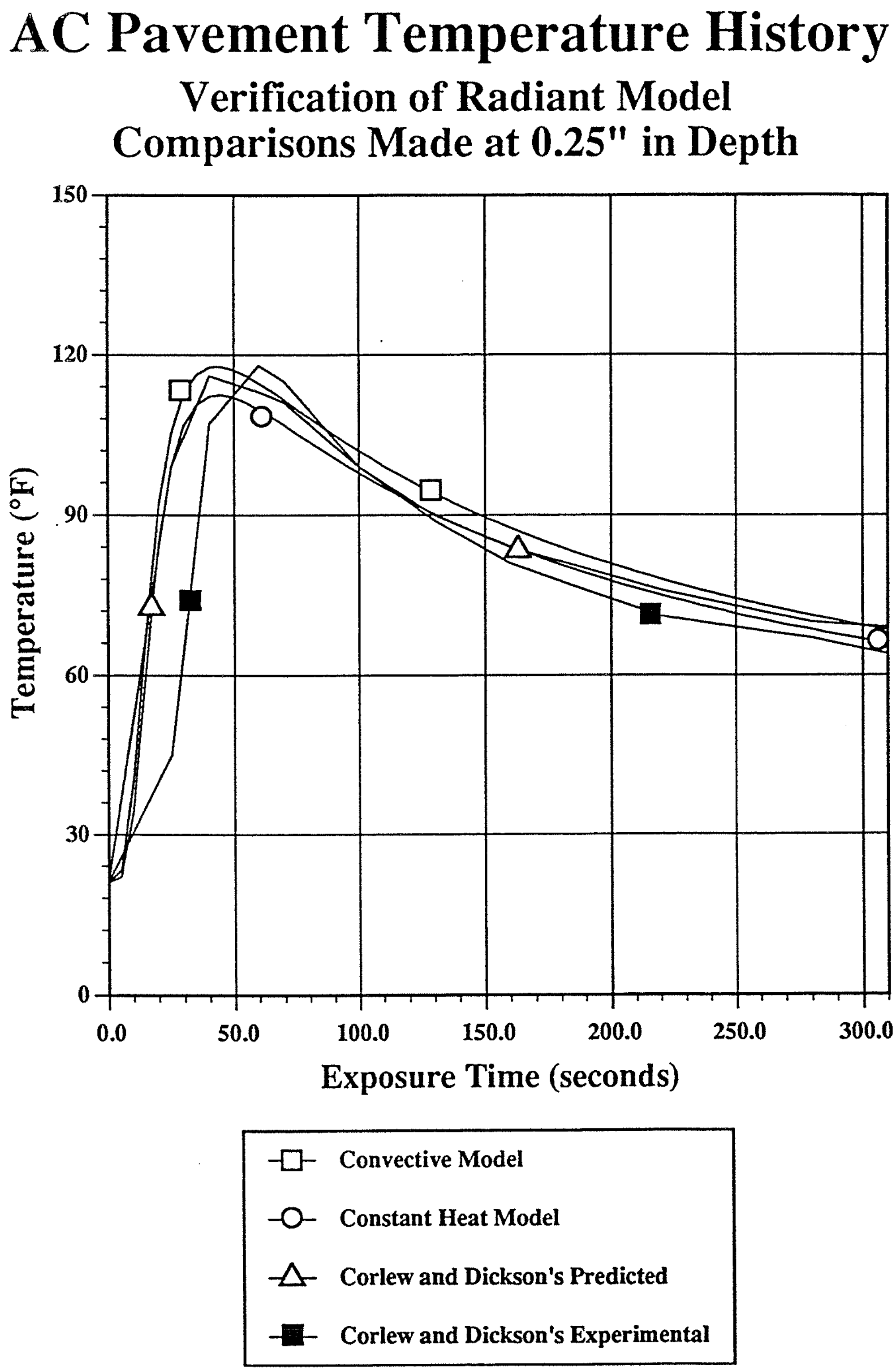


Figure 2.2 - Radiant model comparisons with experimental and theoretical data.

found above and the source temperature became inputs to the new constant heat flux model.

With these changes complete, the Corlew and Dickson experimental *and* theoretical data could then be compared against the data provided by these *two* new models, the constant temperature and the modified constant heat flux models. The FORTRAN program for each of the verification models is presented in Appendix A. These models were then run and the results plotted for AC depths ranging from 1/4" to 2" verifying the performance to within an approximate +/- 10°F error. (Figure 2.2 depicts a representative plot with the rest presented in Appendix A). This seems reasonable given the various assumptions made in simulating the Corlew and Dickson experiment, the difficulty associated with accurately extracted particular data points from their plots, and the non-homogeneous structure of asphalt. Certainly a model of this accuracy should prove adequate in assessing the feasibility of the radiant heating approach.

2.4 - Convective Model Development

It is desirable to build a convective heat transfer model, similar to that constructed above, to size a burner that can heat the road surface while traveling at speeds of perhaps as high as 10 MPH. Fortunately, a minimum number of modifications to the radiant model are necessary since heat conducts within a material in the same manner, whether it got there by radiation or convection. Therefore, a modification to the boundary layer condition is the only significant change needed to transform the radiant model into a convective model. This is accomplished by using Eqns. (1.1) and (1.2) from Chapter 1 to find the forced convective heat transfer coefficient, h_{conv}, as a replacement for Eqn. (2.5) used in the radiant model. The temperature distribution is then determined, as in the radiant model, from Eqns. (2.2), (2.3), and (2.4) neglecting radiant effects (this is permissive since the emissivity of a gas is negligible).

Of course other supporting changes are needed in the program code to properly implement these equations. Gas tables must be installed in the software to reflect the changes in density, kinematic viscosity, and thermal conductivity of air as a function of temperature. Also, due to end-effector space limitations and the extreme dissipation of the high volume hot gases, an assumption as to effective lateral reach (parallel to the surface) of the hot air must be made. Baughn and Shimizu (1989) contend that heating effects are measurable well past 14 diameters since the Nusselt number is still significant. However, their study was conducted using a smooth surface sample with a relatively small air flow and ΔT. It is believed that in this application the extreme mixing that takes place immediately after exiting the burner tube imposes a limitation. Also, blast shields and safety skirts are to be placed adjacent to the burner to help contain the heat thereby further limiting the flow. It was decided therefore, that heating effects can only be valid to approximately 4 diameters, $r/D=4$, and this assumption is reflected in the developed software.

It should be noted that in modeling a convective heater using this new model, additional user inputs particular to the specific heater in question are required. In using the radiant model one must only be concerned with the source temperature and heater face geometry. In using the convective model however, one must also know the amount of air, in cubic feet per minute (CFM), and fuel in CFM that the burner is receiving. Since most manufacturers specify the heat output of their burner in BTU/hr, a conversion to CFM of fuel is needed. For LP gas (propane), the fuel to be used by automated sealing machinery, this is found by dividing the rated heater output in BTU/hr by the heat of combustion for propane, 21,591 BTU/lbm, and by dividing that number by the density of propane, 0.3519 lbm/ft^3, (62°F, 30 PSI) (Baumeister and Marks, 1967) and converting the result to CFM. Together this means:

$$CFM_{LP\,gas} = \frac{BTU}{455{,}872}. \tag{2.9}$$

Eqn. (2.9) represents the volume flow of the propane entering the burner at a given heater BTU. This volume flow can then be added to the CFM of air and the total divided by nozzle area to determine the exit gas velocity. For convenience Eqn. (2.9) is handled in software requiring the user to enter only the BTU/hr of the heater and the CFM of air being supplied. Typically the CFM of fuel will only make up a tiny fraction of the total exit volume and could be probably be neglected. However, in the interest of completeness it is included in the modeling program.

The resulting convective model predicts AC pavement temperature profiles as a function of vehicle velocity, CFM of supply air, BTU of heat, exit gas temperature, and nozzle diameter. FORTRAN code for this computational model is presented in Appendix B. It is important to again point out that data produced by the model may be in significant error due to pavement non-homogeneity, surface roughness, expansion effects, and ideal combustion estimates. Thus, detailed verification testing is necessary to rely on its predictions.

2.5 - Convective Model Verification

Unlike with the radiant model, verification of the convective model is not possible through comparisons with published experiments since no literature reporting on the surface temperature history of AC pavement under convective heating has been located. Instead, unique experiments must be devised to determine the accuracy of the convective model in estimating heater performance. This would require the construction of a propane burner heating system and test apparatus. Once verified the model could then be confidently used to gage the crack surface heating ability of commercially available equipment.

Time and money however, are a prime concern in the crack sealing project - as in any engineering project. The supposition was therefore posed: should the model prove to be accurate during verification testing, then time spent constructing heating equipment and measurement systems used in verifying the model could have been better spent verifying the heating ability of an actual commercially available heater. Therefore, in

Chapter 3 accuracy of the convective model is assumed and tests of available equipment are performed. Model accuracy is then proved implicitly by examining test results.

CHAPTER 3 - HEATING EQUIPMENT TESTS

3.1 - Introduction

In this chapter, both radiant and convective off-the-shelf heating equipment is examined using the heat transfer models developed above to determine the most viable heating system for automated pavement crack repair. From the literature study, it was determined that for this project, the most feasible means of *cleaning* pavement cracks automatically is by using high volume air from a centrifugal blower. In the discussion to follow, therefore, it is assumed that this crack cleaning method will be employed.

Before discussing the testing, a crucial design issue must be resolved. To this point in the report, the desired crack temperature before sealing has not been discussed. This is because there is not any conclusive evidence, to this author's knowledge, dictating optimum crack surface preheat temperature. As mentioned earlier, road crews today currently heat cracks until the surface begins to smoke and discolor. They then typically follow some time afterwards applying sealant. This delay between crack heating and sealant application often approaches several seconds thereby allowing the crack surface time to significantly cool (see Figure 3.1). By permitting the crack to cool, the freshly applied, 425°F sealant sets up quicker, inhibiting good sealant flow into the crack. Therefore, the heating done to enhance sealant quality is often partially negated by delayed sealant application.

Through automation, a goal of the crack sealing project is to shorten this delay by minimizing the time (or distance) between heating and sealant application. This will help ensure adequate sealant flow into pavement cracks. Yet, the temperature of the optimum surface preheat is still unknown.

A brief investigation was conducted by UC Davis crack sealing project personnel to estimate the temperature at which AC pavement discoloration begins. Through the use of a hand held infrared measurement device, this temperature was estimated to be 280°F. This seems reasonable since Highter and Wall (1983) determined that AC pavement combusts at 350°F. Therefore, in the interest of safety and a quality seal, it was decided that a conservative surface temperature goal of 250°F be adopted in developing the heating unit. At such a temperature, moisture should be evaporated and sealant flow should be much enhanced compared to current sealing methods.

Because of the non-homogeneous substance structure of AC and its typically rough surface texture, accurate modeling of individual points on the pavement surface is difficult. And, due to the strong insulating property AC pavement exhibits, its temperature changes *dramatically* with depth increments as small as .02" (see Figures 3.1 and 3.2). Thus, it is important to examine the pavement's temperature/depth profile in small incremental steps near the surface to gain a full understanding of pavement heating phenomena. Taking this into consideration, the models do give a reasonable estimate of the *average* surface temperature and are quite useful for this application.

3.2 - Radiant Heating Tests

In this section, the verified radiant model developed in Chapter 2, is used to size a radiant heater that can perform the crack preheat required. A variety of commercially available radiant heaters were simulated to determine their appropriateness for use on automated crack sealing machinery. Most of these heaters employ proprietary infrared heating techniques using, for example, propane heated metal mesh or absorbent bricks as the radiant source. Typically the output of the heaters is expressed in terms of BTU/hr per linear foot of heating surface (usually 1 ft. wide).

Based on simulations of commercially available heaters, Maxon Corporation's Infrawave heater with a source (face) temperature, T_S, of 2100°F provides the best heating results. This heater produces 132,000 BTU/hr/linear foot, the highest output found amongst commercially available heaters. By trial and error a heater length of 4 ft. was determined as necessary to reach a surface temperature of 250°F while traveling at 2

MPH (assuming a 3" fly height), i.e., approximately 528,000 BTU/hr of radiant heat (see Figure 3.1). While a radiant heater 4 ft. in length would appear feasible for a machine that addresses strictly straight, long cracks, it is apparent that a heater of this length coupled with blower air from the cleaning system would be quite difficult to articulate on a machine that addresses random, meandering cracks. Thus, convective heating will now be examined which has the potential for a much more compact design.

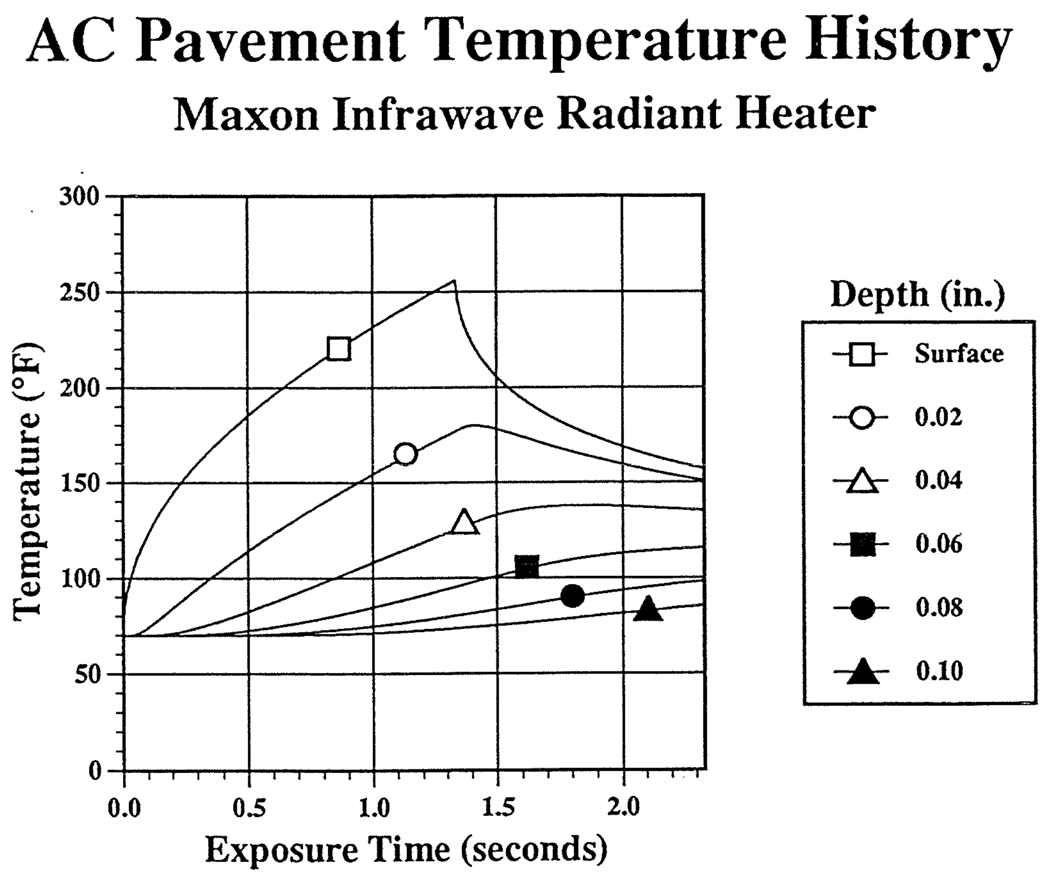


Figure 3.1 - *Maxon Infrawave radiant heater passing at a relative speed of 2 MPH. Length = 4 ft., T_S = 2100°F, fly height = 3", width = 9".*

3.3 - Convective Heating Tests

Convective heating as a crack heating method appears, immediately to have one advantage over radiant. The exhaust gas from the heater could dually serve as a means to heat *and* clean the pavement cracks, as in the HCA lance. This could add to the compactness of any heating system. In order to test such a commercially available convective heater and thereby implicitly verify the validity of the convective model, it was first necessary to construct a test apparatus.

3.3.1 - Set-up

To best simulate the relative motion between the vehicle and pavement surface, a movable test apparatus was built. The top portion was made from steel channels to serve as rails upon which a motorized cart containing the propane heater could ride. This cart could then be moved across the asphalt sample, heating its surface as it passes by (see Figure 3.3). As can seen from Figure 3.2, an infrared pyrometer was used to continuously measure the surface temperature of the sample just after the heater is passed over. This method of temperature measurement was chosen since a real-time, non-tactile means of measuring pavement temperature would most likely be necessary on the final cleaning/heating system. Also, a pyrometer provides a means of averaging the temperature variations, inevitably present from point to point on the non-homogeneous pavement surface, over the region of interest. It does this by measuring the total heat seen through its lens and dividing it by its focal area. While a matrix of thermocouples placed at various depths in the sample are very inexpensive and have been used in studies previously, the tiny 0.005" diameter K-type thermocouples needed to meet the quick response requirements (less than 100 ms) for this application proved to be very fragile and electrically noisy for the data acquisition hardware in use (see below). As such, thermocouples were discarded as a viable test measurement device. While thermocouples do appear in some of the photos that follow, their outputs were not used in analyzing any of the test data. A pyrometer is generally very accurate and quick, yet is much more expensive.

The pyrometer purchased is a Raytek Thermalert ET3LT. It features adjustable emissivity, 12 bit digital circuitry, and outputs a standard linear 4-20 mA control signal representing a surface temperature between 0 and 400°F. For this temperature range, this means a resolution of roughly one 0.1°F can be achieved. It has a 95% response time of 80 ms (2.88" of pavement surface at 2 MPH). Also, the water cooled housing and air purge collar options were purchased to keep the circuitry cool and the lens dust-free in a harsh environment. To continually store the pyrometer surface temperature readings as the heater is passed over the sample, a Microsoft QuickBASIC program was developed using a DAS-16 data acquisition card from Keithley/Metrabyte (program code available upon request).

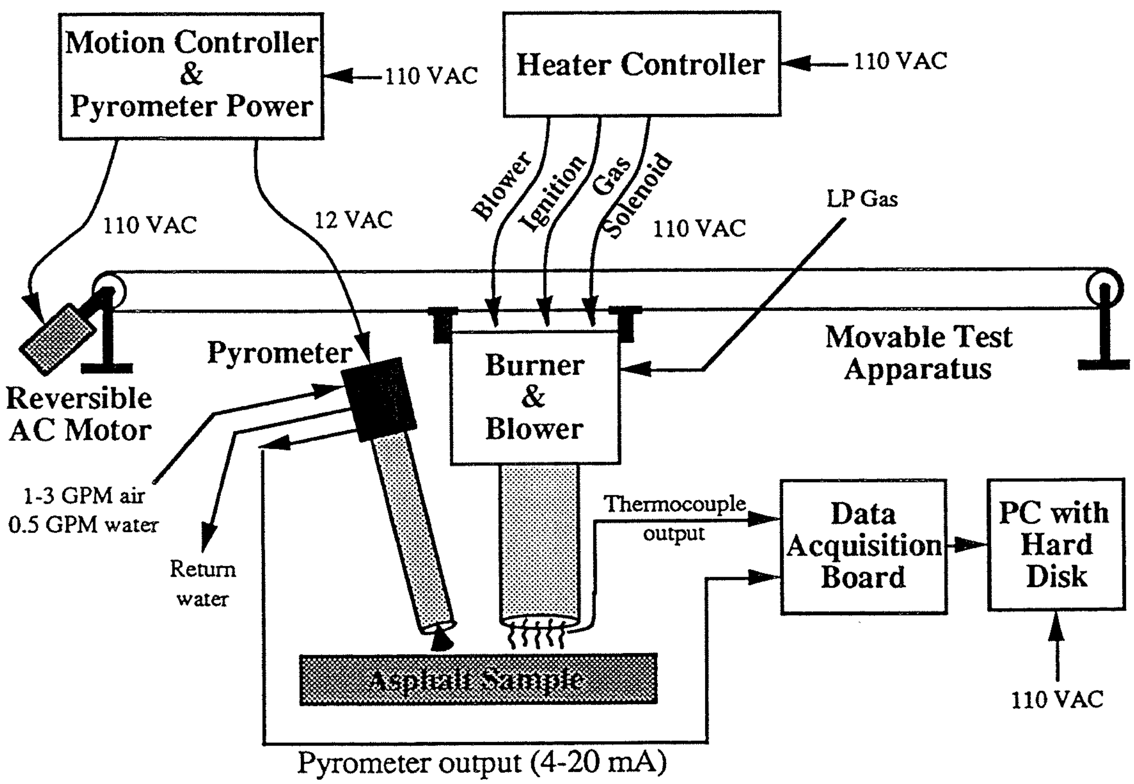


Figure 3.2 - Experimental set-up.

A commercially available burner was then needed to attach to the test apparatus. Using the convective heat transfer model, a burner system able to heat the surface of the roadway as close to 250°F as possible while passing by was sized. It should be noted that burner size is not directly proportional to vehicle speed. This is because heat can only be transferred to the surface of a medium via the local heat transfer coefficient which, as shown earlier, is a non-linear function of Reynolds number or, more specifically, exit diameter. Thus, from Eqns. 1.1 and 1.2, a large BTU rating coupled with a small exit diameter provides the best heat transfer.

It was desirable to maximize the heat transfer and automation of the heating process. Vendors were contacted and various burner configurations were examined. It became apparent during this process that to achieve a surface temperature of 250°F at 5 - 10 MPH would require an expensive, inefficient, noisy, and cumbersome heating system. Keeping in mind the scope of this project, to produce prototype crack sealing machinery that can be used in developing a machine for later commercialization, smaller, more reasonably sized burners and burner control systems were therefore looked at that, during commercialization, could be replaced with a larger unit.

The choice was made to test a 1.8 million BTU/hr tube burner by Sur-Lite Corporation because of its high convective heat transfer ability and small size. It was estimated, using the computational model, that a surface temperature close to 250°F with a relative speed of 2 MPH could be attained with a slightly modified stock unit. The standard stock unit uses air from an onboard 300 SCFM blower mounted to the burner to produce an exit velocity estimated to be 35 MPH from its 6" diameter flame tube. It was felt that by necking down this exit tube to effectively create a nozzle, the exit velocity could be greatly increased, perhaps to over 100 MPH. However, to do so, the standard 1/3 HP, low pressure blower (less than 1/4 PSI) must be replaced with an optional 3-phase electric or hydraulic high pressure blower (approximately 10-15 HP, 2-4 PSI) which would be better equipped to handle the associated pressure losses that accompany the addition of a nozzle. The Sur-Lite system comes as a complete integrated package and is therefore more reliable than a currently used hand held HCA lance. A flame safeguard system is provided which includes automatic ignition, throttling, shut-down, and emergency shutdown.

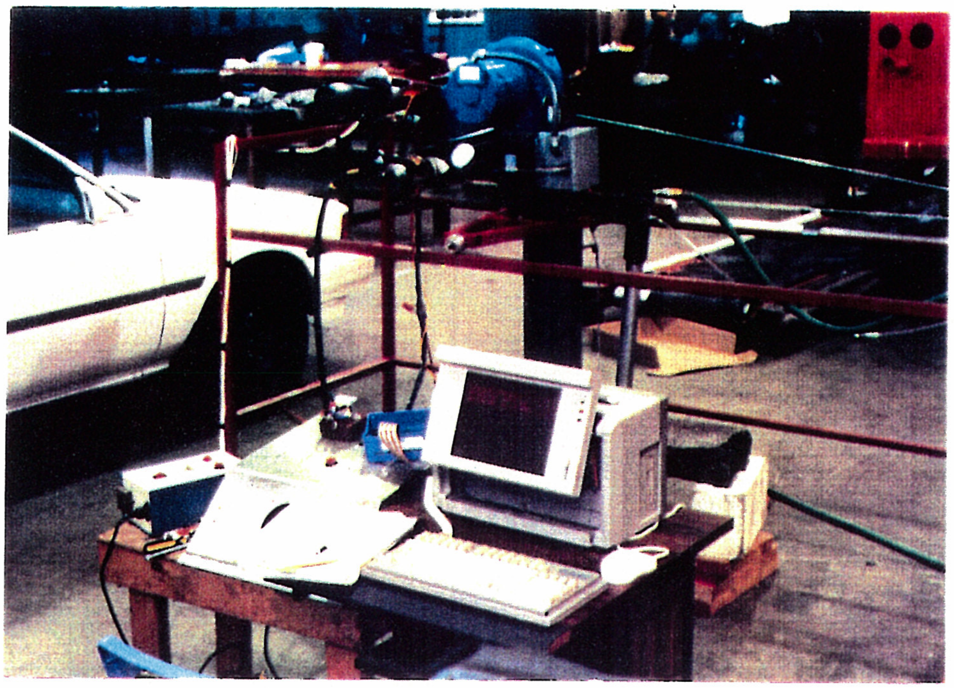


Figure 3.3 - Test apparatus set up with Sur-Lite burner installed.

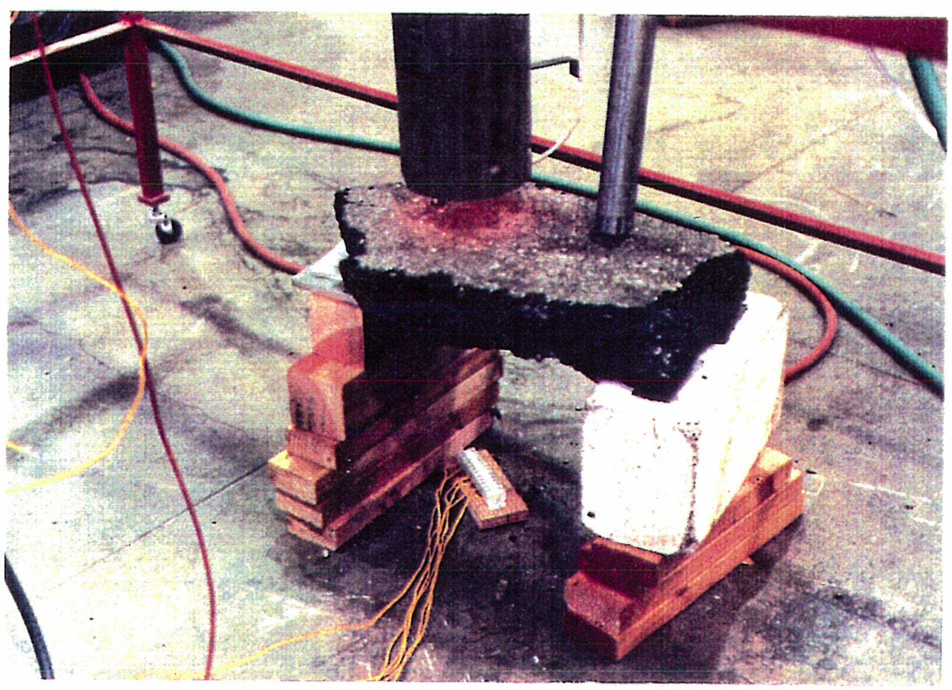


Figure 3.4 - Close up of sample being heated with Sur-Lite burner. Note: the thermocouples mounted in the sample were not used in this study.

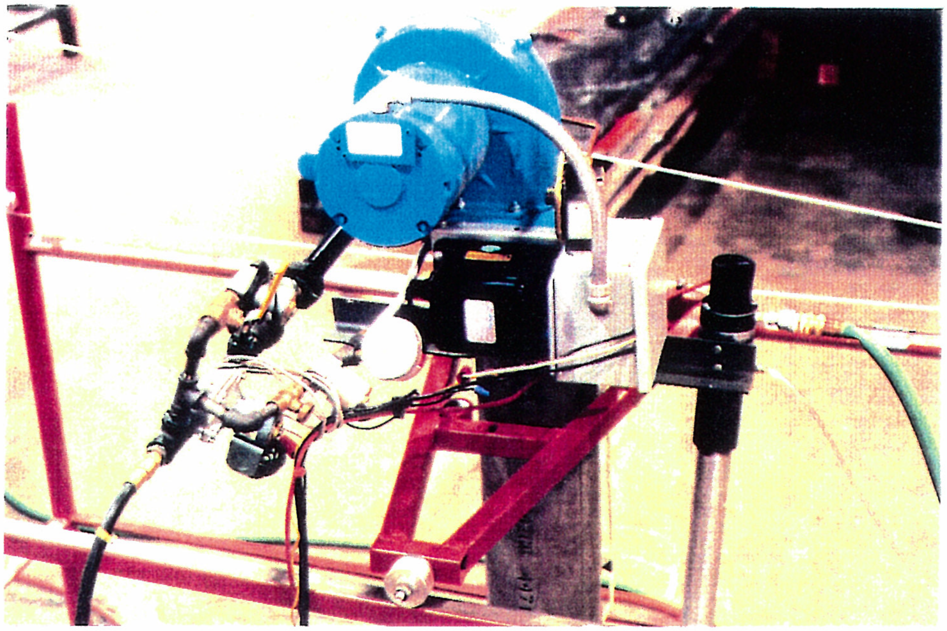


Figure 3.5 - *Sur-Lite Burner with Raytek pyrometer mounted adjacent. Note the water cooled housing and air purge attachments on the pyrometer.*

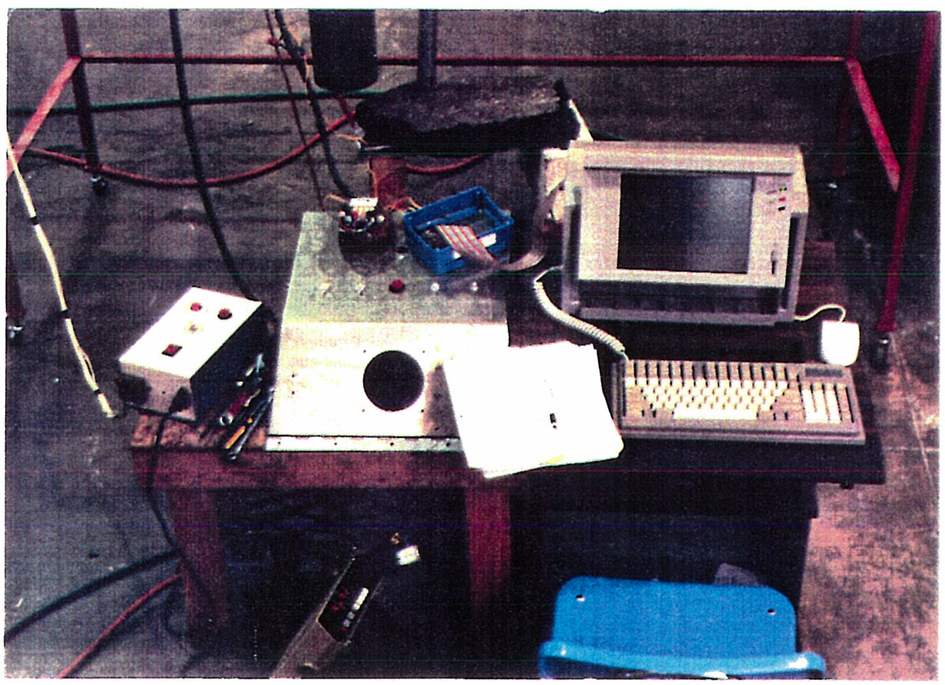


Figure 3.6 - *Data acquisition station. The control box on the left provides power to the cart motor. To its right is the scrap panel that houses the spark ignitor push button and solenoid valve toggle switches for the burner. On top of it is the transformer providing 12 VAC power to the pyrometer and the connector board for the inputs to the DAS-16 card. On the floor a thermocouple is connected through a DVM to measure ambient temperature.*

Sur-Lite was contacted and a standard low pressure tube burner, model 12031-4, configured with a *low* firing fuel train was sent to UCD on loan. While if given the choice, a fully equipped, high firing unit with an optional hydraulic high pressure blower would have been tested, Sur-Lite personnel were kind enough to loan their equipment for the study. The test results therefore reflect the significantly low heat output of the burner (approximately 200,000 BTU/hr) and low burner exit velocity (approximately 35 MPH) associated with the large 6" diameter exit. For purposes of these tests and comparison with the heat transfer model though, these factors were not important.

The borrowed Sur-Lite heater thus described was then mounted on the test apparatus described above, wired through a scrap bench test control panel, and tested against model predictions (see Figures 3.3 - 3.6). As seen in these figures, a K-type thermocouple was placed in the center of the exit stream at the end of the burner tube, approximately 1" from the pavement in most cases. This was done to record the temperature of the impinging air flow for later entry in the software model.

3.3.2 - Procedure

To best compare temperature profile data from the convective model with data gathered testing the Sur-Lite burner, a formal test procedure was adopted. Test runs were typically performed as follows. First, the ambient temperature was measured using a cold-junction compensated, K-type thermocouple device connected to a digital voltmeter and entered into the data acquisition program - and later in the heat transfer model. Next, the height of the burner, sample number, and pyrometer location (distance aft of duct) were recorded. Third, with the heat off, the cart was rolled across the sample at a constant rate (determined by measuring the time taken to cover the test section distance of 62") while collecting surface temperature data. The heater was then ignited and allowed to warm up for several seconds. Then, again with the computer acquiring surface temperature data, the heater was passed over the sample. The surface was then allowed to cool before the next run. These steps were repeated with varying speeds, samples, fly heights, and exhaust temperatures (a function of LP gas pressure).

During each run, the DAS-16 QuickBASIC program recorded to disk, the heat source temperature according to the thermocouple located at the tube exit, and the surface temperature that the pyrometer encountered based on its .95 emissivity setting. Since the data collection program had to be started before the heater was passed over the sample, to capture the entire run, it was useful to develop a method of flagging the data so as to not analyze data that was not of interest. This was accomplished by placing aluminum plates at the both ends of the AC sample. Since, the pyrometer measures reflected infrared energy using emissivity in its calculation to solve for temperature, a drastically incorrect reading is recorded when it comes across a substance with an emissivity that does not match that which it has been set for. In a test run data file this shows up as a spike in the temperature. Therefore, only the data between the two flags or spikes in the file is of interest for analysis.

3.3.3 - Analysis

Following the above described test procedure, 30 tests using the Sur-Lite burner were conducted. For each test, a data file containing pavement sample surface temperature and burner exit temperature at each sampling time was stored on disk. These files were then transferred to spreadsheet file format in order to graphically compare the results to those predicted using the model.

To compare the surface temperature data gathered from each of the test runs to the surface temperature predicted using the convective heat transfer model, the sampling frequency, average source temperature, cart velocity, ambient temperature, and initial surface temperature, had to be entered as parameters to the model. After entering those values, specific to a given test run, into the model's input file, the model was run and an output file was generated.

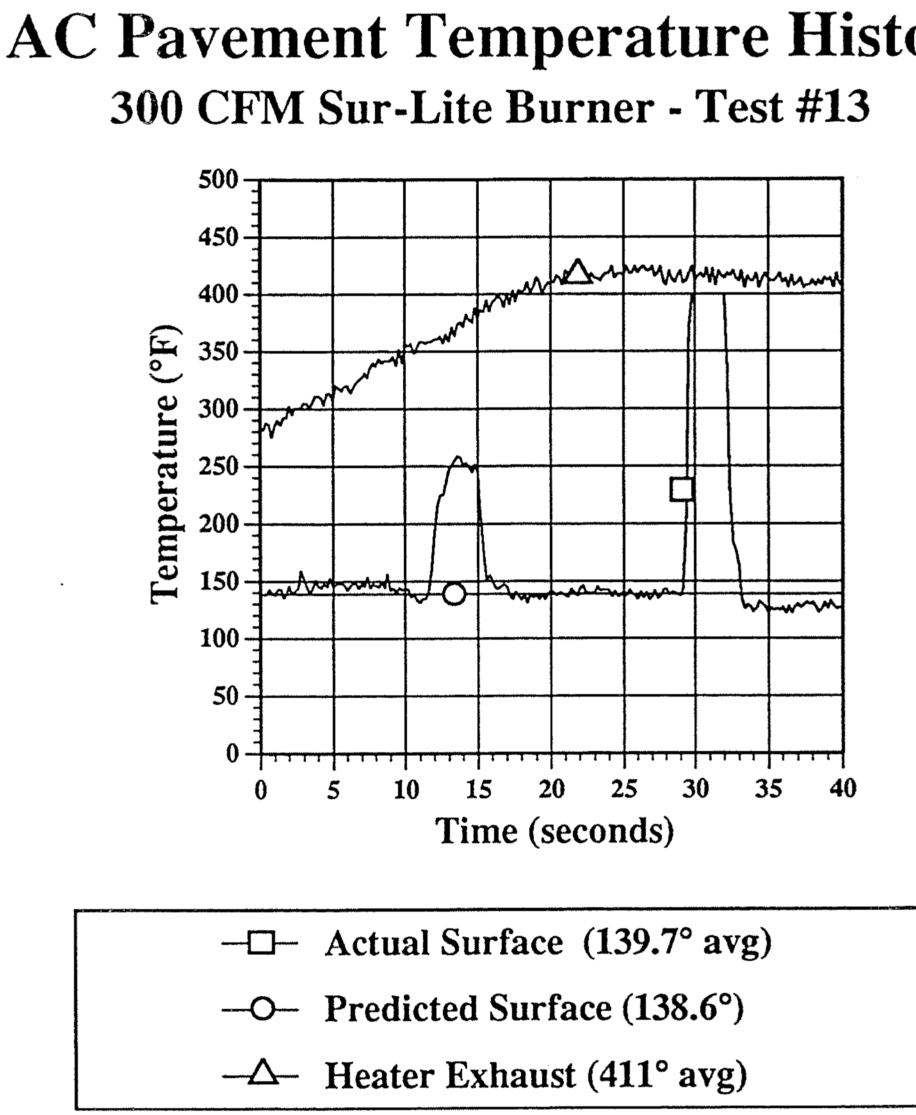


Figure 3.7 - *Sur-Lite burner test #13. Note the flags (spikes) in the data representing the beginning and end of the pavement sample. The average temperatures calculated was based only on the data between these spikes.*

The output file created by the model contains the predicted surface temperature at each time step in the heater's journey across the pavement sample. More specifically, the model predicts the temperature that a specific point on the surface of the sample should experience as the heater is passed over it. For example, given a 6" diameter heater exit and a cart velocity of 10 in/sec, at the beginning of the run (time t=0.0), when r/D=4 in the model, the predicted surface temperature remains unchanged from ambient since the point on the surface is not yet inside of the 4 diameter range (24" in this case) of assumed heating effects (see Chapters 1 and 2). At the next time step, which may be in this hypothetical example, at t=0.02 seconds, the heater has moved a distance of 10 in/sec x 0.02 sec, or 0.2" and, r/D is now equal to 23.8"/6", or 3.967. Using Eqn. 1.2 the Nusselt number is then computed which eventually leads to a new surface temperature which is saved as an entry in the model's output file.

As explained, the model forecasts the temperature history of a specific point on the sample's surface. However, during the tests, the surface temperature is sampled continuously as the heater is passed over the sample. So, to graphically compare the continuously measured temperatures to the model's single predicted temperature, the measured temperature can be plotted as a function of time and the predicted value can be shown as a horizontal line across the graph. To attain a reasonable first order comparison between the two, the average of the surface temperatures measured between the spikes or flags can also be calculated and shown. A plot of a representative run is thusly shown in Figure 3.7. Plots of 28 of the 30 tests can be found in Appendix C (tests #1 and #6 were conducted in error).

In plotting the test data, the model's predicted temperature had to be corrected for the location that the temperature was measured at during the tests, i.e., the location of the pyrometer aft of the centerline of the burner. The distance was measured and divided by the cart velocity to determine the time taken to cover that distance. This time was then added to half of the total predicted time (to account for the heating that took place as the cart approached) to arrive at the total exposure time. The temperature at this time in the output file was taken as the predicted temperature and plotted in the comparison charts. As can be seen, the surface temperature predicted by the model compares reasonably well to that actually measured.

It should be noted that test runs 25-30 were designed to examine the ability of the model to predict pavement surface temperature under longer heat exposure. This was

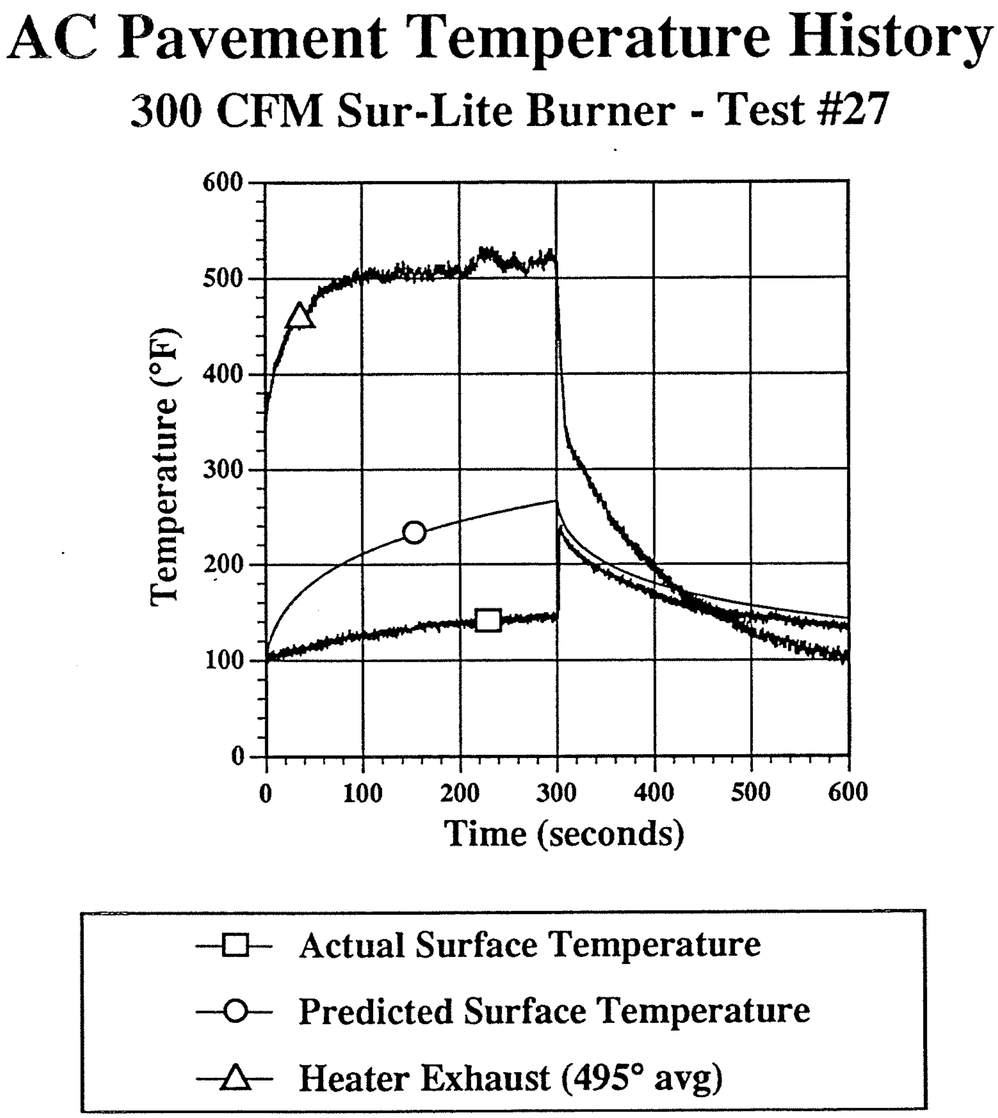


Figure 3.8 - *Sur-Lite burner test #27 (long exposure run). Note the low actual temperature measured during the first half of the run. This is because, during the first 300 seconds, the pyrometer was not aimed at the sample being heated - due to its position aft of burner. After turning off the heater and moving the pyrometer over the hot sample, the actual surface temperature is registered. The average source temperature used in modeling the run is based on the first 300 seconds of data.*

accomplished by slightly modifying the convective FORTRAN model to accommodate a stationary heater, i.e., setting r/D=0 and applying heat for 2-5 minutes while acquiring surface temperature measurements. Due to the physical limitations of the test apparatus though, it was impossible to measure the temperature of the pavement surface while it was being heated (see Figure 3.4). But, the pyrometer could be moved over the heated section just after removing the heat to monitor the sample while cooling. It was felt that if the cooling curves of the experimental and predicted approximately matched, it would be reasonable to assume that the surface was heated to roughly the same temperature and therefore, that the model does adequately predict surface temperature under longer exposure. As can be seen in Figure 3.8, the predicted and measured cooling curves do compare reasonably.

3.3.4 - Results

Overall, plots of the Sur-Lite burner tests show strong correlation between actual and predicted pavement surface temperature. This can be seen upon quick examination of the plots of the 30 test runs located in Appendix C. No statistical analysis was performed to quantify this level of correlation however, since any hypothesis formulated would have been based on the assumptions made earlier in Chapter 2, those being: a homogeneous substance structure, a smooth surface texture, a maximum effective convective reach of 4 diameters (r/D_{max}=4) and, negligible air density changes. Also, since only one heater, the Sur-Lite burner, was used in the tests, nothing conclusively, in the strictest sense, can be stated about the accuracy of the model in simulating other burners. However, for the design aid purpose it was intended, it has been qualitatively proven that the convective model does serve as a sufficient instrument in predicted heater performance.

3.4 - Test Conclusions

Based on the tests and simulations performed above, when fitted with a high pressure blower and appropriate fuel train assembly, the Sur-Lite burner does have the potential to adequately serve the needs of this project (see Figure 3.9). As opposed to the Maxon Infrawave radiant heater, the Sur-Lite burner offers compactness and simplicity to the design while achieving a similar end result. And, since most road crews today use an

HCA lance as a cleaning and heating method, a similar convective heating method would be more readily accepted by the end user.

Before committing to the Sur-Lite system however, it was felt that because of the physical complexities associated with mounting this burner and blower unit, flame tube, and fuel train on the crack sealing machinery end-effectors, certain design issues must be further discussed. For these reasons, a trade-off study between various available convective heaters that addresses the design requirements of the heating system is performed in Chapter 4. It is in this chapter that the total cleaning and heating system is specified for design.

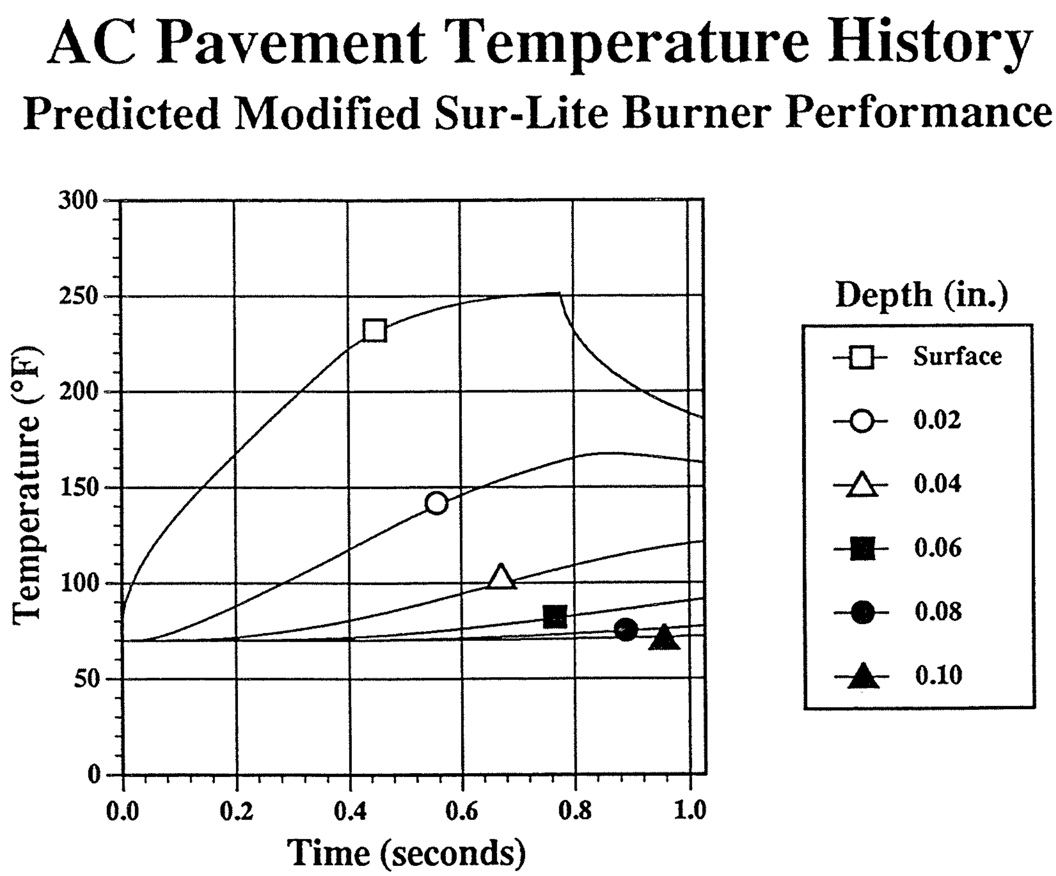


Figure 3.9 - Predicted modified Sur-Lite burner performance. Relative speed is 2 MPH, nozzle exit diameter is necked down to 3.5", and the exit gas temperature is estimated to be 2000°F.

CHAPTER 4 - CRACK CLEANING AND HEATING SYSTEM DESIGN

4.1 - Crack Sealing Machinery Concept

Before beginning a discussion of the relevant cleaning/heating system design issues, an overview of the crack sealing machinery concept for which this system is being developed is presented.

Crack sealing project goals dictate the development of machinery to seal two types of pavement cracks, longitudinal and general (random or meandering). *Longitudinal cracks* exist along the edge of the lane (construction joints, shoulders, etc.) and *general cracks* meander through the pavement and may extend across a full lane width. In developing such machinery, it is obvious that sealing each type of crack presents unique design challenges. Random or meandering crack sealing machinery requires more degrees of freedom and unsteady operation of many of its components. Longitudinal crack sealing requires fewer degrees of freedom, has less stringent sensing requirements, and permits steady-state operation of many machine components. However, many of the same components are necessary to seal both types of cracks. As such, a dual purpose machine with portions to address each type of crack is the logical choice for development and is currently being built at UC Davis.

A 3-D conceptual sketch for this machine is shown in Figure 4.1. As can be seen, the longitudinal crack sealing portion of the machine is mounted on the side of the truck and the general crack sealing portion takes the form of two SCARA type robot arm manipulators mounted on the rear. The components that make up the longitudinal portion include a local laser range finder sensor, a router, a cleaning/heating system, and a sealant applicator. Automatic positioning takes place via an error signal fed from the laser range finder to a hydraulic positioning linkage. (The router can be described as a rotating set of

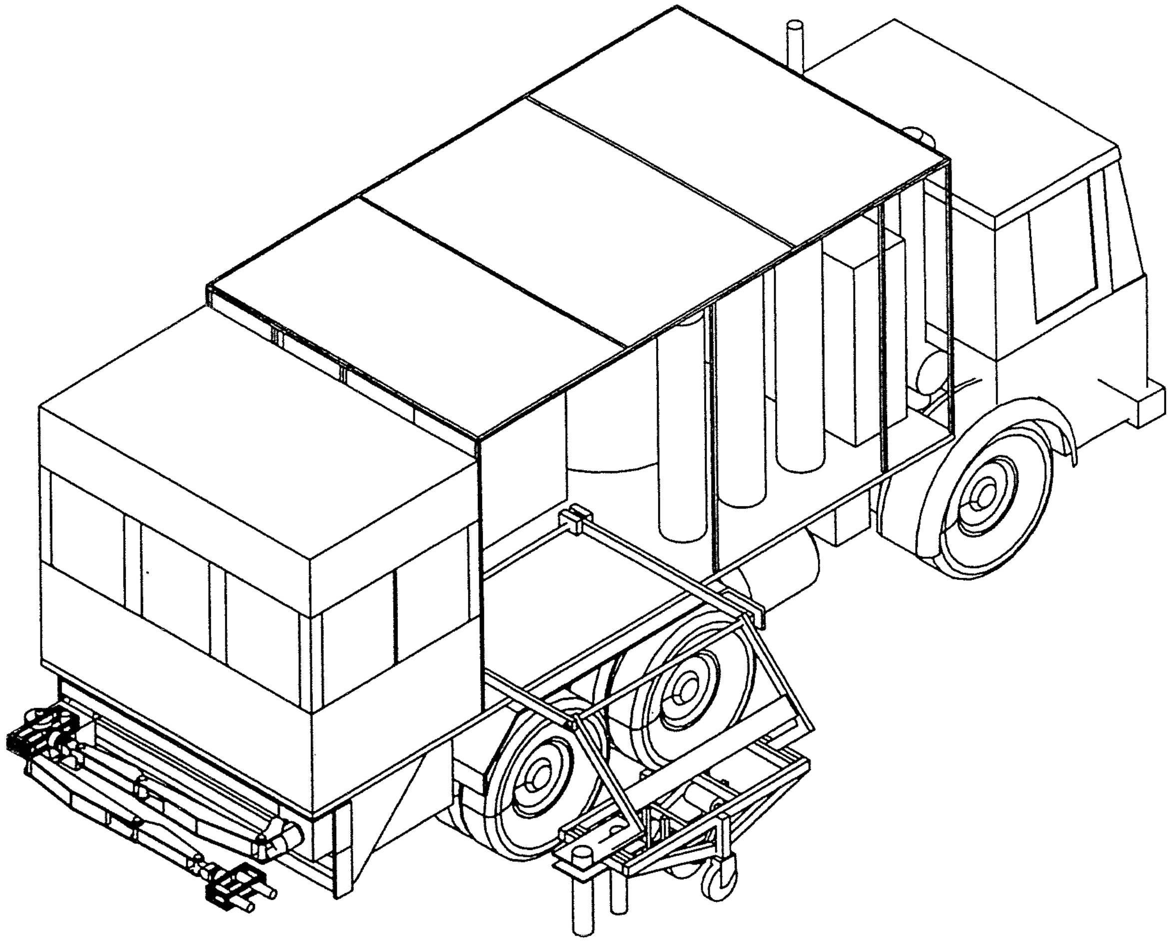


Figure 4.1 -Automated crack sealing machine concept. Longitudinal sealing components operation, general sealing components stowed.

blades used to cut a shape factor profile, typically a 4:1 width to depth ratio, into the pavement surface in order to provide a clean, uncontaminated surface for the sealant to bond to.)

For meandering cracks, a computer vision system mounted on the front of the truck is used to locate cracks across the lane width and the two robot arms mounted on linear slides are used to move two process carts along cracks to perform the related sealing operations. The first cart contains the laser range finder and router and the second contains the cleaning/heating system and sealant applicator unit.

In light of this machine concept, it is immediately obvious that space, weight, heat loss, plumbing, and harnessing/tethering pose the potential to cause significant obstacles in design. Therefore, it is best to assemble a formal set of design constraints and requirements that can be used in evaluating the advantages and disadvantages of various commercial equipment.

4.2- Design Requirements

In this section, the various constraints on design of the crack cleaning and heating system to be used with the machine concept outlined above are discussed. It has been determined that five general requirements must be met in order to meet project requirements.

4.2.1 - General Requirements

Since the development of a prototype automated crack sealing machine can be viewed as a monumental task in itself, early in the development phase it was decided that off-the-shelf components should be used when possible. By doing so, proven performance and reliability can be achieved while time is not spent building and testing parts unnecessarily. It is therefore important and necessary to discuss the details of particular vendor's products as part of this report. Later in this document, manufacturer's specifications are provided and discussed.

Since the crack sealing machine being developed should accommodate the crack maintenance needs of a variety of States and Departments of Transportation (DOT), modularity should be built in to any commercially developed machine. This will allow a district, for instance, which may not route cracks, to remove the router from the machine and proceed without it. In the case of crack cleaning and heating, it is fair to say that many DOTs do not heat cracks, yet still clean them before sealing. This may be because of the presence of paint stripes or raised reflective markers. Therefore, the system developed should allow for a CLEAN ONLY mode where the burner is not used. Obviously noise, safety, and cost should also be addressed during development.

In developing a commercial automated crack sealing machine, cost savings due to component modularity could be achieved through the design and testing of only one set of components to seal both longitudinal and general cracks. While in a commercial sealing operation it may be desirable to seal both types of cracks simultaneously, for the purposes of this research and development, it places undo financial burden on the funding agencies to develop two sets of components. Therefore, when sealing longitudinal cracks, the robots will be stowed as shown in Figure 4.1. When sealing general, meandering cracks, the longitudinal linkage will be retracted to rest on the truck bed and the robots will be in use. By designing mounting couplings for the local laser range finder, router, cleaning/heating system, and sealant applicator to be interchangeable between the two configurations, significant cost savings and modularity can be realized during both prototype development and commercialization.

4.2.2 - Mechanical Constraints

It is immediately obvious that significant mechanical constraints have been placed on the cleaning/heating system by choosing to build the vehicle shown in Figure 4.1. Robots and hydraulic systems, by their nature, are more expensive the larger the load they must carry. It was therefore determined that, in terms of space and weight, a cleaning/heating system entirely located on the longitudinal linkage or a general process cart was not feasible. The options were to place the blower on the truck bed (the heaviest and bulkiest component) and plumb its cool air to the burner located near the pavement if space permitted, *or*, to place both the blower *and* burner on the truck bed and plumb the heated air to the road. In discussions with vendors and burner manufacturers it became apparent that most burners in the output range being considered require at least 2 feet of straight, smooth walled firing tube downstream from the burner face. This allows adequate space for complete combustion of the LP gas and prevents heat concentrations on the walls of the firing tube and upstream from occurring. Also, the safety in plumbing LP gas from the side of the crack sealing vehicle may be questionable should a stray driver ever collide with the crack sealing vehicle. Given these additional constraints, both the burner and blower *must* be located on the truck bed. Therefore, properly routing the high temperature plumbing and minimizing the pipe friction and heat loss become substantial design issues.

In order to allow for the relative motion of the longitudinal and general end-effectors, flexible plumbing must be used. This tubing must also be smooth walled in order to minimize pressure loss and blower size. However, plumbing like this is difficult to find since there is not a large market for high temperature, flexible, large diameter, smooth walled tubing. Vendors were contacted and the best product found was only able to withstand 1500°F. Therefore, the burner purchased must output exhaust air no greater than 1500°F. A sufficient amount of insulation should also be purchased in order to reduce the surface temperature of this tubing and the burner to a safe level, perhaps to 140°F.

Daily fuel consumption of the burner must not exceed that fuel which is available on the crack sealing truck. A bitumen melter that heats its material using 2-100 lb. vapor withdrawal LP gas tanks will be mounted on the crack sealing truck bed. It is desirable that the burner in the heating/cleaning system use fuel from similar tanks, perhaps 2-4 more of them, since the exact layout of the truck has not yet been determined and such tanks are standard items for procurement and are easily relocatable.

Also, a pair of linked 2-way diverter valves should be placed in line with the blower, (upstream of the burner) to allow the user to deflect flow from the pavement when the vehicle is not moving. This will permit the user to keep the blower operating while not disturbing dust in the immediate vicinity of the vehicle.

Lastly, as has previously been stated, the blower purchased should be powered hydraulically, as opposed to electrically, since three phase power would be necessary at the predicted load (10-15 HP). Hydraulics are also already present on the crack sealing machine powering the router and the longitudinal positioning system and are generally more compact.

4.2.3 - Performance Limits

While it has been stated that the Sur-Lite burner tested in Chapter 3 should meet the surface temperature goal of 250°F if modified with a high pressure blower and fitted with a convergent nozzle, that estimate was made assuming a 2000°F exhaust gas temperature. Above it was shown that an output temperature of only 1500°F is possible given flexible plumbing constraints. Therefore, if the Sur-Lite system were used, its full heating potential could not be realized meaning that the original reasoning behind the choice to utilize this burner may be now invalid. Thus, more general performance requirements are outlined here, in order to effectively weigh the pros and cons of purchasing the Sur-Lite system versus one from another manufacturer.

As mentioned earlier, the amount of convective heat transfer that takes place is a function of exhaust velocity and exhaust temperature. Exhaust velocity increases with decreasing exit area (as the square of the flow diameter). In general, exhaust temperature varies as a function of the heat that the burner can produce and the volume of air being heated. At this point, the exhaust temperature appears to be fixed, because of materials considerations, at 1500°F. As a general approximation, 1.1 times the volume of air being heated (CFM) multiplied by the temperature rise (°F) equals the amount of heat required (BTU/hr). So, if a 1 million BTU/hr burner were to be examined and a 1500°F maximum temperature were desired (1430°F rise assuming 70° ambient), approximately 635 CFM of air could be heated.

Since the maximum exhaust temperature has been determined to be 1500°F, the requirements for the maximum allowable volume flow (CFM), dependent on velocity and exit diameter, remain to be determined. Quantifying an acceptable maximum velocity is difficult, but nozzle diameter is more straight forward.

Based on the maximum router band width (4 cm), computer vision limitations, and hydraulic and robotic response time, when automatically sealing a crack, a centerline offset between the end-effector and crack of perhaps 2" is possible. Therefore, the cleaning/heating air nozzle must be wide enough to still maintain significant air flow into the crack and/or routed region. Quantifying the amount necessary to clean the crack in *all* cases obviously means that a 4" wide nozzle should be chosen. However, in the interest of maximizing heat output and assuming that future nozzle modifications could be made, a 2.5" wide nozzle was chosen since it offers an exit velocity nearly 60% greater than a 4" nozzle (velocity varies as the square of diameter) and still provides 1/2" of direct air flow into the crack. At this time it is assumed that a round nozzle will be implemented since the details of a rotational degree of freedom at the end-effector remain to be determined.

Given a 2.5" diameter nozzle, it is possible to model the performance of available commercial equipment and, utilizing the general rule from above, determine the BTU/hr of heat output required and related fuel consumption. This is done in Section 4.3.

4.2.4 - Integration and Operational Considerations

While mechanical and performance issues seem to provide the most severe constraints on the cleaning/heating system design, others still remain. Optimally, it is desirable to totally integrate the cleaning and heating system with the main logic center on the automated crack sealing machine, the Integration and Control Unit (ICU). However, during this phase of prototype development it is important to manage costs and maintain safety and reliability. For these reasons, the cleaning/heating system to be specified should operate as a stand alone unit, meaning that communication links between it and the ICU should be limited. There are two reasons for this. Most commercial burner packages are sold as stand alone units and offer minimum communication to outside devices. As such, many companies do not specialize in digital communications and therefore it would be very expensive to order a customized unit. Secondly, legal issues become significant since industrial burners fall under federal regulatory codes and, in most cases, must operate safely regardless of communication links. However, during later development and commercialization, integration of the cleaning/heating system is desirable. Therefore, when purchasing equipment, future generation supervisory communication should be kept in mind. A computer simulation modeling a possible link between the cleaning/heating system and the ICU has been developed and tested and is available upon request.

In order to regulate fuel flow as a function of pavement surface temperature, a PID type controller connected to proportional fuel control valve should interface directly with the pyrometer. A PID controller will allow a target surface temperature to be set when heating the roadway.

4.2.5 - Router Debris Removal

During testing of the automated crack sealing machine components it was apparent that the debris cut loose with the router leaves a fair amount of ground up asphalt on the road surface. The possibility of using a means of vacuuming up this debris was investigated and it was decided that a cyclone separator could be connected in line with the blower inlet to the cleaning/heating system.

In principle a separator works similar to a home vacuum. The debris enters a shrouded collector mounted on the front of the rotating router wheel. It then is sucked up a flexible hose where it enters a cyclone separator. There the dust and chunks fall to the bottom of a large drum and the cleaned and filtered air then continues through the blower face and on to the burner.

The significant design issues affecting the cleaning/heating system design are the pressure losses associated with the collector entrance, hose length, and cyclone separator *and* the volume flow of air necessary to sustain the debris in motion. After discussions with vendors it was determined that approximately 2 PSI may be lost in the debris removal system and that air flowing at a minimum of 7500 ft/min (approximately a 400 SCFM through a 3" diameter line) is necessary to suck up small asphalt chunks. Therefore, a 400 SCFM, 5 PSI centrifugal blower has been specified which should be able to handle the pressure loss on the inlet side (2 PSI), the pressure loss across the burner (~1 PSI), and the pressure loss associated with the burner side plumbing (~1 PSI) through a standard 3" diameter flex line.

Also, since there is an increased possibility of the blower becoming clogged, safety pressure switches should be installed appropriately to prevent fuel flow to the burner when no air flow is present.

In light of the requirements outlined above, detailed major equipment specifications were developed to be used in evaluating commercial equipment. These detail specifications are presented in Appendix D and include the blower, burner, and flame safeguard/fuel train system. Required features of the debris removal unit were not included as this unit can be viewed as a specialty item. Features of the flame safeguard and fuel train system have been included mainly to provide detail on the non-standard modifications necessary. However, since most fuel train/flame safeguard system vary only slightly, selection criteria are not discussed in this report.

4.3 - Equipment Trade-offs

Based on the specifications detailed in Appendix D and the requirements noted above, additional burner companies were contacted to determine their ability to provide equipment able to meet the formalized requirements. Four potential heating systems were identified and are briefly discussed below, a Maxon LV AIRFLO burner, a Maxon STICKTITE/PILOTPAK burner with VENTITE inspirator, an Eclipse Thermal Blast Air Heater, and the previously examined Sur-Lite tube burner.

Due to machinery space and weight constraints and the need for a high pressure blower, it was decided to examine it separately from the burner, keeping in mind that Sur-Lite offers integrated units. The debris removal unit which interfaces with the blower is also discussed separately.

4.3.1 - Burners

Maxon's LV AIRFLO burner is mainly designed for high volume, low velocity air heating. Commercially it is used to heat massive amounts of process air coming from large ducts. This burner was first investigated because it is a very inexpensive means of heating air and a maximum output of 2,000,000 BTU/hr/linear foot of burner surface is possible. This burner is limited however because of its velocity envelope and size. Since it primarily was designed to heat a high volume of air, it is relatively large (the smallest burner would require the construction of a duct measuring 12" x 16"). And, like any burner, a minimum air flow velocity is required to sustain the flame, approximately 3000 ft/min. Therefore, just to operate at *minimum* output, 4000 CFM of air would be needed. When considering the duct length associated with necking down this huge exit area to a reasonable diameter nozzle, it is obvious that tremendous losses would take place along with incredible noise.

The other burner choice presented by Maxon, one of the largest burner companies in the United States, is the STICKTITE/PILOTPAK with a VENTITE inspirator. Basically the STICKTITE/PILOTPAK is a nozzle with a spark ignitor and flame rod that screws onto the end of the air inspirator (VENTITE). This inspirator uses the venturi principle to mix LP gas with ambient air for combustion. Normally this burner is used to fire into a tube for solution heating. As such, the high velocity convective force of a blower is typically not needed. If a blower were to be connected to provide forced combustion air, a custom duct assembly would have to be constructed to encompass the aft portion of the burner and venturi inspirator. This modification does not seem unreasonable. However, it must be weighed against the possibility of an unsuccessful attempt at modifying this configuration to heat in a manner for which it was not designed (with a blower).

The Eclipse Thermal Blast Air Heater is immediately the most appealing. The unit is made to operate using combustion air supplied at up to 50 PSI, which could prove significant should higher pressure crack cleaning ever be deemed necessary or desired by an end-user. The maximum air flow that the burner can handle is 400 SCFM, yet it can heat this air to a approximately 1600°F, slightly greater than the 1500°F materials constraint noted above. The burner includes a flame rod, and spark ignitor and is relatively compact. A 4" diameter exit can be easily necked down to 2.5" to achieve maximum convective heating - meaning only a small pressure loss with minimal exit noise. The pressure loss across the burner itself approaches 1 PSI at maximum flow, including the 30" straight section of smooth walled tubing required downstream of the face of the burner. All in all, this burner seems very promising for use in this application. In Chapter 5, its heating capability is modeled.

The Sur-Lite burner tested in Chapter 3 showed extreme promise yet must be modified. To be successful in this application the blower must be detached from the burner and relocated. A higher volume (400 CFM or greater) and higher pressure (5 PSI) blower must also be incorporated. And, a necked down nozzle, to no less than 2.5", is necessary to increase exit velocity. While the flexibility of its design seems to afford these modifications, questions remain as to the ability of the burner to perform well given this degree of customization for which it was not built to operate. Flame stability may become a critical issue.

4.3.2 - Blowers

With the specifications outlined in Appendix D, various blower companies were contacted. EG & G Rotron and Paxton are two of the industry leaders and provide what appear to be the best products. EG & G Rotron's solution to the needs of the crack cleaning and heating system include purchasing a motorless centrifugal blower, model DR-12, and having a hydraulic motor attached independently. Paxton actually sells a centrifugal blower powered hydraulically, model CB-87 with hydraulic option. Both blowers, when all necessary parts are considered, price comparably.

4.3.3 - Debris Separators

Three companies selling off-the-shelf industrial vacuum units were also contacted. In short, EG & G Rotron provides the nicest set-up, the Vacu-Master utilizing a 55 gallon drum mounted on casters. It was felt that this option was necessary since the weight of routed asphalt could be quite burdening to move around. The Vacu-Master can remove 99.97% of the particulate matter which should be of sufficient quality for combustion.

In the next chapter, actual equipment is selected for procurement based on the trade-offs outlined above. Integration of these components with the crack sealing vehicle is discussed and recommendations for commercialization are made.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

5.1 - Review of Development Procedure

The purpose of this report was to report on the design, testing and implementation of an automated pavement crack cleaning and heating system that best meets the goals of the overall crack sealing project in terms of feasibility, effectiveness, and efficiency.

To begin the development, in Chapter 1, a feasibility study and literature search was performed to examine practical means of automating methods of crack cleaning and heating. Since the automated crack sealing machine is being developed as a possible prototype for future commercialization, a heating system that will allow for traveling speeds faster than walking is necessary and must be provided. Given the nature of robotic path planning algorithms, whereas faster sealing performance can be achieved the more the actual path is allowed to deviate from the desired path, sealing of cracks can occur more rapidly if increased crack eccentricity is permitted. A high volume centrifugal blower, similar to that on a street sweeper, therefore, was chosen as the preferred means of crack cleaning as opposed to a small nozzled compressed air jet.

Next, radiant and convective heating methods were examined. It was decided that for this application, to best determine the relative differences between these heating methods and to develop a tool that could help evaluate the heating performance of available commercial equipment, finite difference heat transfer models should be assembled. In Chapter 2, these models were constructed using basic principles of classical heat transfer and experimentally formed hypotheses from literature. Verification of the accuracy of the models, to the reasonable extent necessary to effectively estimate the performance of commercial equipment, was proven through comparisons with other authors' experimental data and through testing a commercial burner in Chapter 3.

Simulations were also run in Chapter 3, resulting in the choice to discard radiant heating as a viable heating alternative since the lengthy heater that proved necessary would be difficult to articulate through turns.

The convective heater tested, a 300 CFM Sur-Lite tube burner correlated well with predicted results in the laboratory test stand. It relied on a built-in 300 CFM centrifugal blower to provide combustion air for the burner and exhausted the resultant hot combustion gases to the pavement surface in much the same way a garden leaf blower operates. The tests performed were used to dually evaluate the performance of this off-the-shelf heating system and to verify the model's accuracy. While the Sur-Lite burner studied showed much promise for use in this application it was apparent that further design considerations needed to be considered before deciding on a system to be purchased.

In Chapter 4, the concept vehicle for the overall crack sealing project was outlined and design constraints concerning integration with it were discussed. Among these, general overall project goals, mechanical compatibility with the concept vehicle, performance of the heater, ability to integrate, and debris separator compatibility were identified as the important issues for design. Formalized specifications based on these criteria were then developed for purchasing, and vendors with possible products meeting these specifications were contacted. The advantages and disadvantages of the available equipment were then discussed.

5.2 - Equipment Selection

The main objective in undertaking this report was to arrive at a total system designed to clean and heat pavement cracks as part of an automated crack sealing machine. The heat transfer models that were built, tests that were run, and design constraints presented can now be used to select the best equipment for this application.

As presented in Chapter 4, four heating systems from major burner manufacturing companies appear to closely meet the performance criteria discussed in the previous chapters. However, two can logically be concluded to best meet the design criteria: the modified Sur-Lite unit and the Eclipse Thermal Blast Heater. As mentioned, Sur-Lite's modular design affords the possibility of incorporating a larger blower. However, Eclipse's Thermal Blast Heater is limited to a maximum 400 SCFM of air flow. Yet, this burner is built for high pressure operation, up to 50 PSI, and has been designed around the operating envelope specific to this application. The Eclipse burner also ejects its hot exhaust via a 4" diameter duct as opposed to Sur-Lite's 6" exit. This means that in order to reduce the exhaust area at the nozzle to increase flow velocity, the Sur-Lite system will experience a much greater pressure drop. The Thermal Blast Heater is also designed specifically for remote blower placement. In the case of the Sur-Lite burner, less routine modifications would be necessary. Therefore, it seems reasonable to conclude that if the heat output from the Eclipse burner is not significantly limited by the 400 SCFM maximum flow and the burner can heat the crack to 250°F at a relative speed of 2 MPH, then it should be selected as the preferred method. A simulation using the convective model was run and indeed a sufficient surface temperature of 260°F was achieved (see Figure 5.1 below). Thus, the Eclipse burner was chosen for integration with the automated crack sealing vehicle. As mentioned, the flame safeguard and fuel train were not discussed in this report because they are fairly straight forward and available through most burner manufacturing companies. For convenience, a local vendor, Control Technology Specialists, was chosen to help install and fine tune the heating system as needed.

More straight forward are the component selection choices for the blower and debris separator. As discussed in Section 4.3, Paxton's CB-87 comes as a complete package and therefore, best meets project goals in terms of off-the-shelf reliability. EG & G Rotron provides a debris separator that is able to be easily emptied using a standard 55 gallon drum mounted on casters. Both of these units were therefore purchased for use with the heating system outlined above.

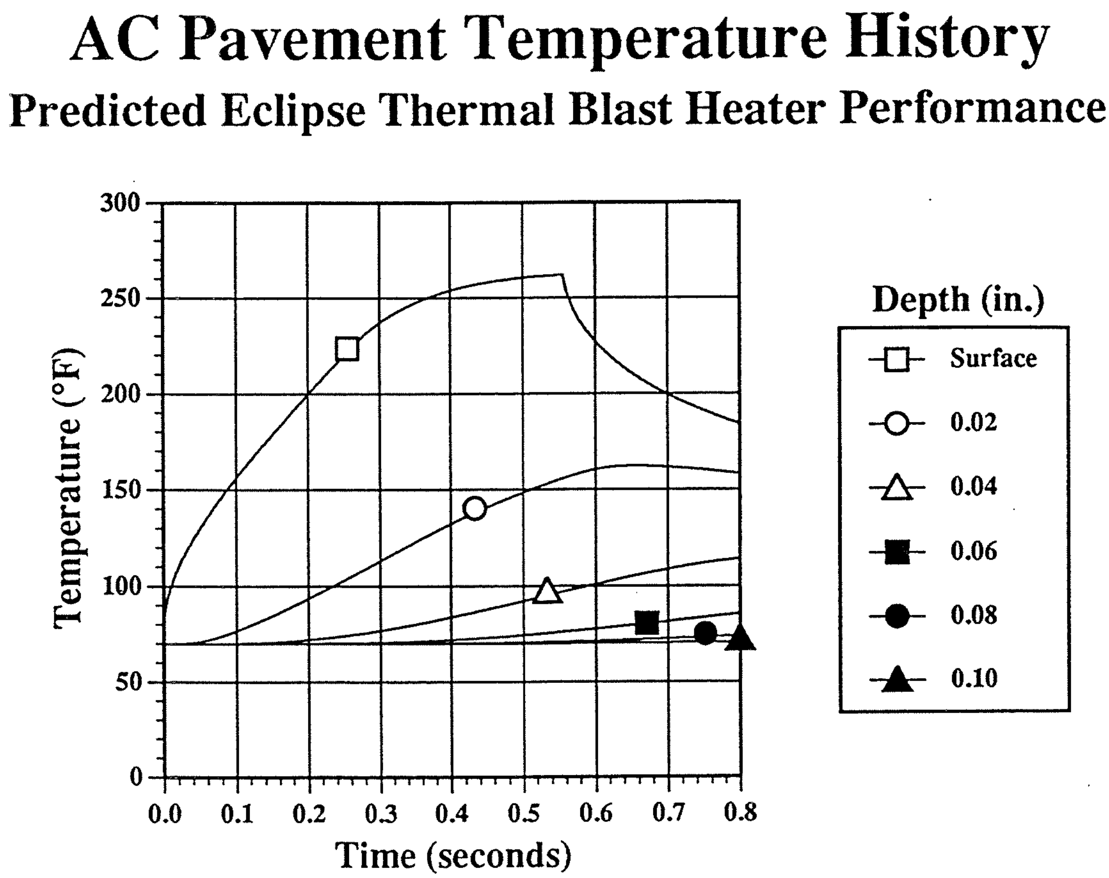


Figure 5.1 - *Predicted Eclipse Thermal Blast Heater performance. Relative speed is 2 MPH, nozzle exit diameter is necked down to 2.5", and the exit gas temperature is set at 1500°F.*

5.2.1 - System Description

Currently, there are two crack sealing machine component subsystems in parallel development at UCD, the longitudinal crack sealing method, used for sealing highway shoulder cracks and joints, and the general crack sealing method, used to address meandering highway cracks. Both concepts will be demonstrated on the final vehicle however, as mentioned, they will not run concurrently due to the project team's avoidance of redundant development costs. When commercialized, both systems could run concurrently should a second set of components be provided. The resultant cleaning and heating system therefore, was designed with modularity in mind. By specifying off-the-shelf modular components, development costs are minimized. And, testing of the two concepts on the final vehicle and intermediate laboratory and shop platforms can easily take place. For the sake of discussion, it is assumed that the system discussed below is mounted to the *longitudinal* cart deployed from the side of the automated sealing vehicle (See Figure 4.1).

The automated pavement crack cleaning and heating system designed and purchased primarily consists of an EG & G Rotron debris separator, model IVM2000PF (approximately the size of 2 - 55 gallon drums stacked vertically), a 5 PSI, 400 SCFM hydraulically powered centrifugal blower, Paxton Centrifugal Blowers model CB-87, a 692, 000 BTU/hr Eclipse Thermal Blast Heater, and an infrared pyrometer, Raytek model ET3LT, which measures crack temperature and thereby modulates fuel flow to the burner. Overseeing safe operation of the burner is a standard flame safeguard control panel built by Control Technology Specialists. It features additional control panel functions for diverter valve actuation, CLEAN ONLY operation (no heat), and a PID controller to interface with the pyrometer. The pyrometer is located just aft of the burner exhaust nozzle on the longitudinal sealant cart. Both the blower and burner units are to be located on the truck in a location which minimizes pressure and heat losses through minimal bending and plumbing distance. Proper insulation will protect subsystems and operators from danger. Hydraulic power to the blower is provided by the central hydraulic system. Perhaps in the future, a drive train power take-off unit could be used to power other subsystems. Figure 5.2 illustrates a mock-up assembly of the longitudinal sealing linkage. Appendix E contains the manufacturer's specifications for the major equipment purchased exclusive of the flame safeguard unit and fuel train.

The Eclipse burner purchased, at maximum output, consumes approximately 28 lb of liquid propane (LP gas) per hour, meaning that for a normal eight hour work day, 224 lb of fuel could be consumed. By outfitting the support vehicle with 2 additional vapor withdrawal 100 lb. tanks, in addition to the 2 tanks already present for use with the melter, this consumption rate can be met.

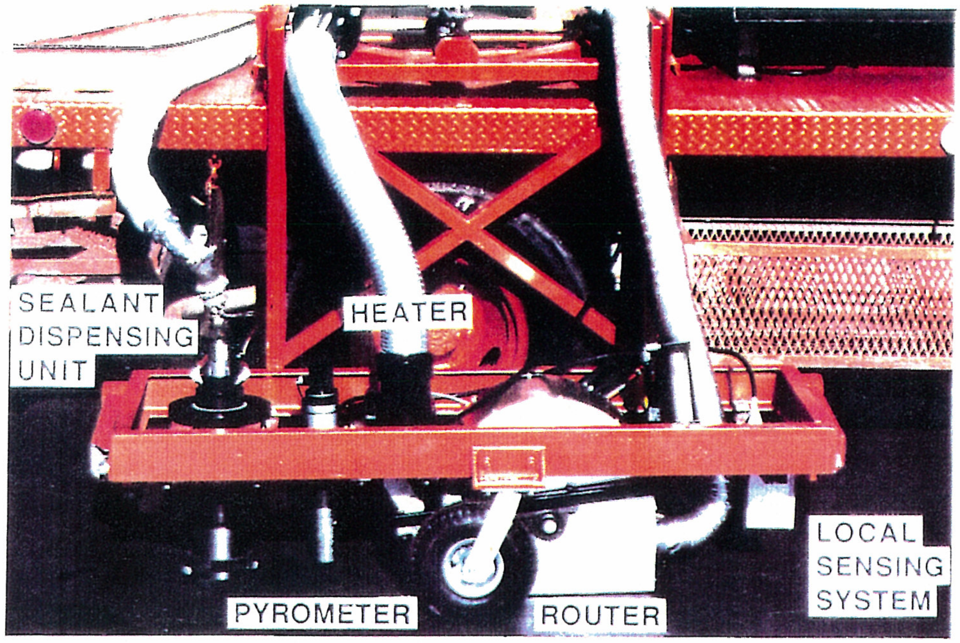


Figure 5.2 - Mock-up of longitudinal crack sealing unit deployed from test vehicle. Note the placement of the pyrometer and cleaning/heating nozzle between the router and sealant unit.

5.2.2 - Description of Operation

The cleaning and heating system has been designed using all commercially available components. As such, manufacturer's specifications detailing the features of each of the components of the system can be found in Appendix E.

In general, this system operates similar to most LP gas burner packages with a few exceptions. Fuel flow control is maintained through a PID controller connected to the pyrometer as opposed to a manually or permanently set flow rate. Based on the surface temperature of the pavement, the pyrometer sends a signal, roughly between 12 and 16 mA (200°F and 300°F), back to the PID controller which in turn sends out its own 4-20 mA signal linear over the turn down range of the fuel control valve either increasing or decreasing fuel flow in order to approach the pyrometer's measured surface temperature. The burner output is therefore automatically proportionally adjusted for the set point programmed into the PID controller.

Additionally, the cleaning and heating system can operate in the CLEAN ONLY or HEAT AND CLEAN mode. In the CLEAN ONLY mode the heater is not ignited and the blower is used by itself, with or without the debris removal attachment. This is an obvious and necessary feature since many DOTs do not heat the roadway prior to sealing. The diverter valve is also necessary to adjust for the proper component pressure loads during system qualification. This will ensure maximum performance of the components while not causing damage to them.

5.3 - Recommendations for Commercialization

As a final section to this report, recommendations for a commercially developed crack cleaning and heating system are made. One of the main difficulties in developing an optimal heating system was the lack of specific performance criteria relative to the heat required to remove entrained crack moisture and decrease the sealant to surface temperature gradient. To realize the greatest economic advantage from wide scale automated crack sealing, a formal study should be embarked upon examining the optimal surface pre-heat temperature required to best enhance the quality of the seal. Also, a cost benefit analysis detailing the average surface life enhancement as a function of cleaning/heating performance should be completed. By doing so, optimum return on investment can occur in the form of decreased nationwide highway maintenance costs.

Due to a delay in the delivery of the automated crack sealing vehicle platform shown in Figure 4.1, installation of the components selected could not take place in a manner timely for the publishing of this report. Upon integration of the system with the crack sealing machine, it is therefore recommended that a full battery of tests be performed in order to effectively make recommendations for commercialization concerning performance and overall design.

During development of the cleaning and heating system, CalTrans technical personnel expressed interest in a means of deflecting the heat from raised reflective markers when detected. This design feature could be supplied simply by adding a tactile sensor or mechanical linkage designed to cause a deflection of flow momentarily until the pavement marker is passed. By adding such a feature, many end users who currently have many miles of raised pavement markers placed on cracks could be accommodated.

Lastly, since the collected router debris has the potential to form a massive amount of dust and debris very quickly (varies as a function of size of cut and vehicle speed), it may be of interest to investigate the development of an automatic means of dispensing or sprinkling the collected debris back over the newly applied sealant. This would allow for a more abrasive surface finish providing better traction for vehicles, could shorten lane closure time, and may enhance the aesthetic appearance of the seal.

REFERENCES

Baughn, J. W. and Shimizu, S. (1989) "Heat Transfer Measurements from a Surface With Uniform Heat Flux and an Impinging Jet," ASME Journal of Heat Transfer, Vol. 111, pp. 1096-1098.

Baumeister, T. and Marks, L. S. (1967) Standard Handbook for Mechanical Engineers, McGraw-Hill Book Company, Inc., New York.

Belangie, M.C. (1989) "Factors Influencing Joint System Performance," Transportation Research Board preprint, No. 890768, pp. 1-23.

Best, C. (1975) "Vacuum Sweeper Meets Cheyenne Requirements," Public Works, Feb., pp. 66 & 110.

Carmichael, T., Boyer, R. E., and Hokanson, L. D. (1972) "Modeling Heater Techniques for In-Place Recycling of Asphalt Pavements," Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio.

Chehovits, J. and Manning, M. (1984) "Materials and Methods for Sealing Cracks in Asphalt Concrete Pavements," Transportation Research Record, 990, pp. 21-30.

Corlew, J. S. and Dickson, P. F. (1971) "Cold-Weather Paving of Thin Lifts of Hot-Mixed Asphalt on Preheated Asphalt Base," Highway Research Record, No. 385, pp. 1-6.

Davidson, W. G. and Callahan, M. (1987) "Special Surface Preparation Prior to Bituminous Overlays," Iowa Department of Transportation Report.

Dickson, E. J. (1978) "A Method for Calculating the Temperature Gradients in Asphalt Concrete Pavement Structures Based on Climatic Data," Australian Road Research, Vol. 8, No. 4, pp. 16-34.

Fishback, J. W. and Dickson, P. F. (1973) "Two-Dimensional Finite Difference Techniques Applied to Transient Temperature Calculations in Hot-Mix Asphalt Concrete Windrows," Highway Research Record, No. 454, pp. 32-38.

Goldstein, R. J. and Behbahani, A. I. (1982) "Impingement of a Circular Jet With and Without Cross Flow," International Journal of Heat and Mass Transfer, Vol. 25, pp. 1377-1382.

Highter, W. H. and Wall, D. J. (1983) "Thermal Properties of Some Asphaltic Concrete Mixes," AIAA 18th Thermophysics Conference, Montreal, 1983.

Hollworth, B. R. and Gero, L. R. (1985) "Entrainment Effects on Impingement Heat Transfer: Part II - Local Heat Transfer Measurements," ASME Journal of Heat Transfer, Vol. 107, pp. 910-915.

Hrycak, P. (1983) "Heat Transfer from Round Impinging Jets to a Flat Plate," International Journal of Heat and Mass Transfer, Vol. 26, No. 12, pp. 1857-1865.

Layman, J. (1987) "Change is Sweeping City Street Cleaning," American City and County, Jan., pp. 34-36.

Marek, C. R. and Dempsey, B. J. (1972) "A Model Utilizing Climatic Factors for Determining Stresses and Deflections in Flexible Pavement Systems," Proceedings from the 3rd International Conference on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, Vol. 1, pp. 101-104.

Neise, W. and Koopmann, G. H. (1984) "Noise Reduction on the Centrifugal Suction Fan of a Berlin Street Sweeper Truck," Noise Control Engineering Journal, Vol. 23, No. 2, pp. 78-88.

Novak, J. (1988) "Versatility of New Machine Pays Dividends," Public Works, Oct., pp. 76-77.

Osborne, B. K. (1988) "Solving a Weak Link in Pavement Patches," Public Works, July, 1988.

Palmiter, D. and Chermak, M. (1974) "Air/Oil Circuits Provide Clean Sweep," Hydraulics and Pneumatics, Feb., pp. 51-53.

Peterson, D. E. (1982) "Resealing Joints and Cracks in Rigid and Flexible Pavements," Transportation Research Board, National Cooperative Highway Research Program, No. 98, pp. 1-61.

Rossman, R. H., Tufty, H.G., Nicholas, L., and Belangie, M. (1990) "Value Engineering Study of the Repair of Transverse Cracking in Asphalt Concrete Pavements," U.S. Department of Transportation, Federal Highway Administration, No. FHWA-TS-89-010, pp. 1-42.

Schultheis, E. D. and Velinsky, S. A. (1991) "On the Development of a Design Concept for Automated Pavement Crack Sealing Machinery," University of California, Davis, pp. 39, 83-84.

Toynton, D. W. (1986) "Flow Dividers Control Street Sweeper's Operating Speeds," Hydraulics and Pneumatics, Apr., pp. 66-67.

White, F. M. (1988) <u>Heat and Mass Transfer</u>, Addison-Wesley Publishing Company, New York, pp. 478-479, 674.

APPENDIX A - RADIANT MODEL CODE AND VERIFICATION PLOTS

```
c     This program estimates the temperature profile of AC pavement
c     heated by a radiant heater moving by at a constant velocity. The
c     assumption of a conductive semi-infinite slab with a free
c     convective-radiant boundary has been made.  It was designed for
c     use in modeling pavement surface heating and cooling as it relates
c     to the automated highway crack sealing project.
c
c     define variables
c
c     temp      output temperature matrix
c     d         depth matrix
c     ts        source temperature matrix (heater temperature)
c     pi        arithmetic pi
c     blzs      Blasius radiation constant
c     ta        the ambient air temperature
c     alpha     asphalt thermal diffusivity
c     dt        sampling frequency
c     dx        depth between samples
c     thk       asphalt thermal conductivity
c     e1        heater emissivity
c     e2        asphalt emissivity
c     hl        heater length
c     width     heater width
c     dist      heater height above asphalt surface
c     v         heater velocity
c     nu        velocity code (1=ft/s, 2=ft/min, 3=mph)
c     cool      cooling time (seconds)
c     m         number of depth increments to model
c     ndepinc   frequency of depth increments to print out
c     tinc      frequency of time increments to print out
c     f         shape factor
c     ext       sample exposure time to radiant heat source
c
      dimension temp(50,5000), d(50), ts(5)
      open(unit=1,file='radin.dat',status='old')
      open(unit=2,file='radout.dat',status='new')
      pi=3.141592654
      blzs=1.7121e-9
   10 nb=1
c
c     read input data
c
      read(1,*) ta,alpha,dt,dx,thk,e1,e2,hl,width,dist
      read(1,*) v,nu,cool,m,ndepinc
      read(1,*)(ts(i),i=1,nt)
c
c     shape factor calculation
c
      x=hl/dist
      x2=1.0+x**2.0
      y=width/dist
      y2=1.0+y**2.0
```

```
      f=(2.0/(pi*x*y))*(alog(((x2*y2)/(x2+y**2.0))**.5)+y*x2**.5*
     'atan(y/x2**.5)+x*y2**.5*atan(x/y2**.5)-x*atan(x)-y*atan(y))
c
c     define depth matrix
c
      ly=m+1
      d(1)=0.0
      do 20 i=2,ly
      d(i)=dx*(i-1)
   20 continue
c
c     velocity conversion
c
      go to (30,40,50), nu
      feet per second
   30 go to 60
      feet per minute
   40 v=v/60.0
      go to 60
      miles per hour
   50 v=1.46666667*v
c
c     number of time increments
c
   60 ext=hl/v
      nx=ext/dt
      ax=ext/dt
      di=ax-nx
      if(di-.5)70,80,80
   70 n=nx
      go to 90
   80 n=nx+1
c
c     preset temperature at ambient
c
   90 write(2,190) ts(nb),v,hl,dx,f
      write(2,200)(d(i),i=1,m,ndepinc)
      do 110 i=1,ly
      do 100 j=1,n
      temp(i,j)=ta
  100 continue
  110 continue
      write(2,210)0.0,(temp(k,1),k=1,m,ndepinc)
c
c     calculate an equivalent convection coefficient for radiation
c
      do 140 j=1,n
      t1=temp(1,j)+460.0
      t2=ts(nb)+460.0
      h=1.4+blzs*(t1**3+t1**2*t2+t1*t2**2+t2**3)/(((1.0-e1)/e1)
     '+1.0/f+((1.0-e2)/e2))
      dbx=12.0*thk/h
c
c     calculate surface temperature
c
      temp(1,j+1)=(dbx*temp(2,j)+dx*ts(nb))/(dbx+dx)
c
c     calculate temp at depths required
```

```
c
      do 120 i=2,m
      temp(i,j+1)=temp(i,j)+0.04*alpha*dt*(temp(i+1,j)+temp(i-1,j)
     '-2.0*temp(i,j))/(dx**2)
  120 continue
c
c     set temperature at boundary
c
      temp(ly,j+1)=temp(m,j+1)
c
c     determine when to write data
c
      time=j*dt
  130 write(2,210)time,(temp(i,j+1),i=1,m,ndepinc)
  140 continue
c
c     begin to cool
c
      icool=cool/dt
      do 170 j=n+1,n+icool
c
c     calculate surface temperature
c
      temp(1,j+1)=temp(1,j)+(.04*alpha*dt/(dx*dx))*(temp(2,j)-temp(1,j))
     '-(12.0/3600.0)*e2*alpha*dt*((temp(1,j)+460.0)**4)*blzs/(dx*thk)
     '-1.4*((12.0/3600.0)*alpha*dt/(thk*dx))*(temp(1,j)-ta)
c
c     calculate temp at depths required
c
      do 150 i=2,m
      temp(i,j+1)=temp(i,j)+0.04*alpha*dt*(temp(i+1,j)+temp(i-1,j)
     '-2.0*temp(i,j))/(dx**2)
  150 continue
c
c     set temperature at boundary
c
      temp(ly,j+1)=temp(m,j+1)
c
c     determine when to write data
c
      time=j*dt
  160 write(2,210)time,(temp(i,j+1),i=1,m,ndepinc)
  170 continue
c
c     format statements
c
  190 format(1x,'source temperature = ',f6.1,'  deg. F',
     '/,1x,'heater velocity = ',f7.4,'  ft/s',/,1x,
     ''heater length  = ',f7.4,'  feet',/,1x,
     ''depth increment = ',f5.4,'  inches'/,1x,
     ''shape factor = ',f5.4,/)
  200 format(5x,'time',12(5x,f7.4))
  210 format(12f12.4)
 1000 close(1)
      close(2)
      stop
      end
```

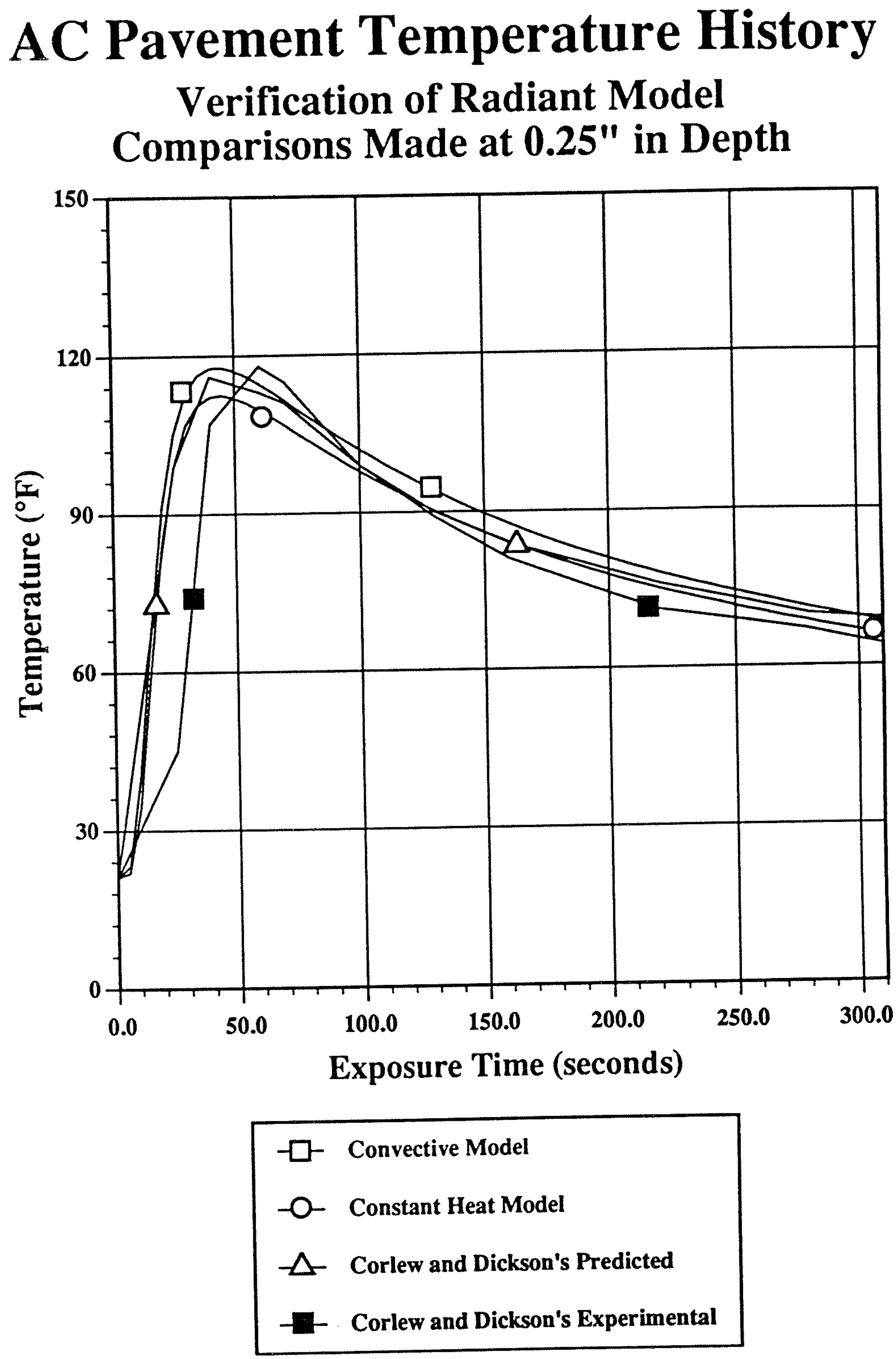


Figure A.1 - Radiant model verification plot, depth = 0.25".

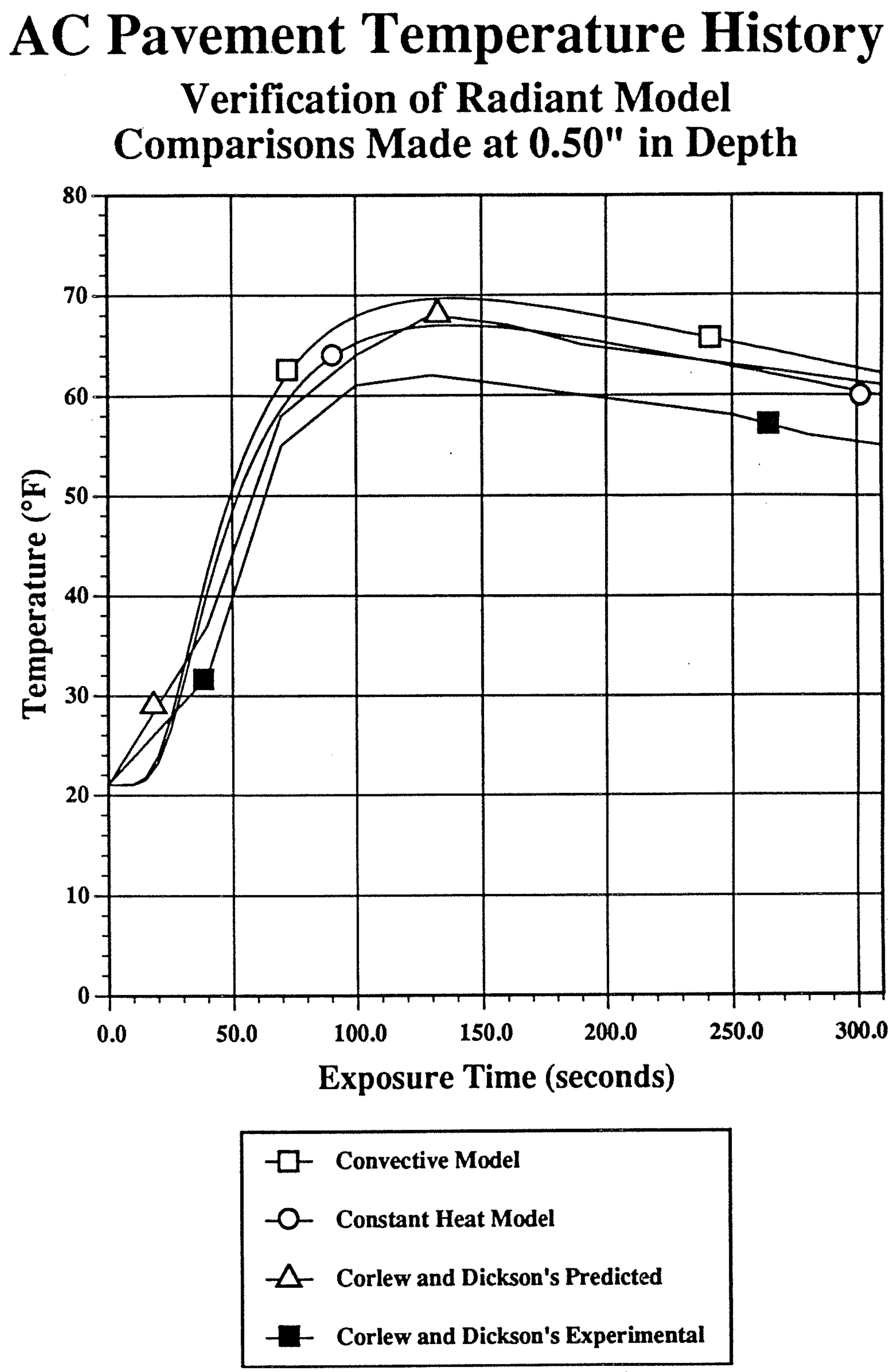


Figure A.2 - Radiant model verification plot, depth = 0.50".

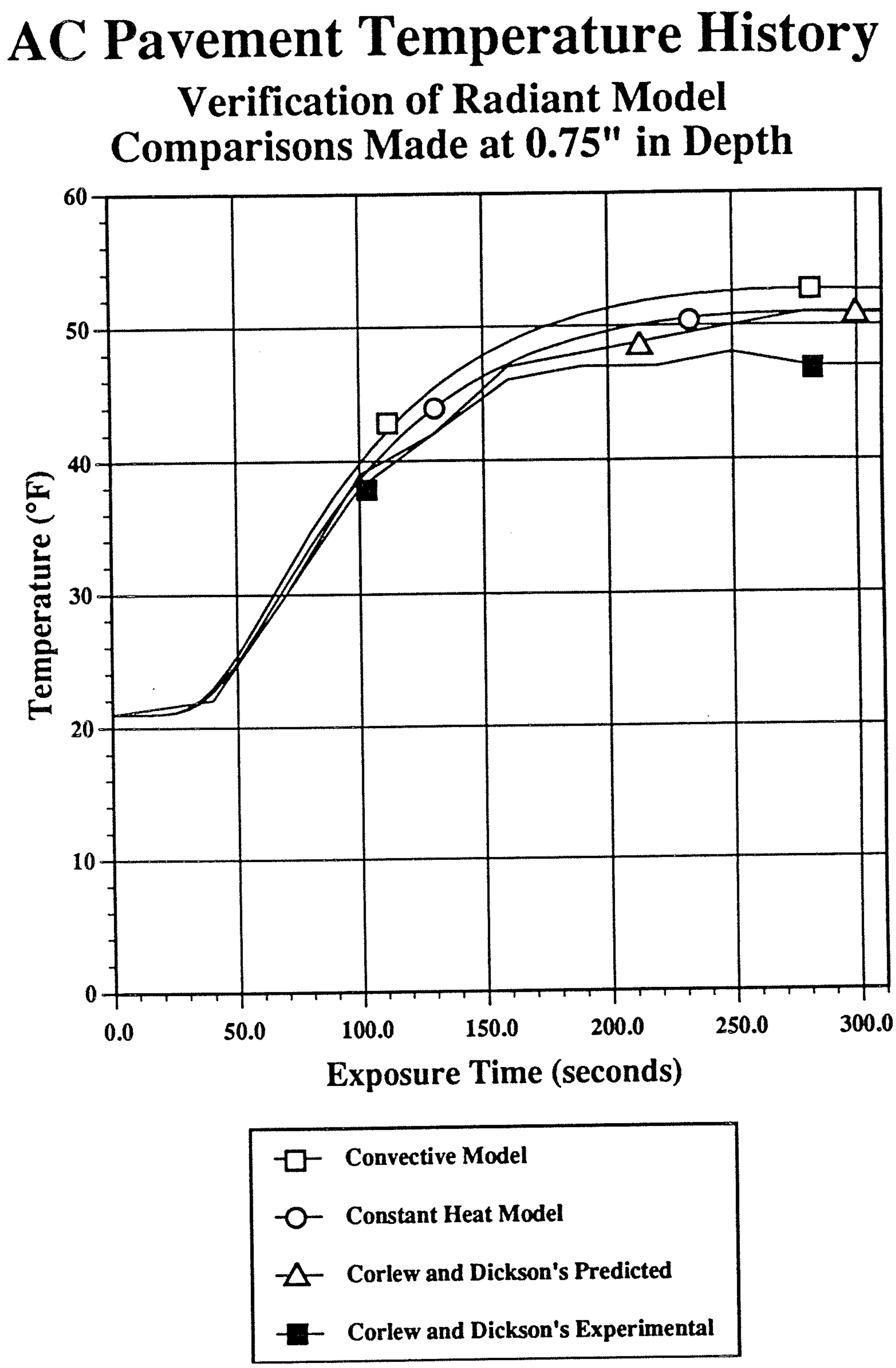


Figure A.3 - Radiant model verification plot, depth = 0.75".

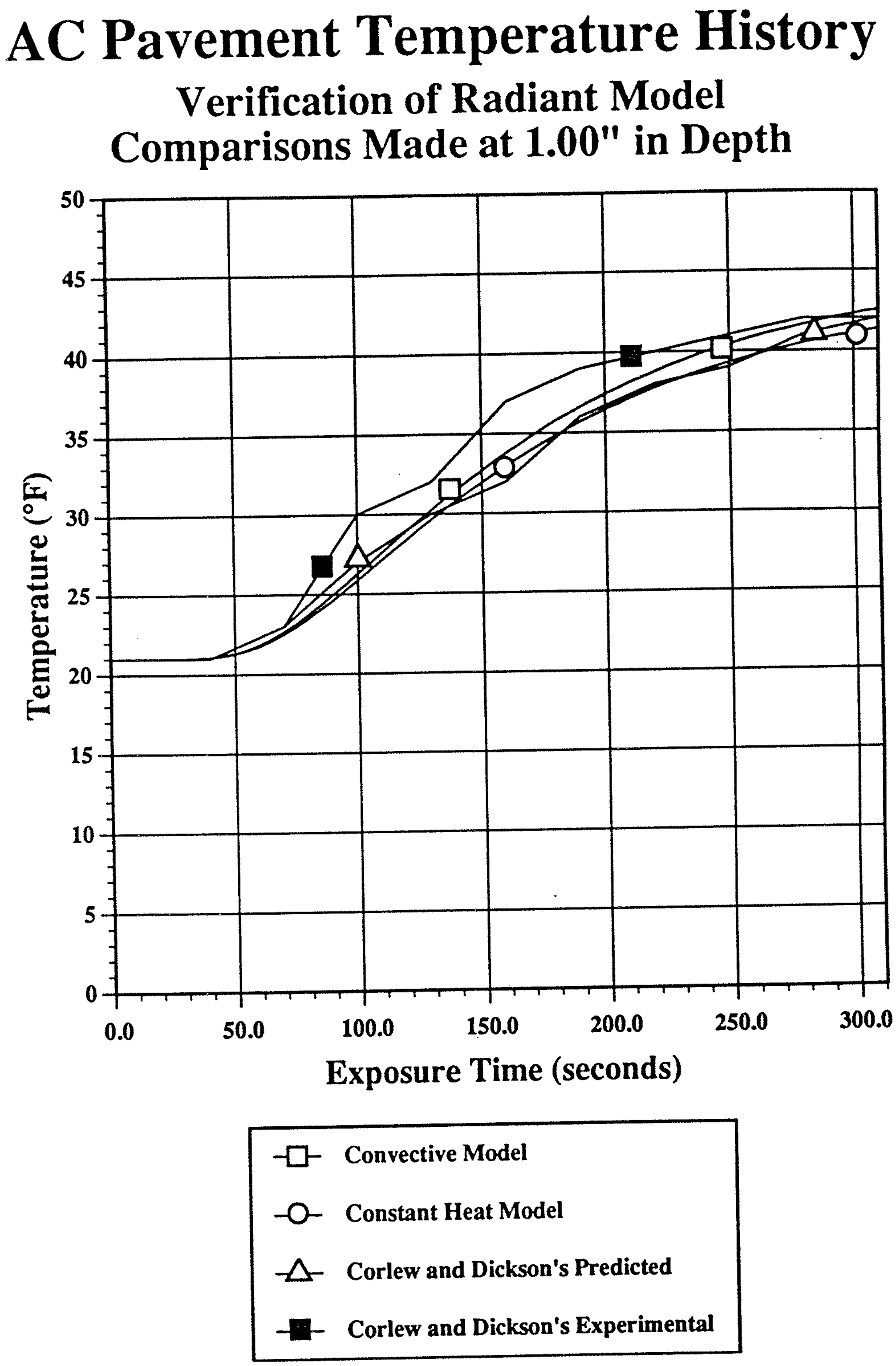


Figure A.4 - Radiant model verification plot, depth = 1.00".

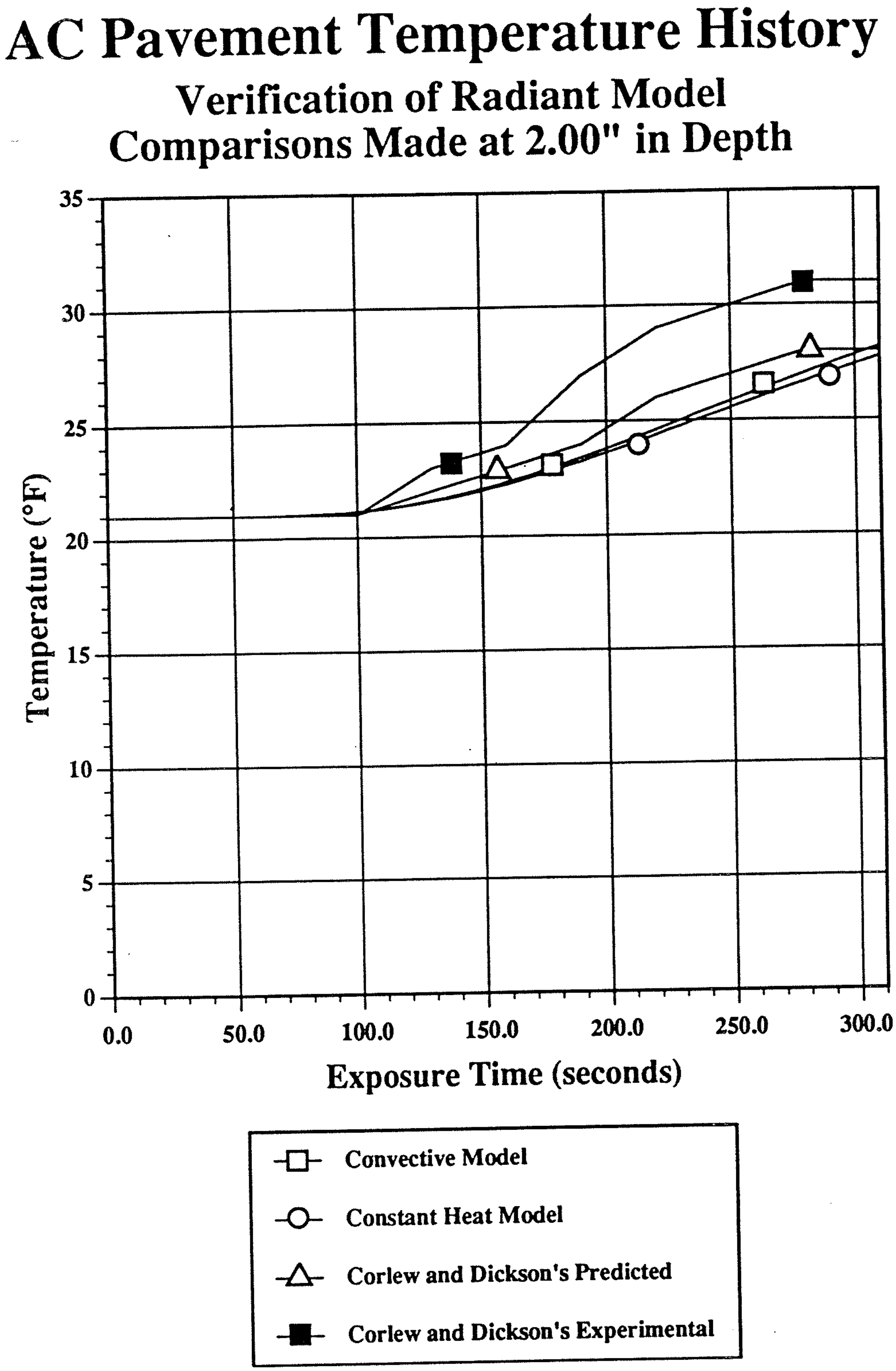


Figure A.5 - Radiant model verification plot, depth = 2.00".

APPENDIX B - CONVECTIVE MODEL CODE

```
c     This program estimates the temperature profile of AC pavement
c     heated by a convective heater moving by at a constant velocity.
c     The assumption of a conductive semi-infinite slab with a free
c     convective-radiant boundary has been made.  It was designed for
c     use in modeling pavement surface heating and cooling as it relates
c     to the automated highway crack sealing project.
c
c     define variables
c
c     temp      output temperature matrix
c     d         depth matrix
c     ts        source temperature
c     pi        arithmetic pi
c     blzs      Blasius radiation constant
c     ta        the ambient air temperature
c     alpha     asphalt thermal diffusivity
c     dt        sampling frequency
c     dx        depth between samples
c     thk       asphalt thermal conductivity
c     emiss     asphalt emissivity
c     diam      heater diameter (inches)
c     vel       heater velocity (ft/sec)
c     effdis    effective total reach of heat (diameters)
c     cfm       rated CFM of blower
c     thkexit   thermal conductivity of exit gas
c     vexit     exit velocity (ft/sec)
c     cool      cooling time (sec)
c     m         number of depth increments to model
c     ndepinc   frequency of depth increments to print out
c     viskin    kinematic viscosity of exit air (ft^2/sec)
c     ext       sample exposure time to convective heat source
c
      dimension temp(82,1500),d(82)
      open(unit=1,file='convectin.dat',status='old')
      open(unit=2,file='convectout.dat',status='new')
      pi=3.141592654
      blzs=1.7121e-9
c
c     read input data
c
      read(1,*) alpha,thk,emiss,cool,m,ndepinc
      read(1,*) dt,dx,diam,vel,effdis,cfm,ta,ts
c
c     define depth matrix
c
      dd=dt*vel
      n=2*int((effdis*diam/(12.0*dd))+.5)
      ddadj=2.0*effdis*(diam/12.0)/n
      ly=m+1
      d(1)=0.0
      do 20 i=2,ly
      d(i)=dx*(i-1)
   20 continue
c
c     calculate kinematic viscosity, thermal conductivity at exit
```

```
c      and velocity at exit
c
       viskin=2.083567e-10*ts**2.0+5.7070707e-7*ts+1.229302e-4
       thkexit=-2.616527e-9*ts**2.0+2.108487e-5*ts+1.325811e-2
       denfac = 4.020954E-10*ts**3.0 + -5.714779E-7*ts**2.0
      '+ 1.999122E-3*ts + 8.566306E-1
       vexit=((cfm*1.04)*denfac/60.0)/((diam**2.0*pi/4.0)/144.0)
c
c      preset temperature at ambient
c
   90  write(2,190) ts,vexit,diam,dx
       write(2,200)(d(i),i=1,m,ndepinc)
       do 110 i=1,ly
       do 100 j=1,n
       temp(i,j)=ta
  100  continue
  110  continue
       write(2,210)0.0,(temp(k,1),k=1,m,ndepinc)
c
c      calculation of forced convection coefficient
c
       reyn=vexit*(diam/12.0)/viskin
       do 140 j=1,n
       ihalfn=n/2
       if(j.lt.ihalfn)rd=effdis-j*ddadj*12.0/diam
       if(j.eq.ihalfn)rd=0.0
       if(j.gt.ihalfn)rd=(j-ihalfn)*ddadj*12.0/diam
       rnusselt=(reyn**.6)/(3.329+.273*rd**1.3)
       hconv=12.0*rnusselt*thkexit/diam
       dbx=12.0*thk/hconv
c
c      calculate surface temperature
       temp(1,j+1)=(dbx*temp(2,j)+dx*ts)/(dbx+dx)
c
c      calculate temp at depths required
       do 120 i=2,m
       temp(i,j+1)=temp(i,j)+0.04*alpha*dt*(temp(i+1,j)+temp(i-1,j)
      '-2.0*temp(i,j))/(dx**2)
  120  continue
c
c      set temperature at boundary
c
       temp(ly,j+1)=temp(m,j+1)
c
c      increment time
c
       time=j*dt
  130  write(2,210)time,(temp(i,j+1),i=1,m,ndepinc)
  140  continue
c
c      begin to cool
c
       if(cool.eq.0.0)goto 1000
       icool=cool/dt
       do 170 j=n+1,n+icool
c
c      calculate surface temperature
c
```

```
      temp(1,j+1)=temp(1,j)+(.04*alpha*dt/(dx*dx))*(temp(2,j)-temp(1,j))
     '-(12.0/3600.0)*emiss*alpha*dt*((temp(1,j)+460.0)**4)*blzs/(dx*thk)
     '-1.4*((12.0/3600.0)*alpha*dt/(thk*dx))*(temp(1,j)-ta)
c
c     calculate temp at depths required
c
      do 150 i=2,m
      temp(i,j+1)=temp(i,j)+0.04*alpha*dt*(temp(i+1,j)+temp(i-1,j)
     '-2.0*temp(i,j))/(dx**2)
  150 continue
c
c     set temperature at boundary
c
      temp(ly,j+1)=temp(m,j+1)
c
c     increment time
c
      time=j*dt
  160 write(2,210)time,(temp(i,j+1),i=1,m,ndepinc)
  170 continue
c
c     format statements
c
  190 format(1x,'heater exit temperature
     ' = ',f6.1,'  deg. F',/,1x,'heater exit velocity = ',f7.1,
     '' ft/s',/,1x,'heater diameter  = ',f7.4,'  inches',/,
     '1x,'depth increment = ',f7.4,'  inches',/)
  200 format(4x,'time',12(1x,f7.3,' in.'))
  210 format(1x,f7.4,11f12.4)
 1000 close(1)
      close(2)
      stop
      end
```

APPENDIX C - SUR-LITE BURNER TEST PLOTS

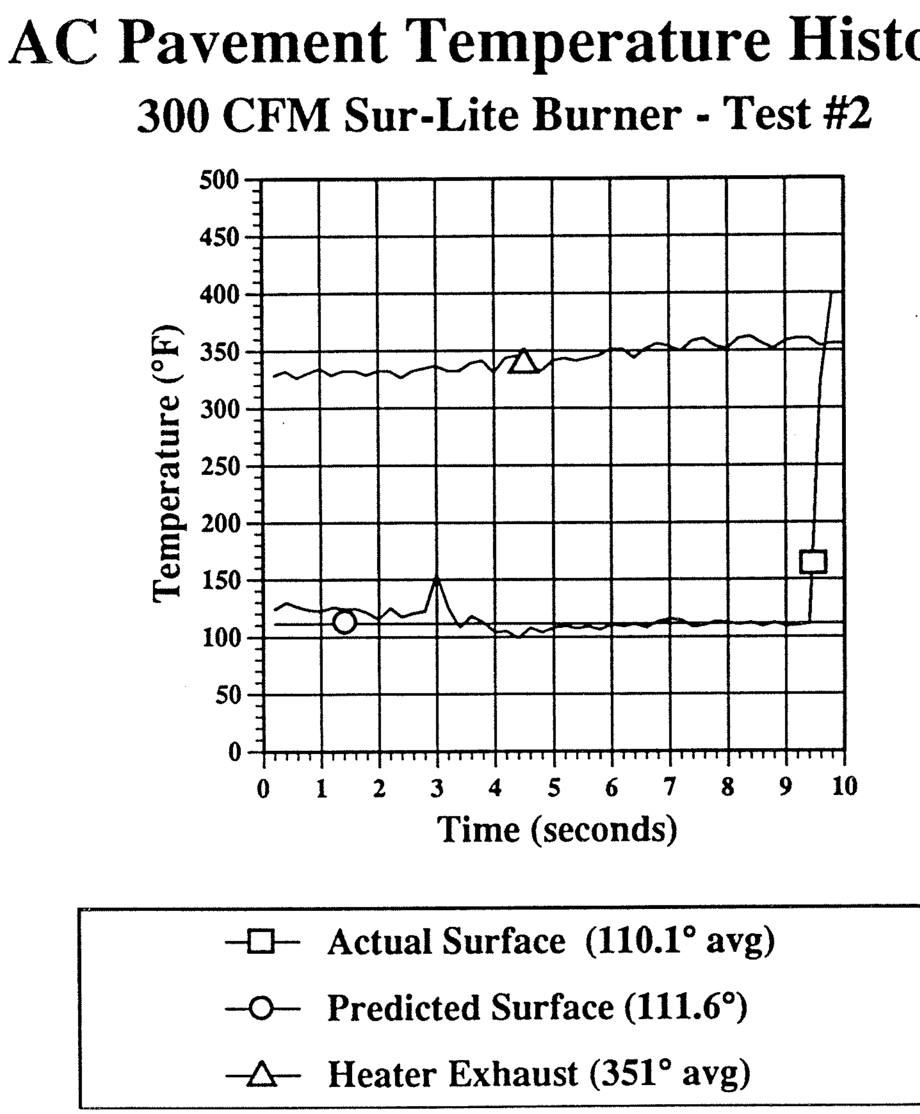
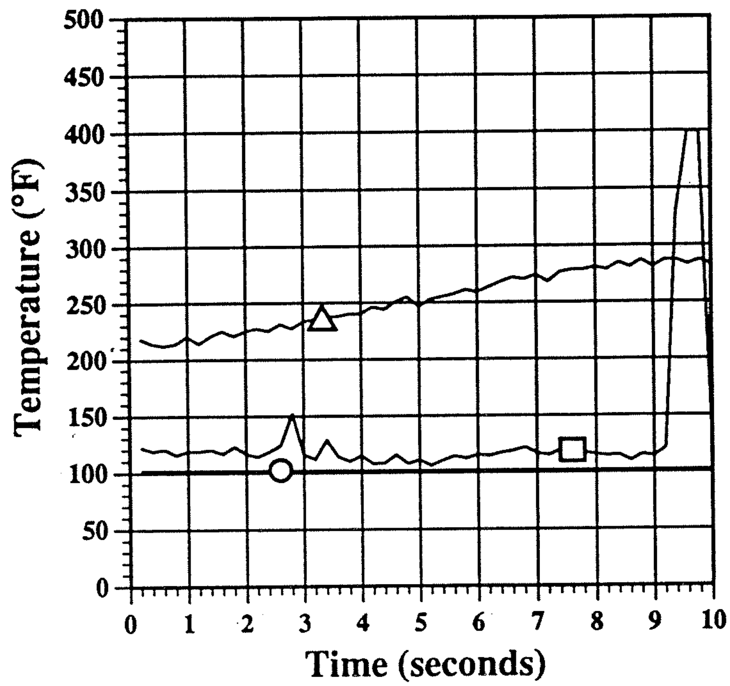


Figure C.1 - Sur-Lite burner test #2. Test #1 was performed in error.

AC Pavement Temperature History

300 CFM Sur-Lite Burner - Test #3



—□— Actual Surface (114.6° avg)
—○— Predicted Surface (102.1°)
—△— Heater Exhaust (263° avg)

Figure C.2 - *Sur-Lite burner test #3.*

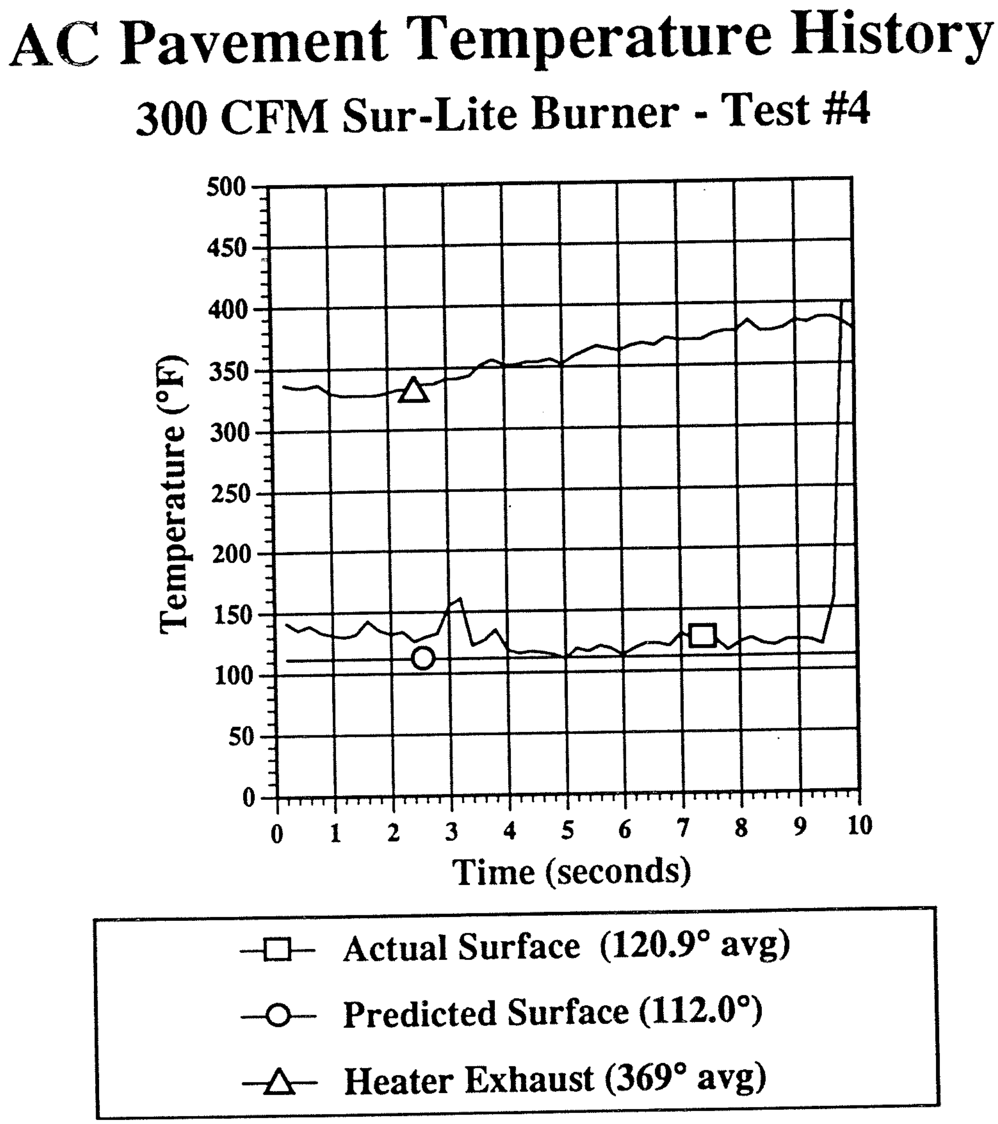


Figure C.3 - Sur-Lite burner test #4.

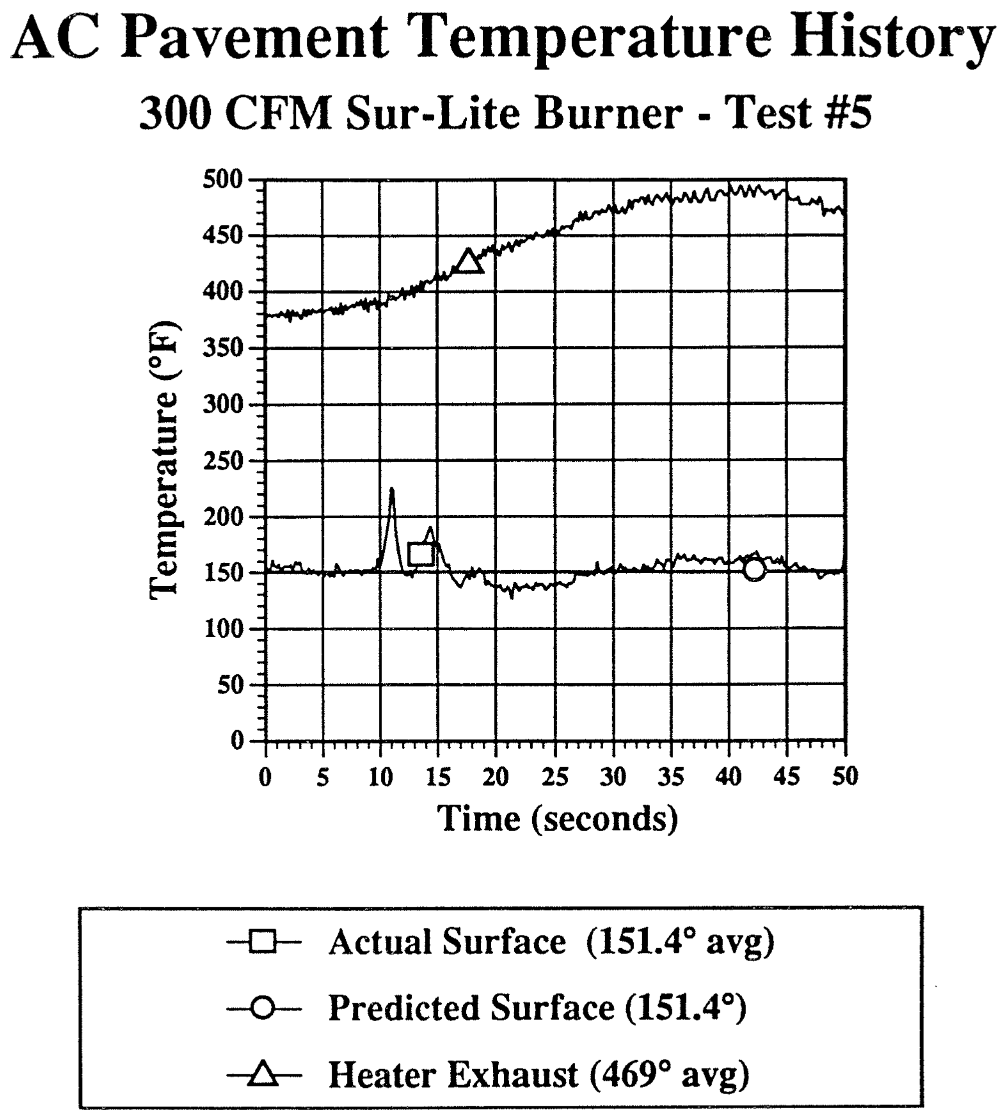


Figure C.4 - Sur-Lite burner test #5.

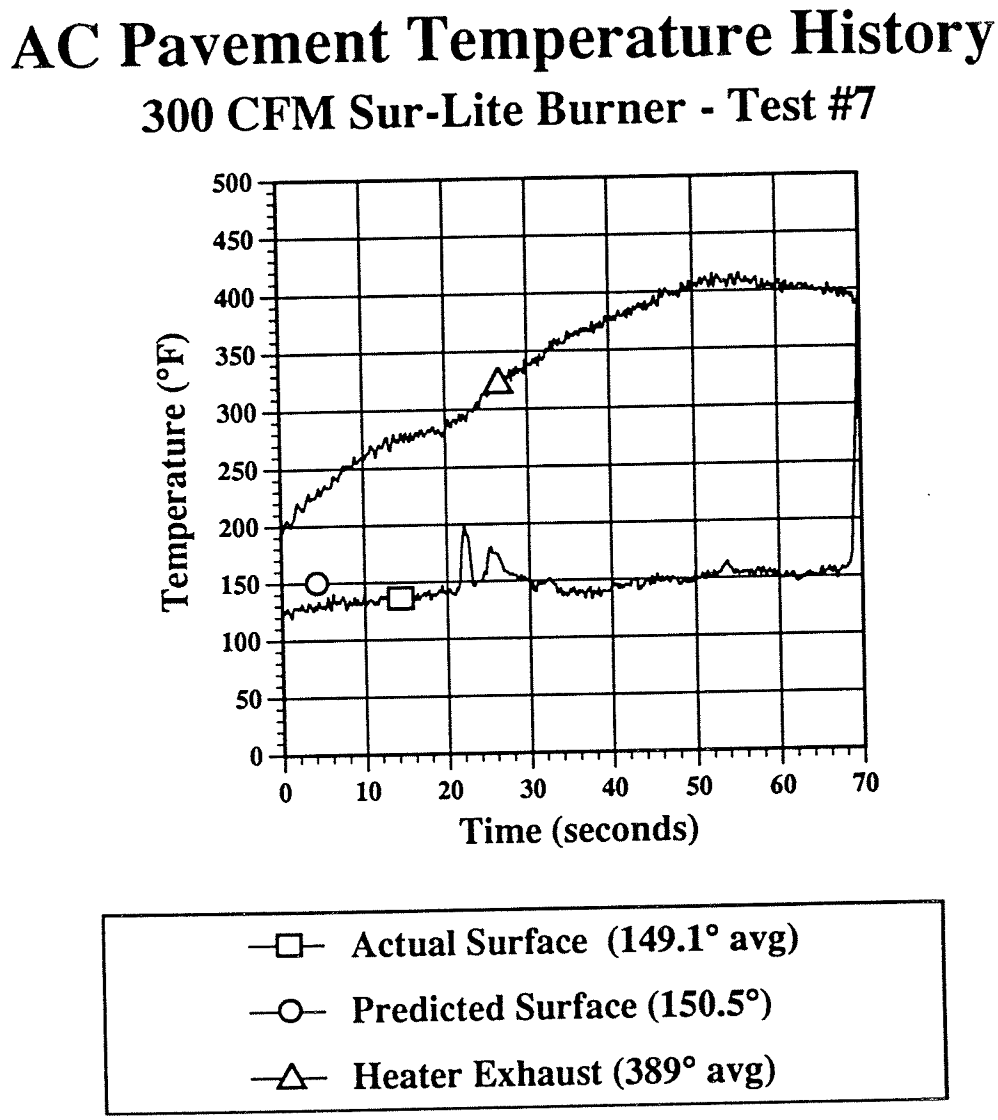


Figure C.5 - *Sur-Lite burner test #7. Test #6 was performed in error.*

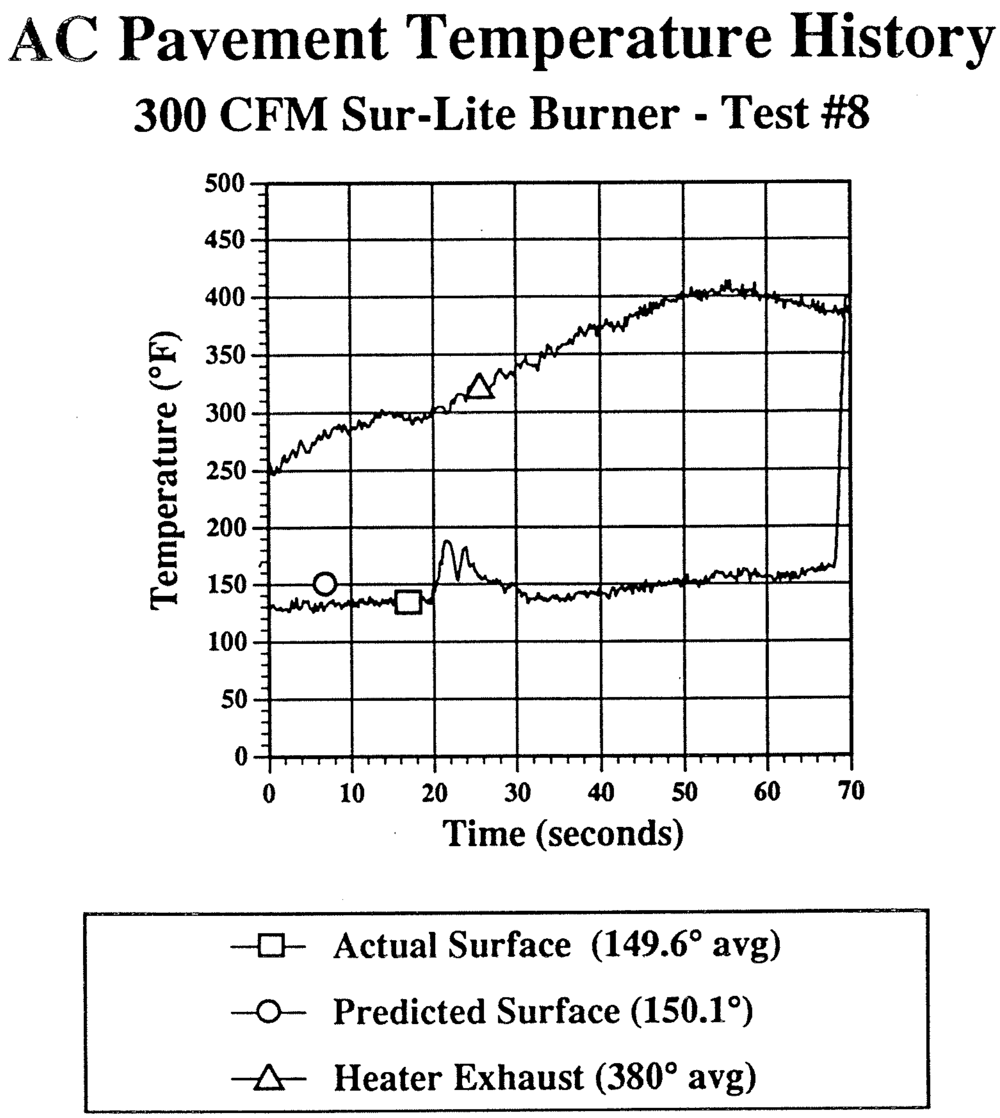


Figure C.6 - Sur-Lite burner test #8.

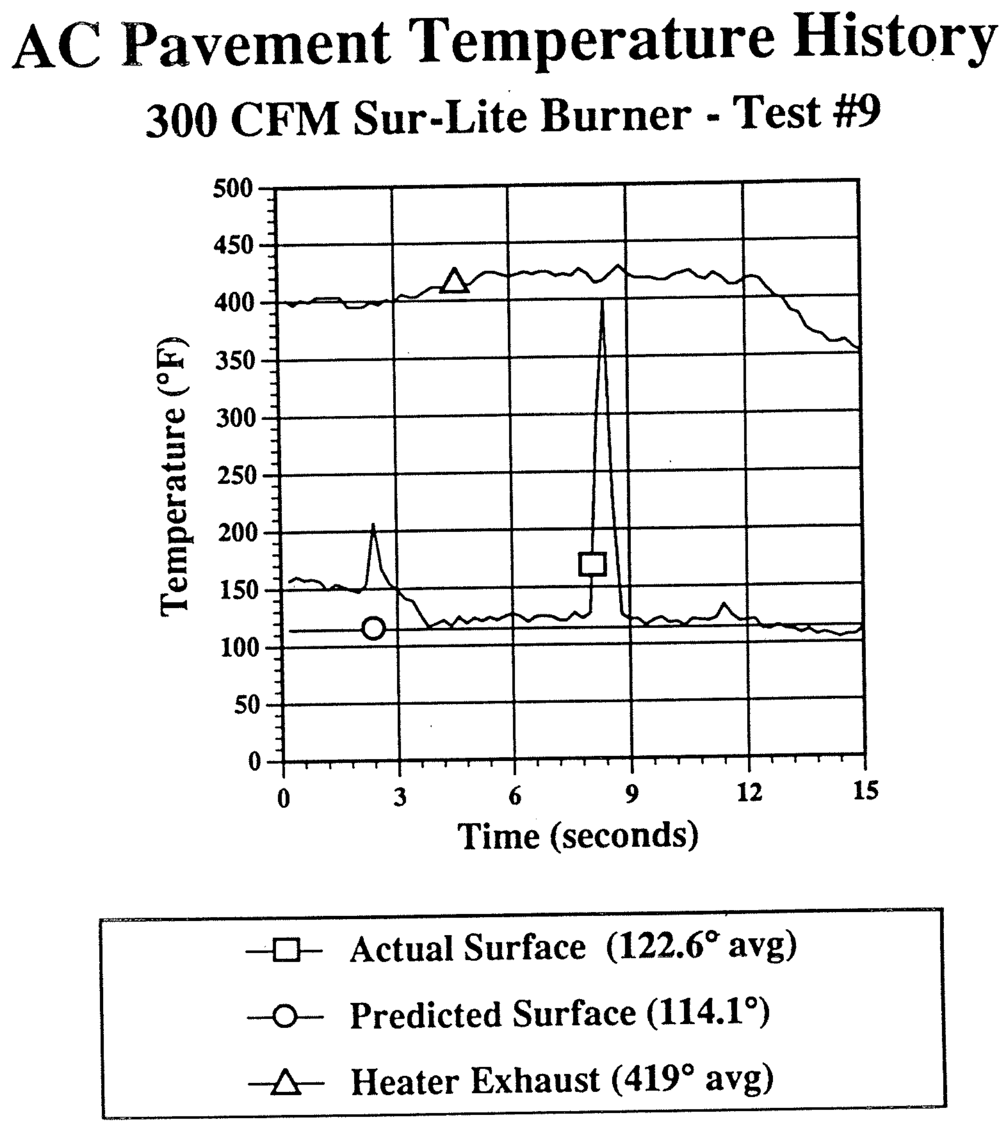


Figure C.7 *- Sur-Lite burner test #9.*

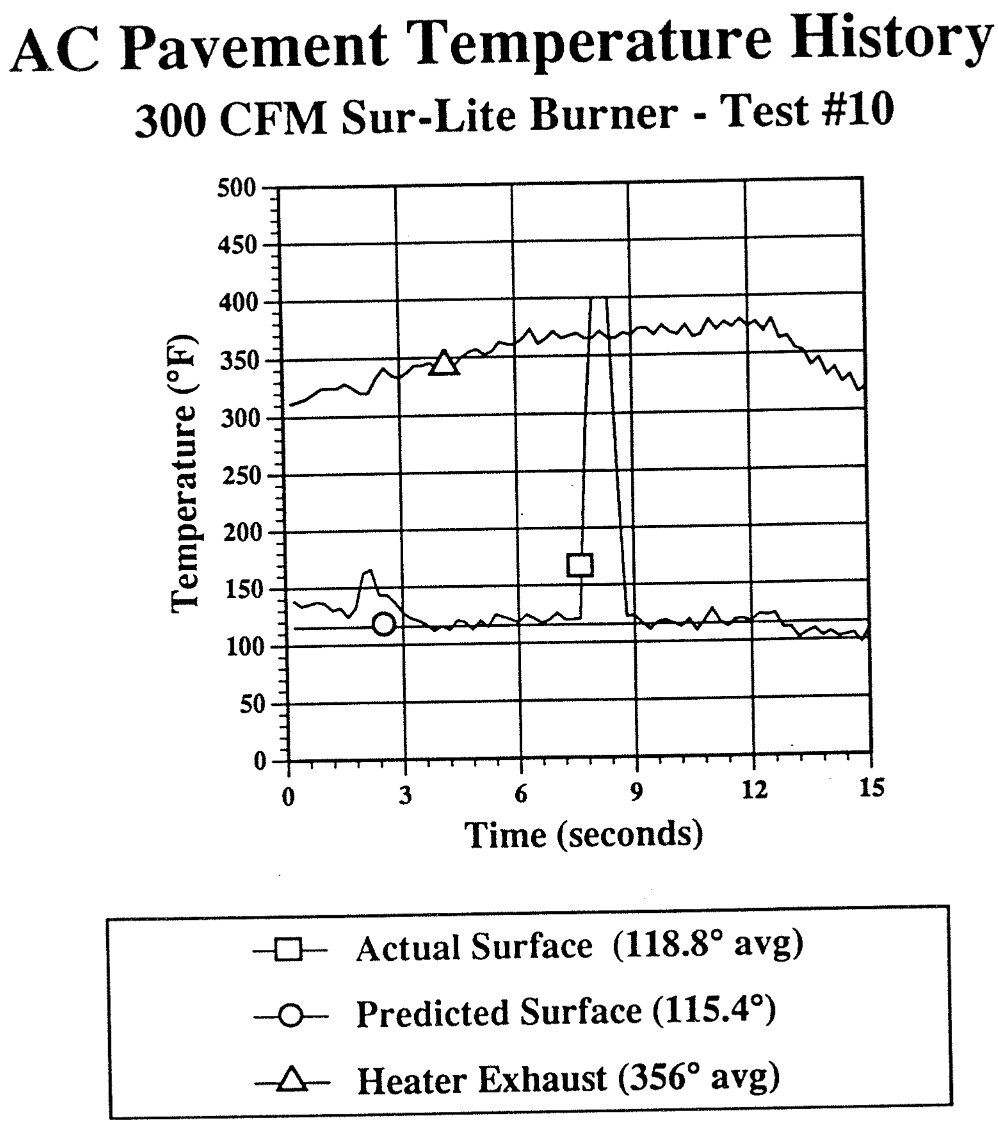


Figure C.8 *- Sur-Lite burner test #10.*

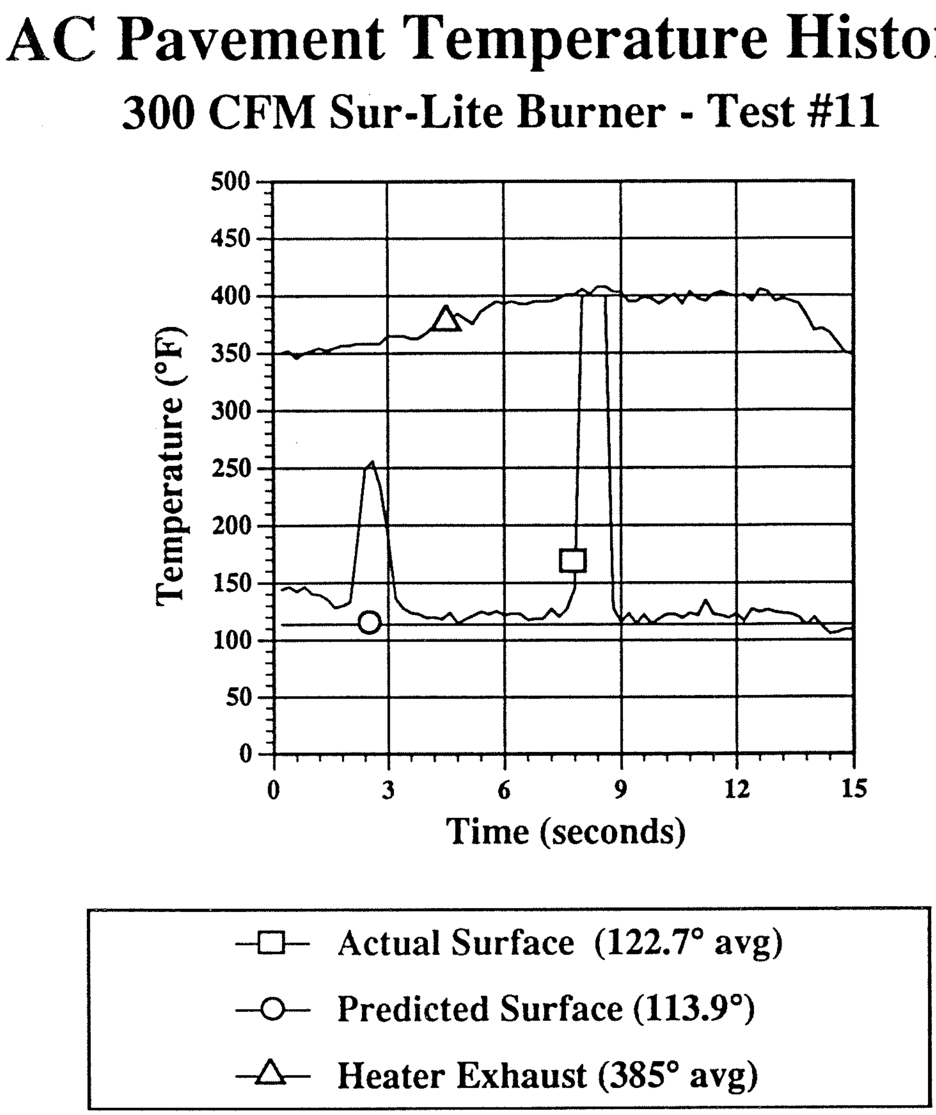


Figure C.9 - Sur-Lite burner test #11.

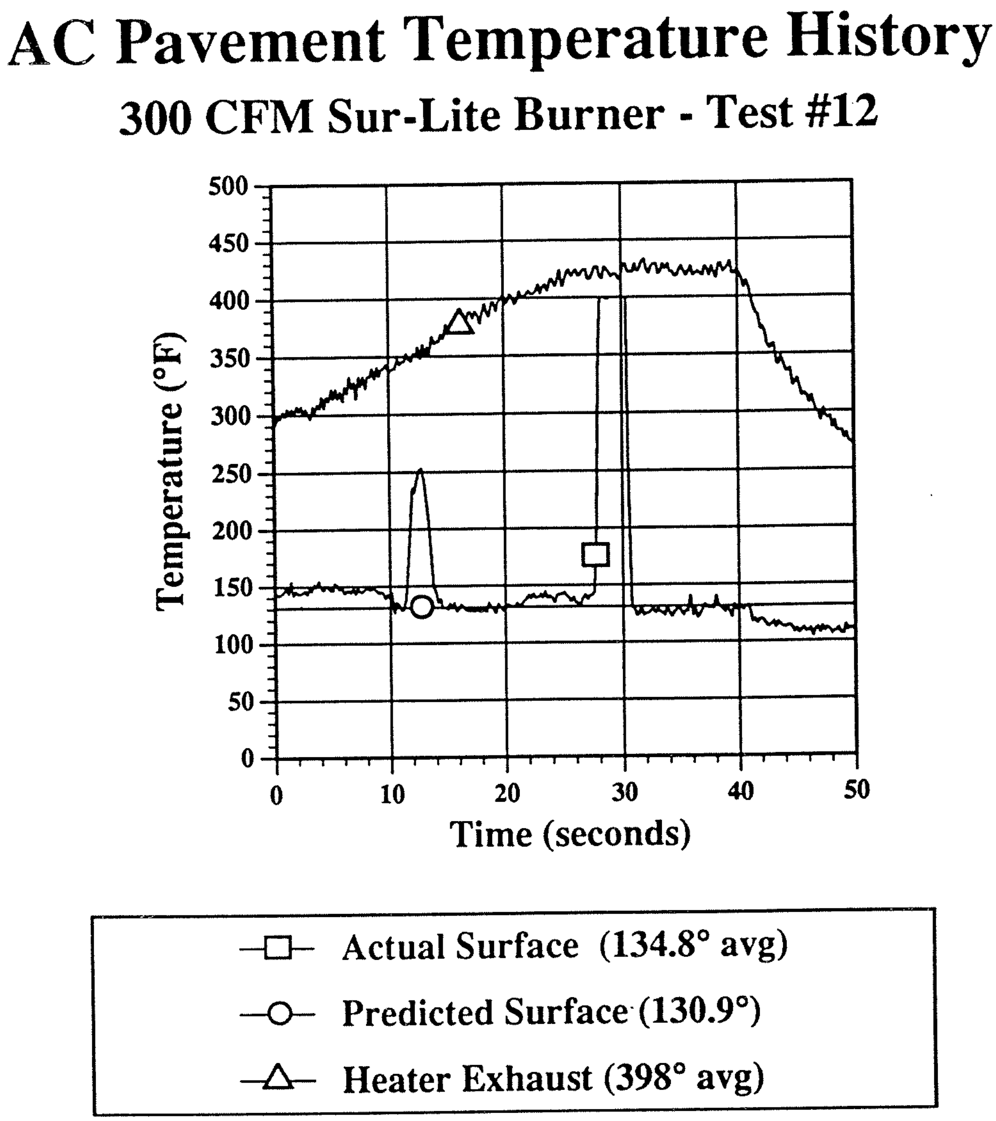


Figure C.10 - Sur-Lite burner test #12.

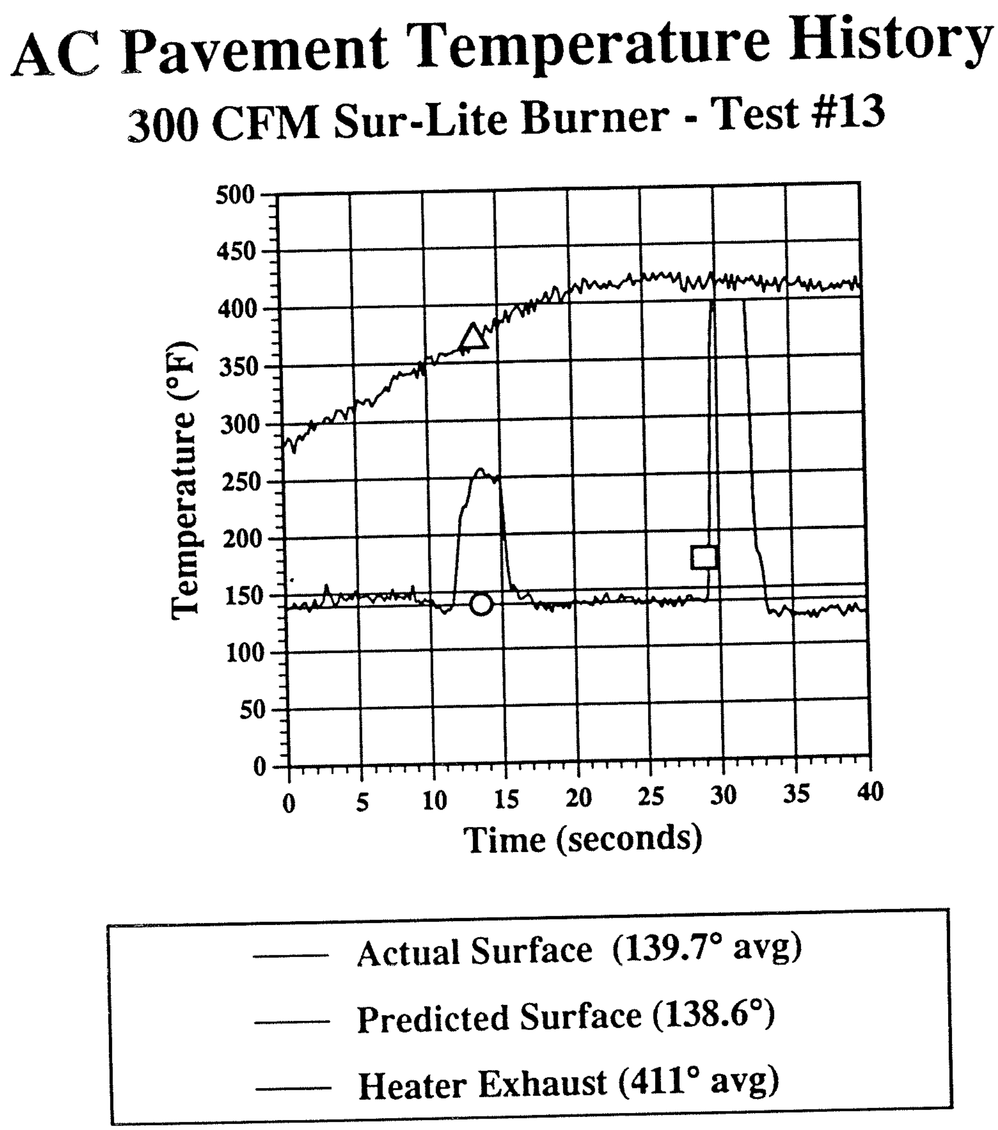


Figure C.11 - *Sur-Lite burner test #13.*

AC Pavement Temperature History

300 CFM Sur-Lite Burner - Test #14

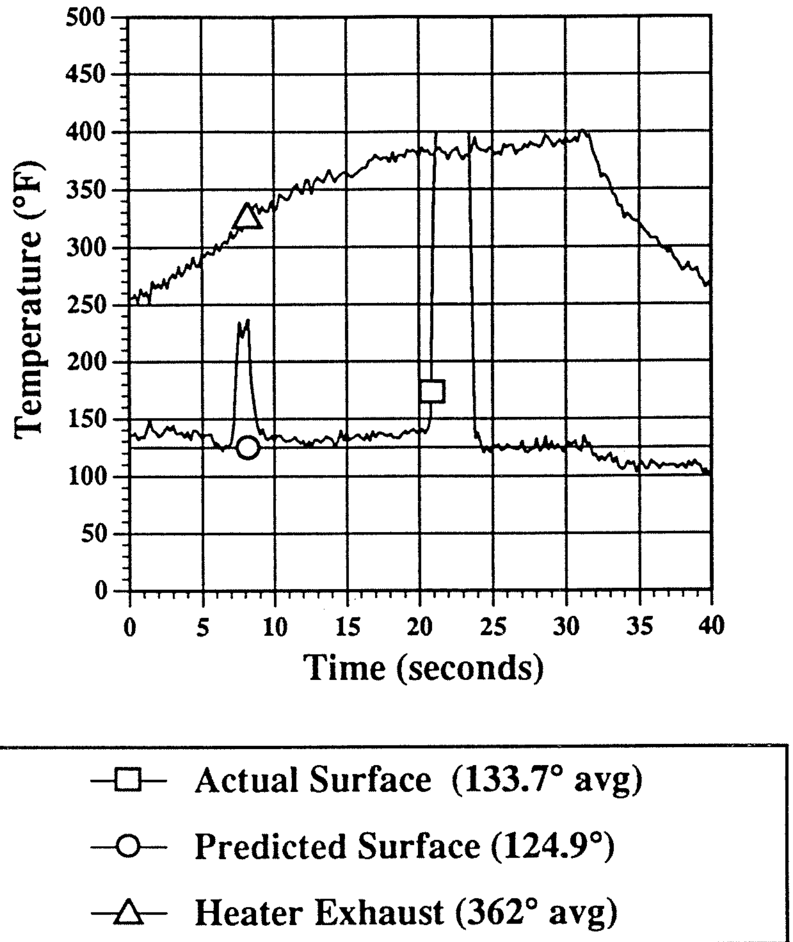


Figure C.12 - Sur-Lite burner test #14.

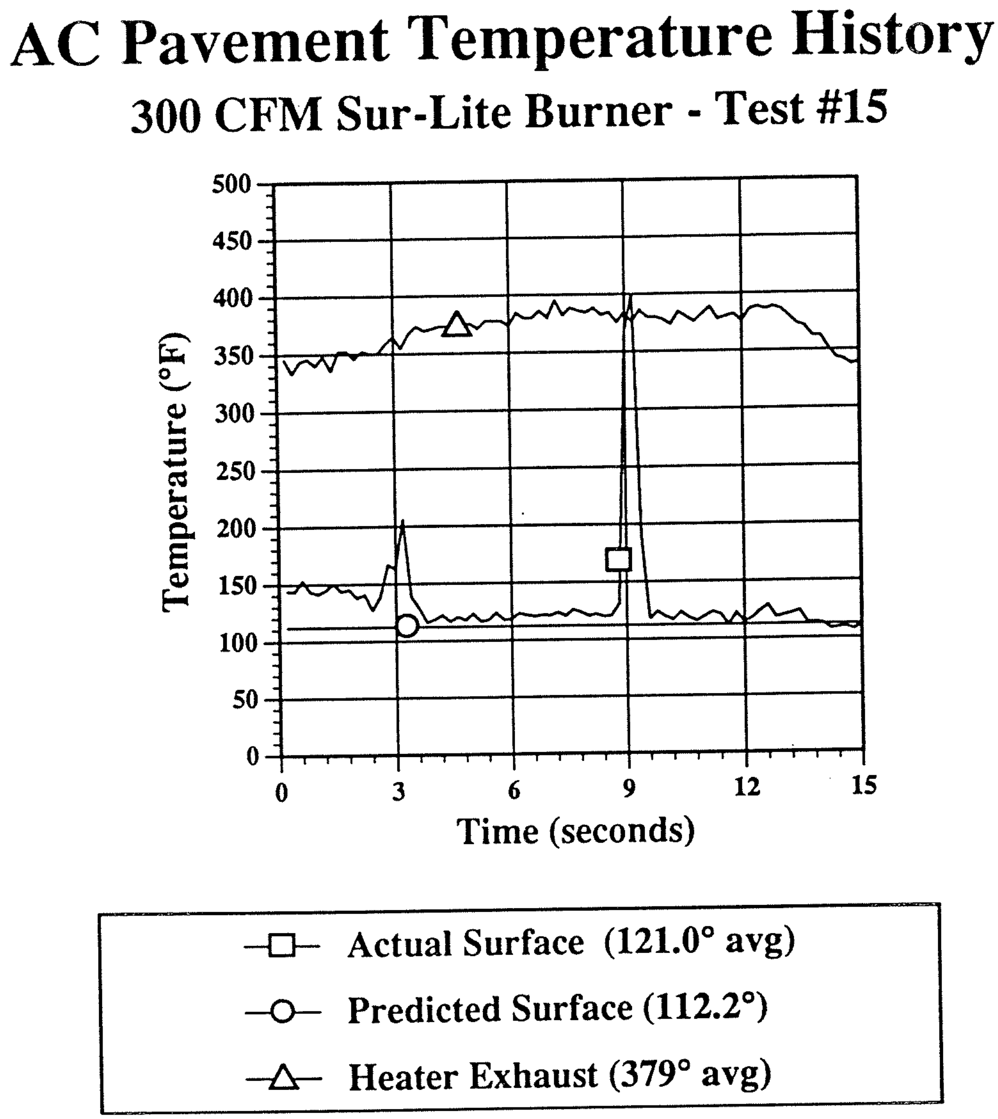


Figure C.13 - *Sur-Lite burner test #15.*

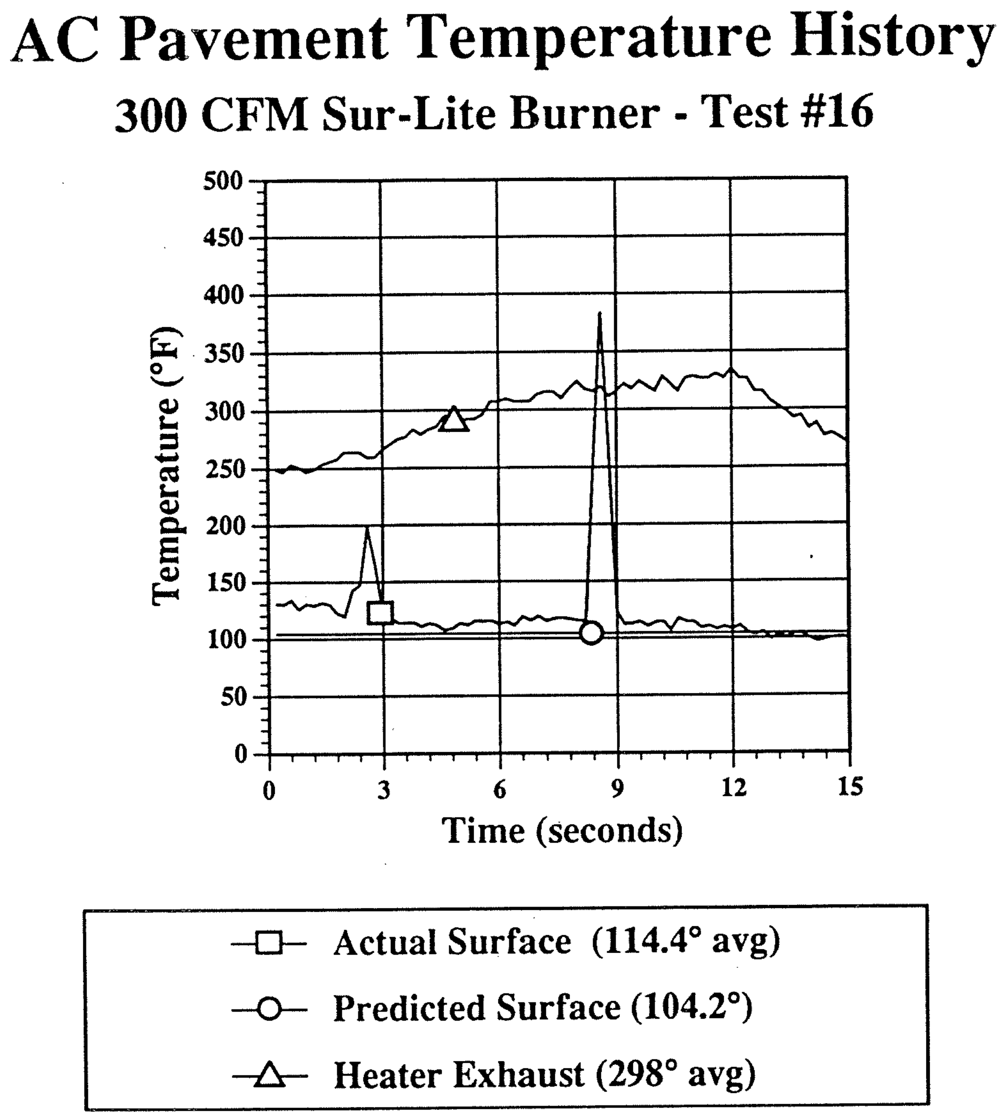


Figure C.14 - Sur-Lite burner test #16.

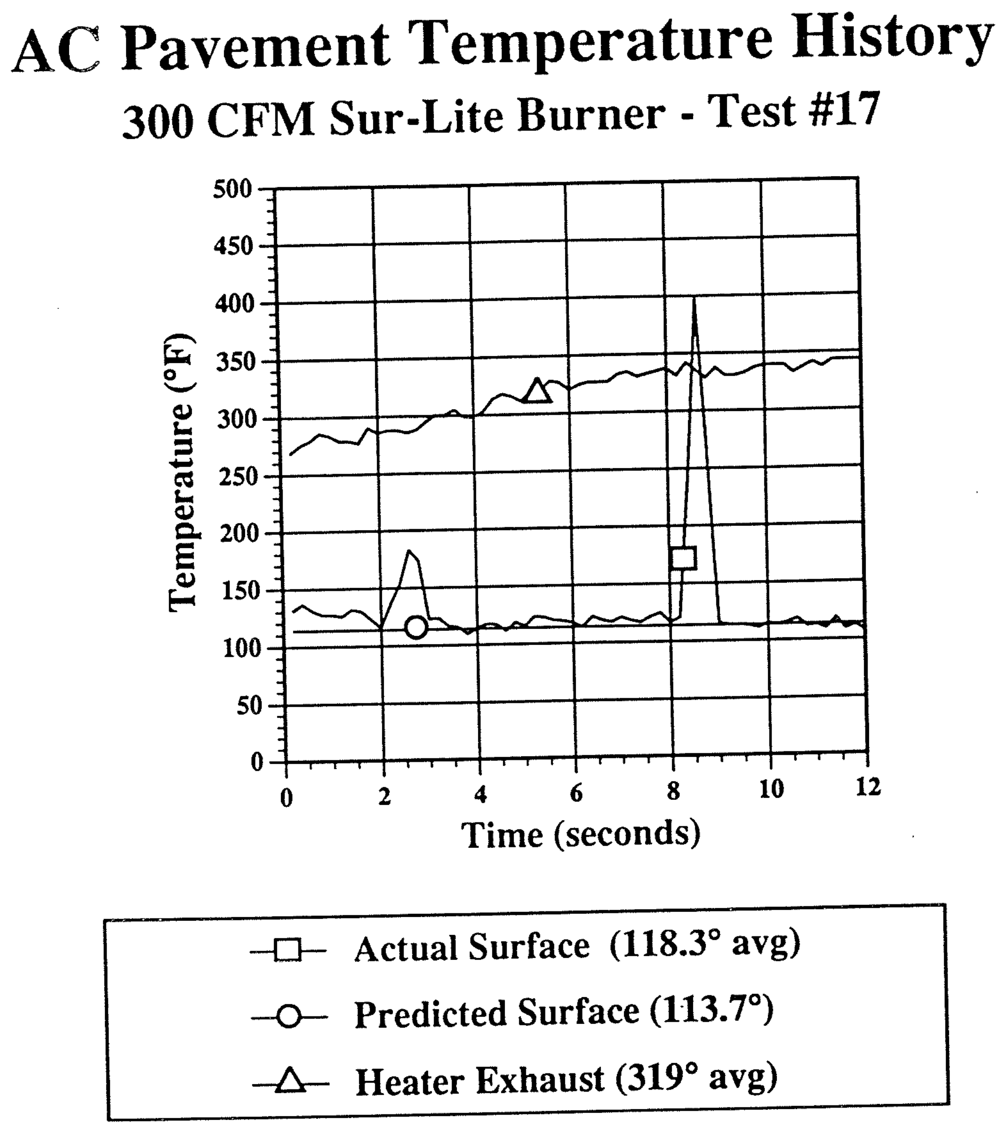


Figure C.15 - Sur-Lite burner test #17.

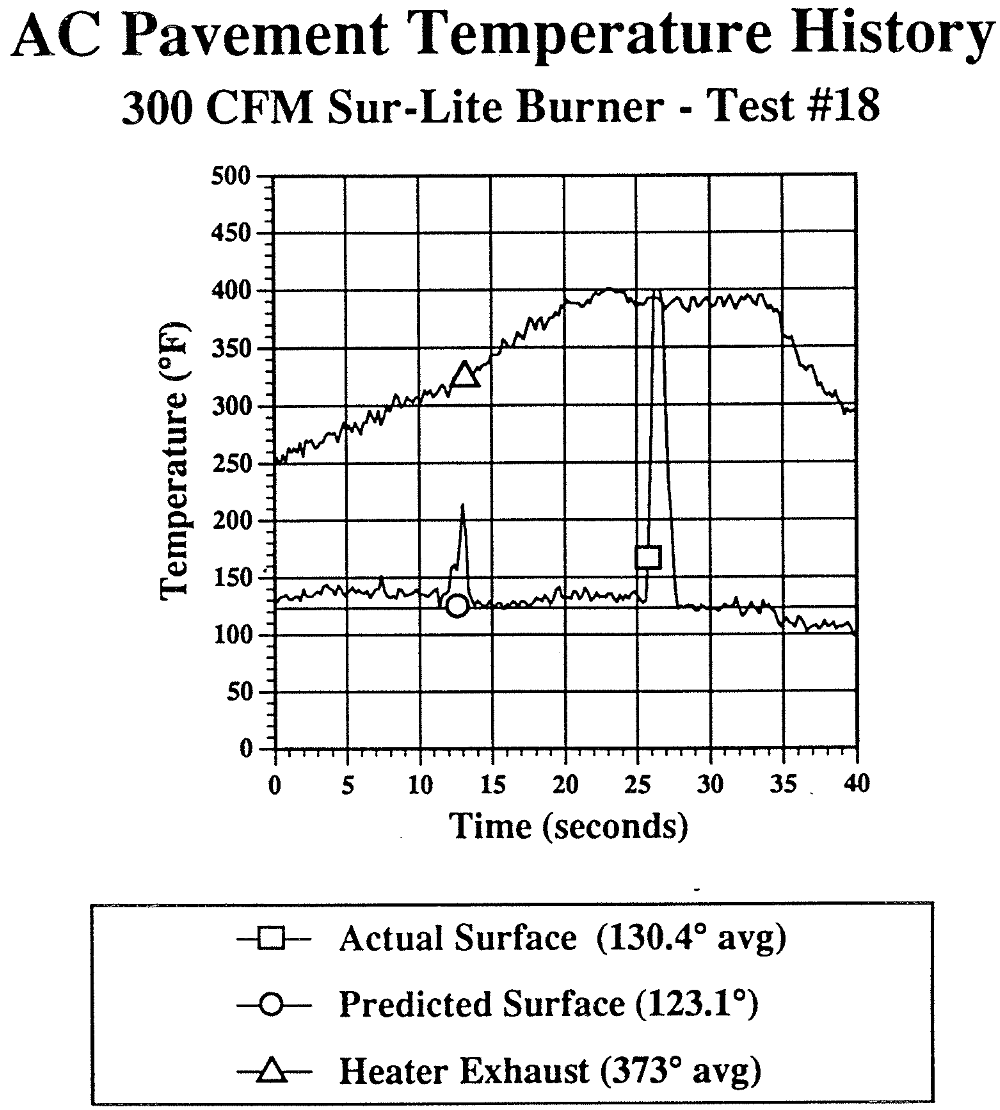


Figure C.16 - Sur-Lite burner test #18.

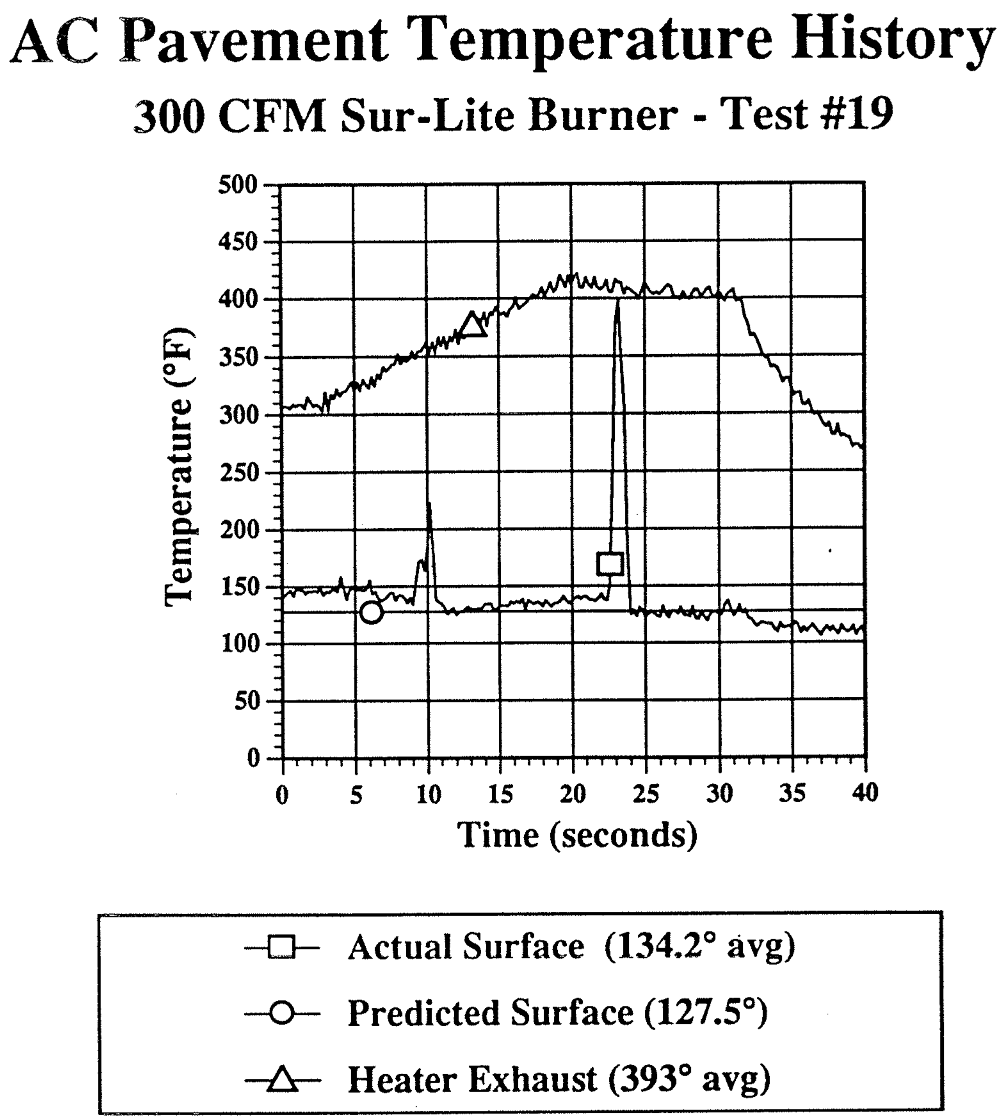


Figure C.17 - Sur-Lite burner test #19.

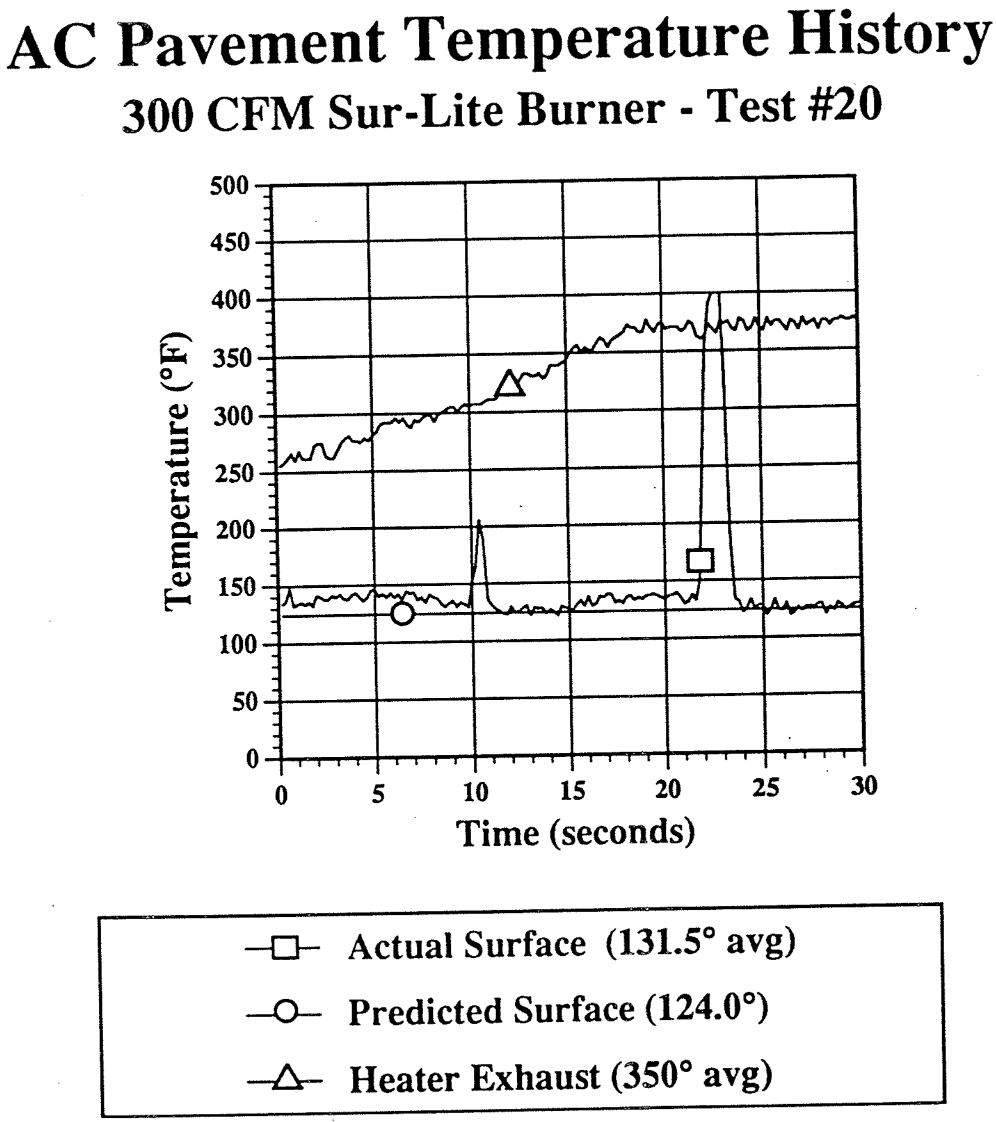


Figure C.18 - Sur-Lite burner test #20.

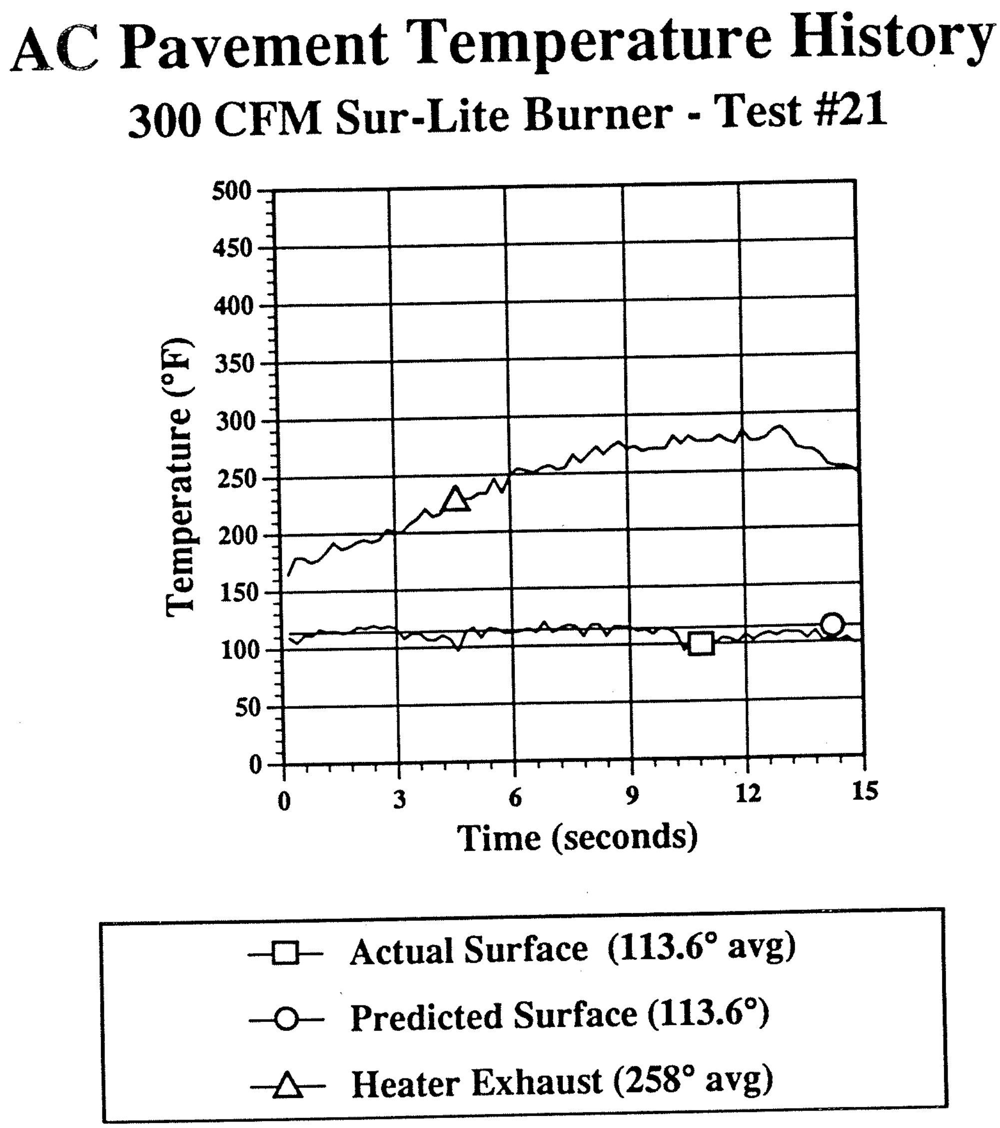


Figure C.19 - Sur-Lite burner test #21.

AC Pavement Temperature History

300 CFM Sur-Lite Burner - Test #22

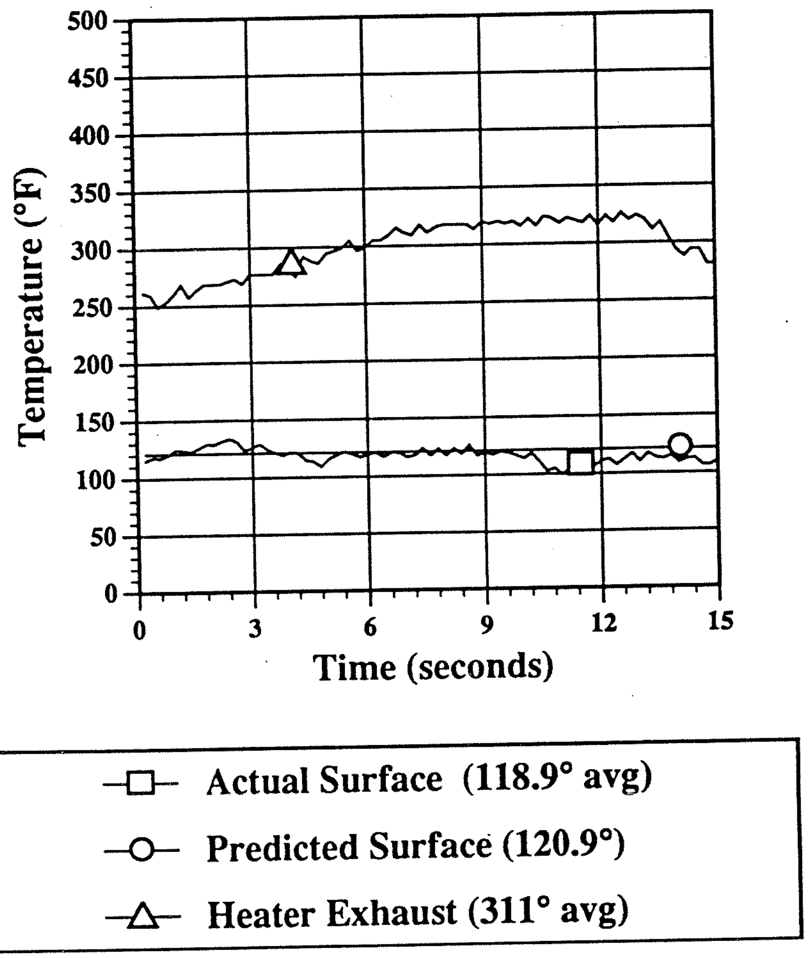


Figure C.20 - Sur-Lite burner test #22.

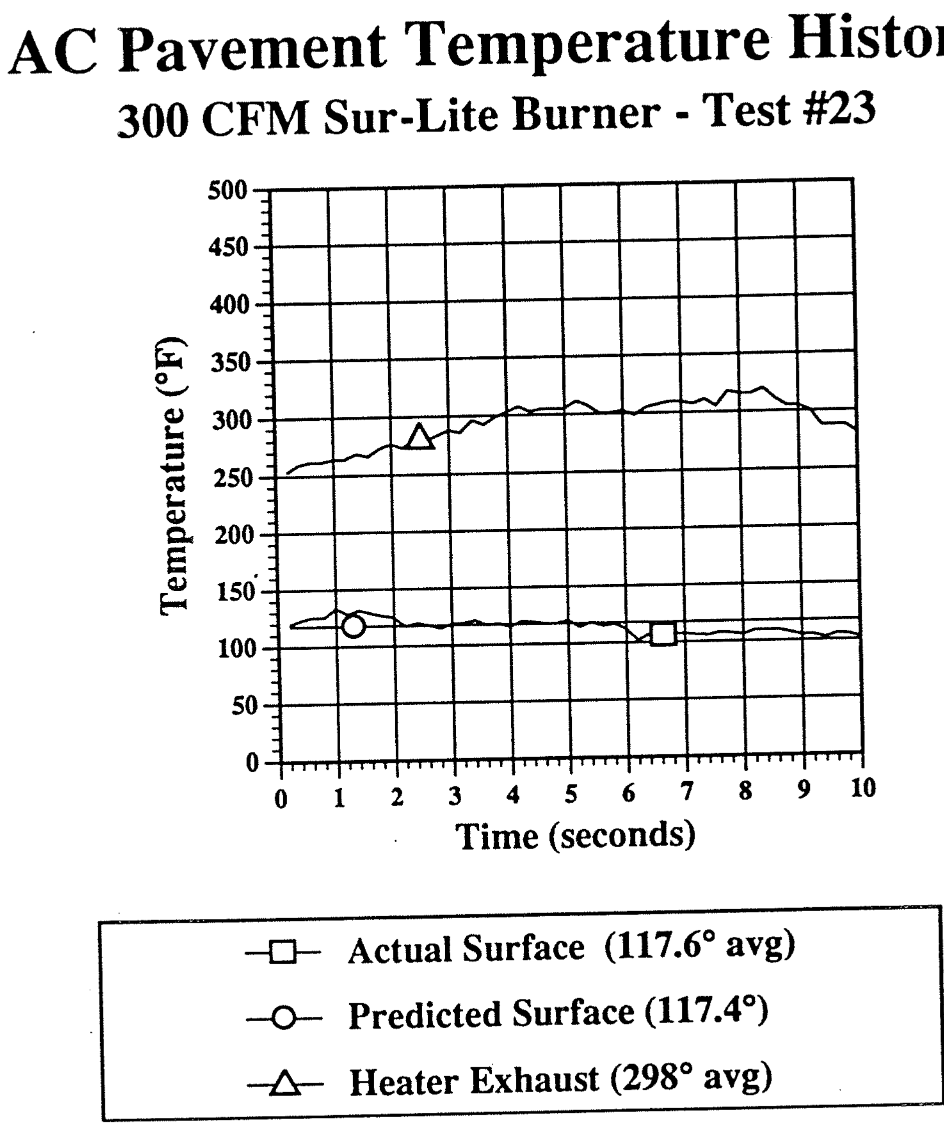


Figure C.21 - Sur-Lite burner test #23.

AC Pavement Temperature History

300 CFM Sur-Lite Burner - Test #24

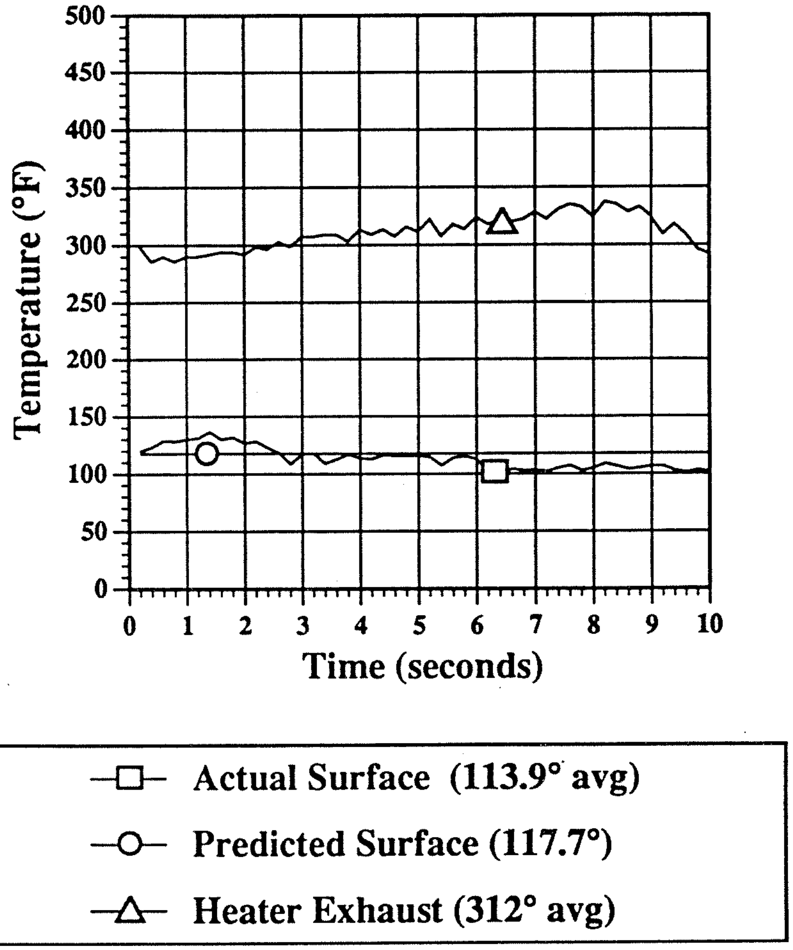


Figure C.22 - Sur-Lite burner test #24.

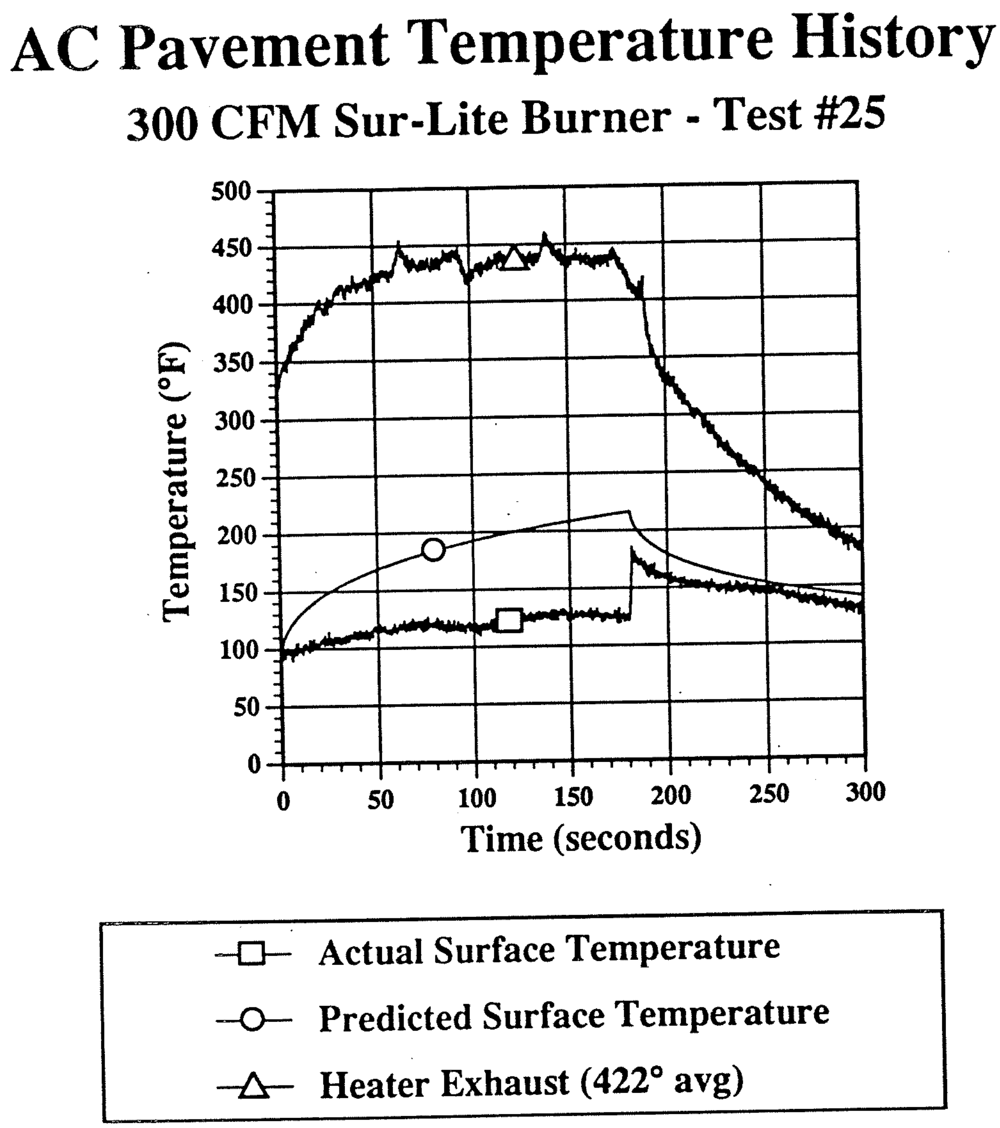


Figure C.23 - Sur-Lite burner test #25.

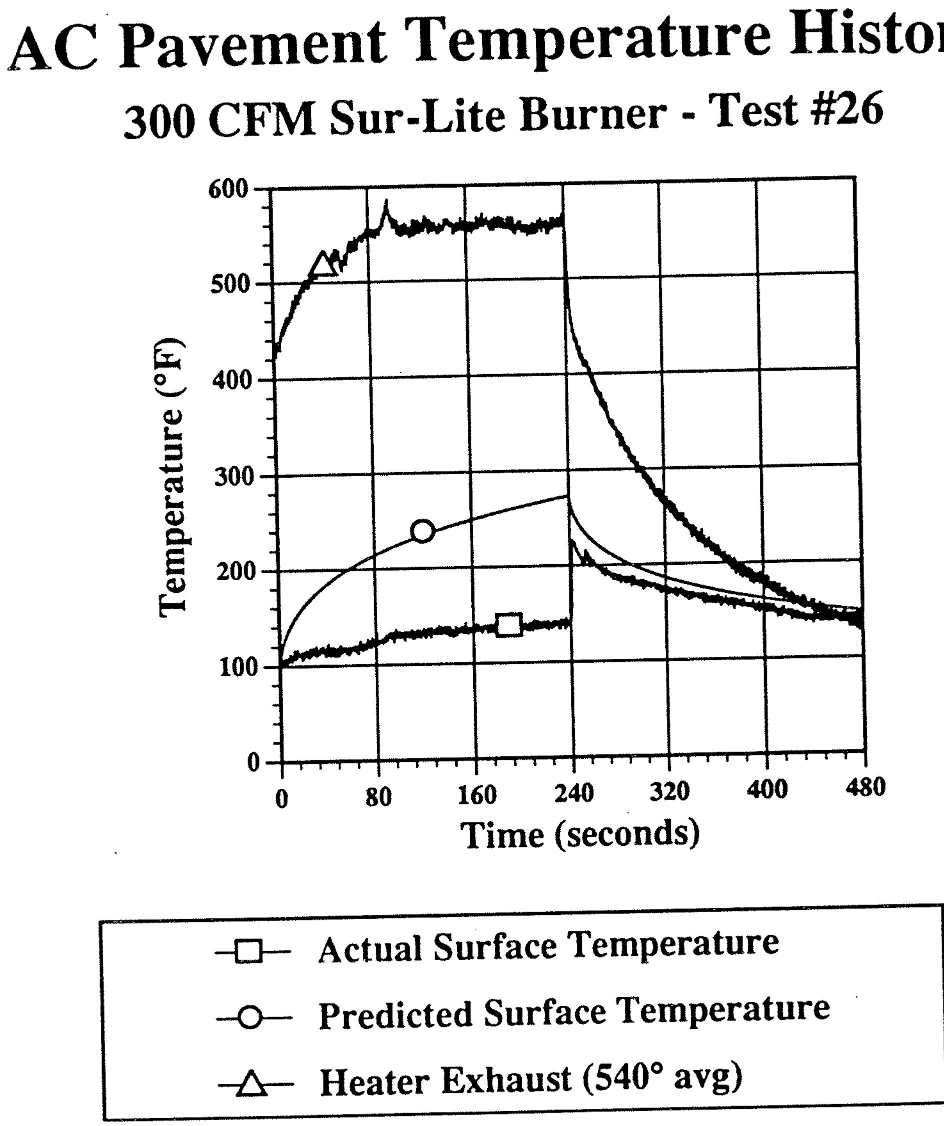


Figure C.24 - Sur-Lite burner test #26.

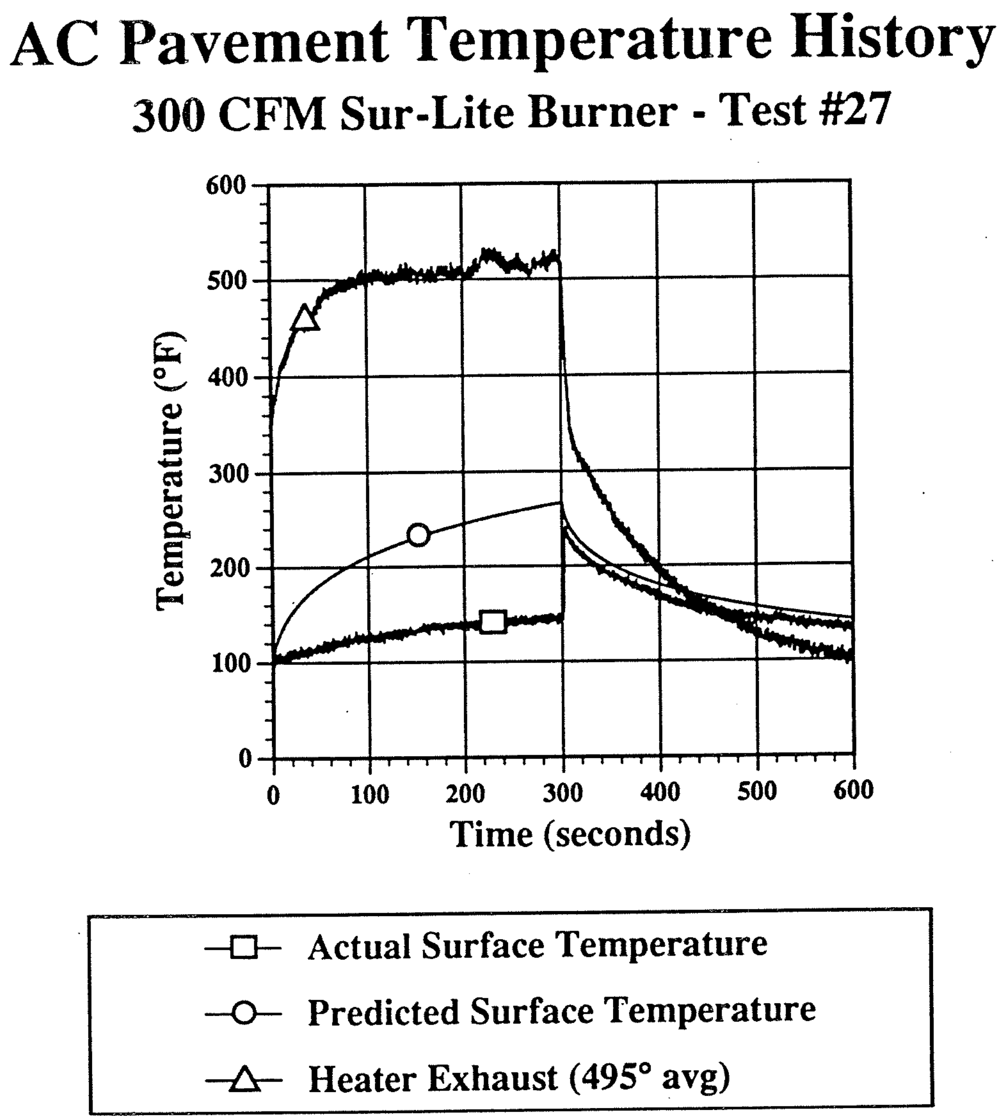


Figure C.25 - Sur-Lite burner test #27.

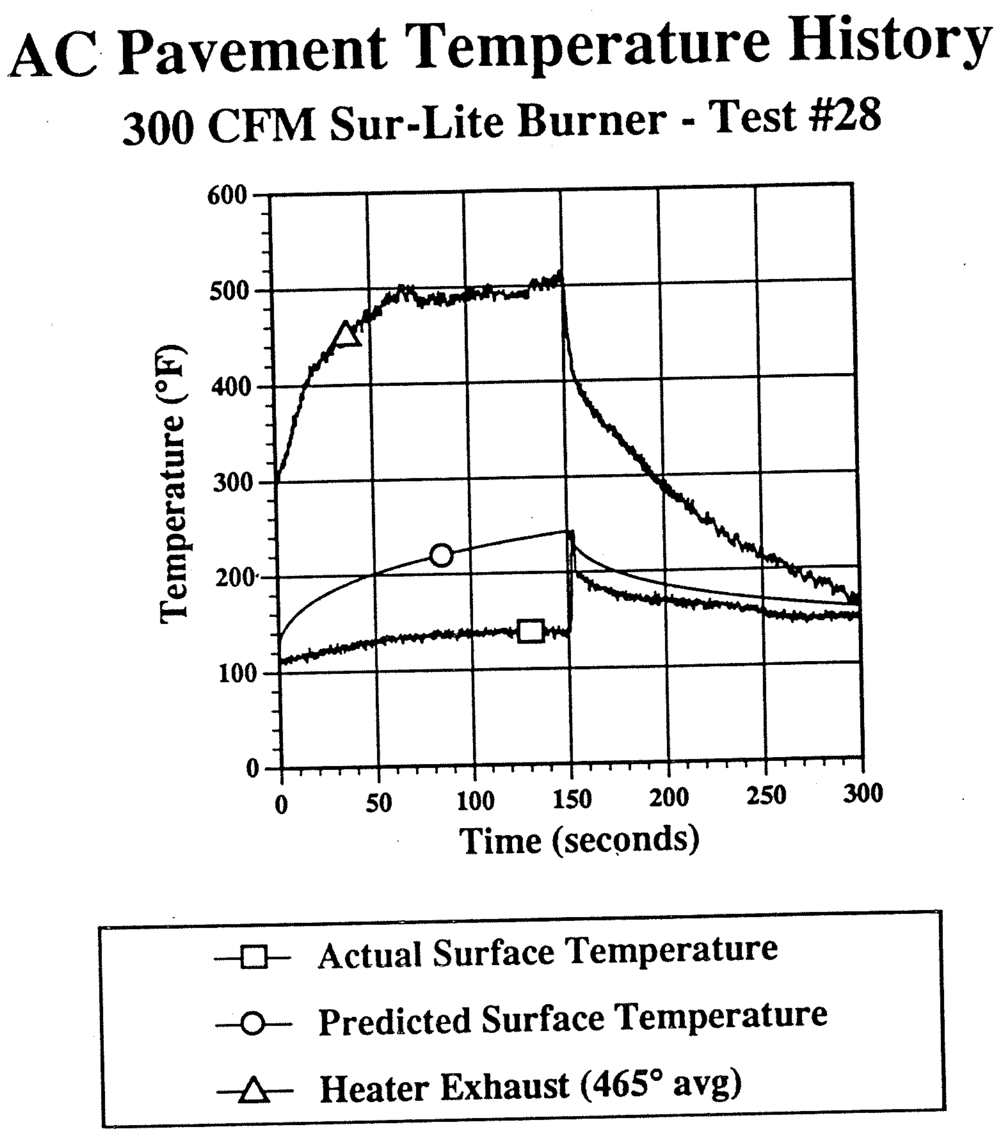


Figure C.26 - *Sur-Lite burner test #28.*

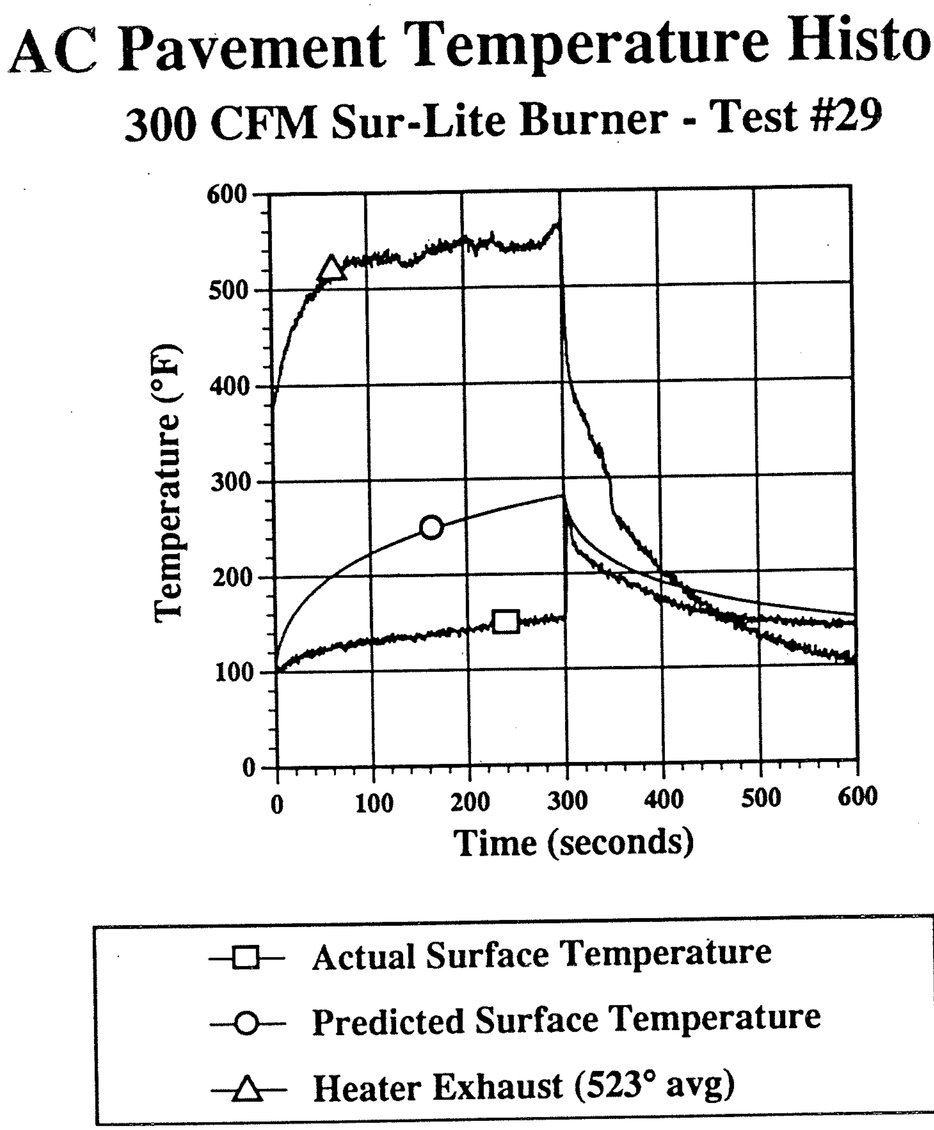


Figure C.27 - Sur-Lite burner test #29.

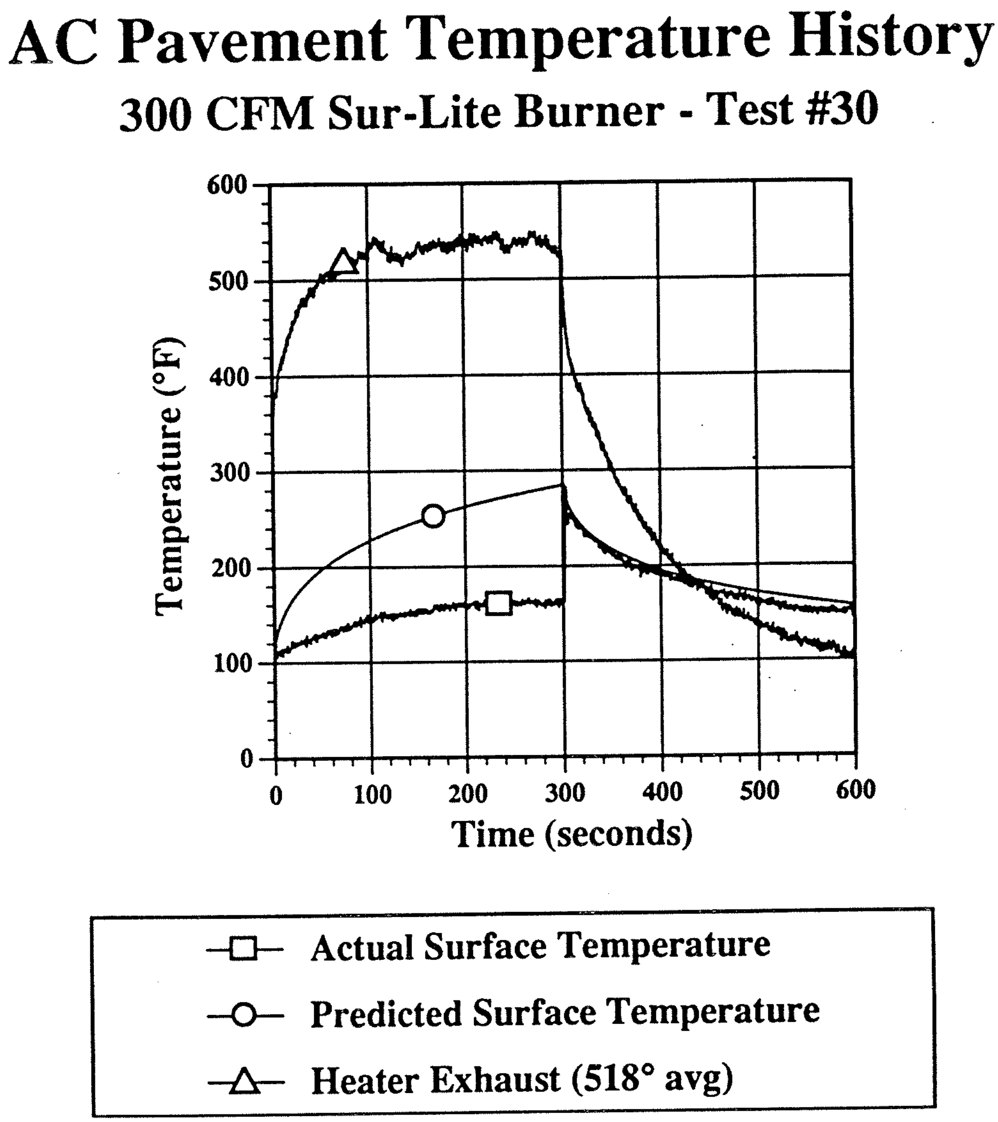


Figure C.28 - Sur-Lite burner test #30.

APPENDIX D - CLEANING AND HEATING SYSTEM SPECIFICATIONS

1.0 INTRODUCTION

1.1 The crack sealing machine described in this specification will be designed and built by the University of California - Davis, Department of Mechanical, Aeronautical, and Materials Engineering. It will be used in a research project to automatically identify, clean, heat, and seal cracks in road surfaces.

1.2 This document serves to provide detail specifications for the BLOWER, BURNER, and FUEL TRAIN/FLAME SAFEGUARD units to be provided by vendors and installed by UCD on the above mentioned crack sealing machine.

1.3 The heating/cleaning system shall be sold to UCD as components only and will be assembled by UCD. Section 7.0 contains a list of deliverables.

2.0 BLOWER SPECIFICATIONS

2.1 The blower shall move air at no less than 400 standard cubic feet per minute (SCFM) at no less than 5 PSI.

2.2 The blower shall be hydraulically driven and actuated electrically using 110 VAC solenoids.

2.3 Inlet and exit diameters shall be no less than 3" and no greater than 4".

2.4 Blower shall operate using hydraulic fluid supplied at 2000 PSI and pumped at up to 20 gallons per minute (GPM).

3.0 BURNER SPECIFICATIONS

3.1 The burner shall heat no less than 400 standard cubic feet per minute (SCFM) to no less than 1500°F.

3.2 The burner shall be able to accommodate a gage pressure at the burner exit of no less than 2 PSI.

3.3 The burner shall take no longer than 15 seconds to reach 90% of its steady state heat output.

3.4 Combustion air shall be provided to the burner inlet by UCD via a hydraulically powered 5 PSI, 400 SCFM centrifugal blower.

3.5 All necessary plumbing and insulation downstream of the burner nozzle exit shall be designed and purchased separately by UCD.

4.0 FUEL TRAIN AND FLAME SAFEGUARD SYSTEM SPECIFICATIONS

4.1 A standard control box/panel shall house all major electrical components and a wiring pin diagram shall be provided to UCD outlining connections to fuel train components.

4.2 All primary controls and switches shall also be mounted on the face of the box/panel in a "user friendly" manner. These shall include an easily accessible emergency shut off type switch. Other necessary meters, lights, etc... may be added provided they shall enhance the ease and safety of operation of the system.

4.3 Two 2-way, electrically actuated, 3" diameter valves shall be provided by the vendor. They shall be configured such that when one is open the other is closed. They shall provide a means of deflected flow from the pavement, upstream of the burner. A properly sized DPDT toggle switch located on the control box/panel face shall toggle these valves.

4.4 A 110VAC, 3A push button switch shall be added to the face of the control box/panel. This switch will serve as a means of turning on the blower solenoid provided by UCD.

4.5 When the air flow is switched to deflect flow from the burner, or DIVERT as it will be referred to herein, fuel flow to the burner should be cut off without turning off power to the blower.

4.6 A pressure differential circuit breaker in the blower airway shall protect crack sealing machine subsystems by shutting down the burner fuel flow *and* blower in proper succession should an obstruction in the inlet or exit of the heating system occur.

3.7 Fuel flow control shall occur via a 4-20 mA input from a UCD provided infrared pyrometer which will measure pavement surface temperature between 0 and 400°F. The fuel flow shall be automatically continuously adjusted by a PID type controller to attain a surface temperature of 250°F. The fuel flow control valve shall have a 95% response time of 0.5 seconds or less.

4.8 The specifications mentioned above should by no means bypass or override the standard and legally required flame safeguard system.

4.9 All necessary wiring and minor plumbing supplies shall be provided by UCD. They need not be quoted by the vendor but must be specified.

4.10 The heating system may be able to be operated in either the BLOW ONLY or HEAT mode.

5.0 POWER SYSTEMS

5.1 All electrical systems and subsystems shall operate using 110 VAC requiring no more than 3 kW of combined power.

5.2 All methane fuel used shall be standard commercially available liquid propane.

5.3 LP gas will be provided by UCD via 4-100 lb. vapor withdrawal tanks. The burner and fuel train system provided must be able to operate at maximum fuel flow given this fuel system.

5.4 All electrical systems shall have circuit breakers to protect other unrelated systems on the crack sealing machine. In the event of a power failure to any system, proper sequenced shut-down should automatically occur in the heating/cleaning system.

6.0 PHYSICAL CONSTRAINTS

6.1 All deliverables shall be able to withstand typical vehicle shock and vibration.

6.2 The control panel need NOT be NEMA 4 rated. It will only be operated in a closed room or dry weather day.

7.0 DELIVERABLES - shall meet all of the above and below specifications.

7.1 Blower meeting Section 2 specifications

7.2 Burner

- 7.2.1 (1) Burner meeting Section 3 specifications
- 7.2.2 (1) Flame rod
- 7.2.3 (1) Spark ignitor
- 7.2.4 Complete set of manufacturer instructions and documentation.

7.3 Fuel train and flame safeguard system

- 7.3.1 (1) Control panel/box and flame safeguard system (see Section 4)
- 7.3.2 (1) PID digital process controller for fuel flow control.
- 7.3.3 (1) Fuel flow control valve.
- 7.3.4 Standard fuel train components necessary to ensure the safe, efficient operation of the above described system.
- 7.3.5 List of wiring and minor plumbing supplies (nipples, connectors, elbows, etc.). (All necessary wiring and minor plumbing supplies will be provided by UCD).
- 7.3.6 (2) 2-way, electrically actuated, 3" diameter valves for DIVERTER.

7.3.7 (1) DPDT switch for DIVERTER actuation mounted on control panel face.

7.3.8 (1) 110VAC, 3A push button switch mounted on control panel face.

7.3.9 (1) Pressure differential switch.

7.3.10 All necessary and standard regulators, filters, safety valves, etc.

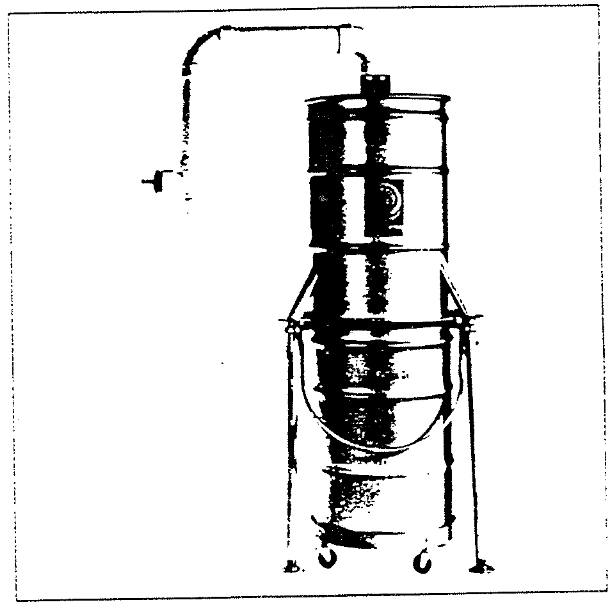
APPENDIX E - MANUFACTURE'S EQUIPMENT SPECIFICATIONS

EG&G ROTRON
Industrial Division

ROTRON IVM2000PF FLOOR MOUNT VACUUM UNIT

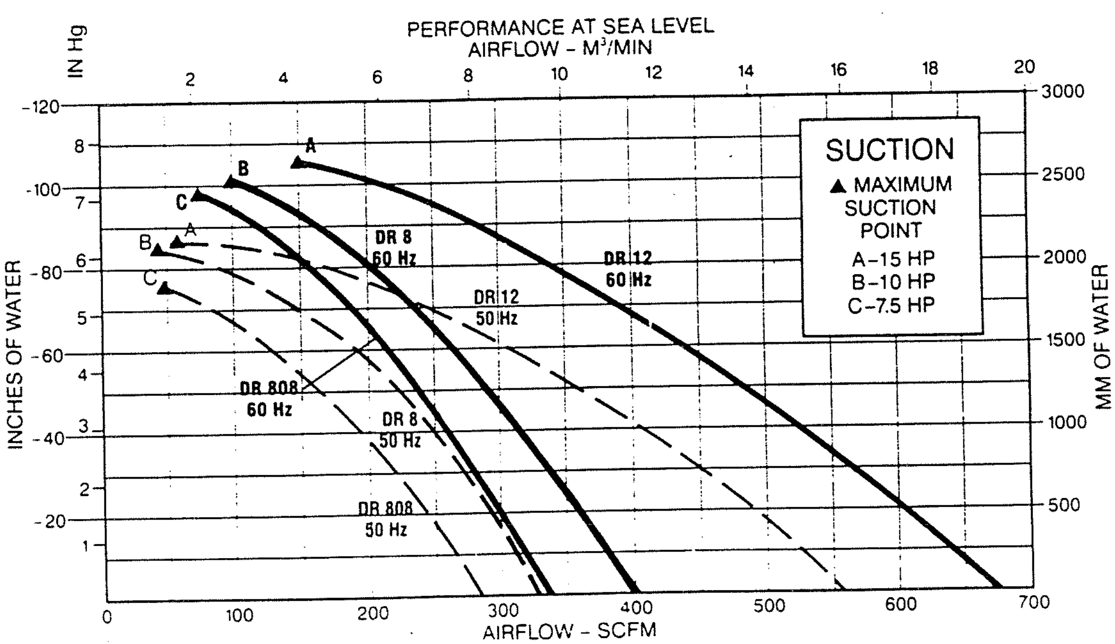
FEATURES

- Manufactured in the U.S.A.
- Dry Material Collection
- Epoxy Coated Steel Separator and Receiver
- Centrifugal Separation and Self-cleaning Permanent Filter
- Secondary 8-10 Micron Cartridge Filter
- Easy Access Filter
- Dolly-mounted Collection Canister
- Accepts Industry Standard Drums for Collection
- Blower-to-Separator Interconnecting Piping
- Brass Vacuum Relief Valve
- Continuous-duty Regenerative Blower
- Blower Construction-Cast Aluminum Housing, Impeller and Cover
- Noise Level Within OSHA Standards when Properly Piped and Muffled
- Capacity: 55 gallons (208 liters) 7.5 cu ft



OPTIONS

- **H**igh **E**fficiency **P**articulate **A**ir Filtration
- 575 Volt and Explosion-proof Motors
- Stainless Steel Receiver and Separator
- Surface Treatments or Plating
- Accessories Available



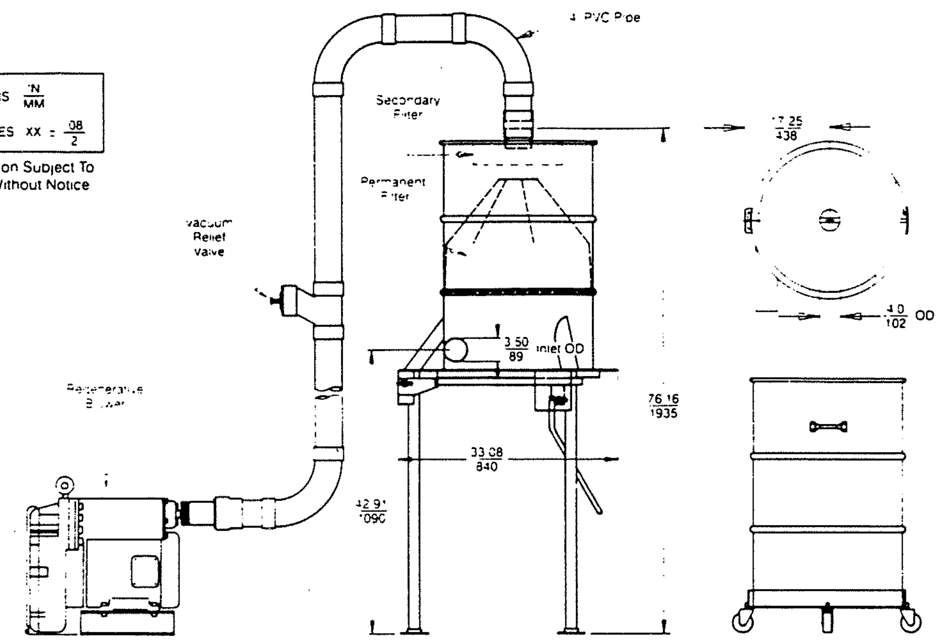
EG&G ROTRON
Industrial Division

EG&G ROTRON
Industrial Division
North Street
Saugerties, NY 12477
Tel: 914/246-3407
Telefax: 914/246-3802
Telex: 981511

DIMENSIONS $\frac{IN}{MM}$

TOLERANCES XX $\pm \frac{.08}{2}$

Specification Subject To Change Without Notice

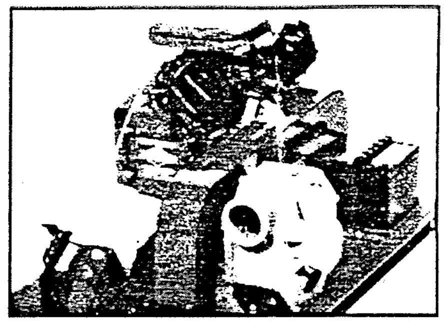


SPECIFICATIONS

Model		IVM2000PF 12BE72W	IVM2000PF 8BB72W	IVM2000PF 808AY72W	IVM2000PF
Part No		037826	037825	038140	037959
Motor Type		TEFC	TEFC	TEFC	—
Motor Horsepower		15.0	10.0	7.5	—
Voltage*		230/460	230/460	230/460	—
Phase		3	3	3	—
Frequency* (Hz)		60	60	60	—
Recommended NEMA Starter		2/2	2/1	1/1	—
Total Shipping Weight–lbs (kg)		804 (364)	636 (288)	579 (262)	378 (171)
Max. # of Operators[2]	1.25" Hose Diameter	9	5	4	—
	1.5" Hose Diameter	6	3	2	—
	2.0" Hose Diameter	4	2	1	—
Blower Dimensions L x W x H	in.	24.3 x 19.6 x 25.4	24.1 x 18.6 x 23.9	22.6 x 18.7 x 21.1	—
	mm	617 x 498 x 645	612 x 472 x 607	574 x 475 x 536	—
Blower Inlet Outlet Diameter		3" NPSC	2½" NPSC	2½" NPSC	—

PAXTON Centrifugal Blowers

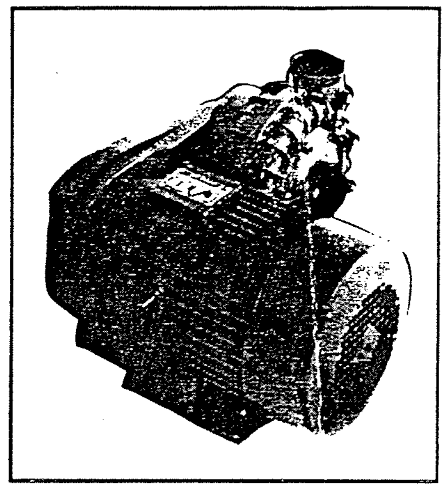
The leading blower



EFFICIENT

Paxton specializes in powerful but compact blowers for pressure and/or vacuum applications. If your requirements fall within the Paxton performance range, you probably won't find another blower competitive with Paxton's features.

The belt drive design allows the RM series to be driven with 1/2, 1, 2, 3, 5, 7-1/2, 10, 15 and 20 HP, Single or Three-Phase, TEFC or Explosion Proof, motors. We also regularly ship these units with complete engines or hydraulic motors. No special foundation or vibration isolation is required. Blowers may be mounted in any rotation - even upside down.



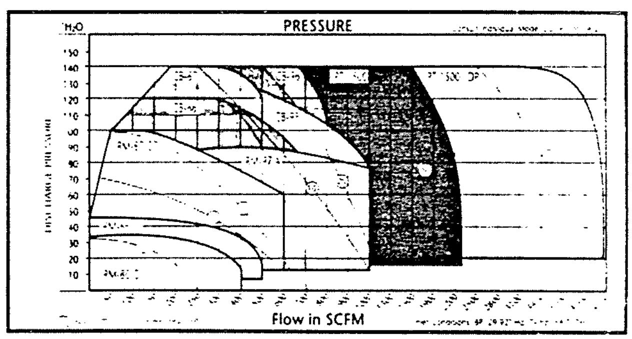
COMPACT

Most Paxton blowers take up less than one cubic foot of space and weigh less than 30 lbs, yet comfortably deliver over 1,000 CFM. Competitive blowers can weigh from 300 to 2,000 lbs, require heavy foundations, costly silencing equipment, more floor space, and present major problems in shipping and handling - all factors which represent unnecessary hidden costs. Paxton's compact design eliminates these unnecessary hidden costs.

USED ALL OVER THE WORLD

Paxton centrifugal blowers are performing vital roles for literally thousands of major food, metal, automotive, photographic, wood, aviation, disposal, and chemical companies around the world. Wherever noise, weight or space is a factor, you'll find Paxton Centrifugal Blowers.

A WIDE PERFORMANCE RANGE



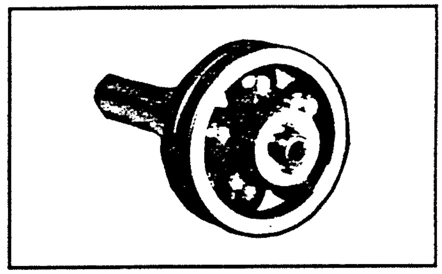
CALL OUR ENGINEERS

For costs and delivery information, to accurately specify optimum RPM, BHP and Accessories, or to help solve a problem, call or write our engineers with your requirements. Telephone (213) 450-4800 or FAX (213) 452-8093, 7:00 am to 3:30 pm Pacific Time.

PAXTON Centrifugal Blowers

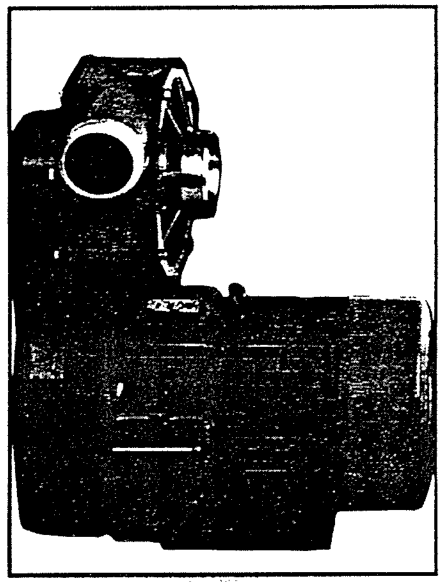
RELIABLE

Paxton CB models have a unique internal planetary ball drive that steps up input shaft speed without gears. Five matched grade chrome steel ball bearings within a raceway, machined to within ±.00005", steps up shaft speed quietly and without vibration. Reliable blower-motor set-ups are available with 1/2 to 100 BHP motors. Within their recommended performance ranges Paxton blowers produce efficiently, are very reliable, and are warranted for continuous unattended duty.



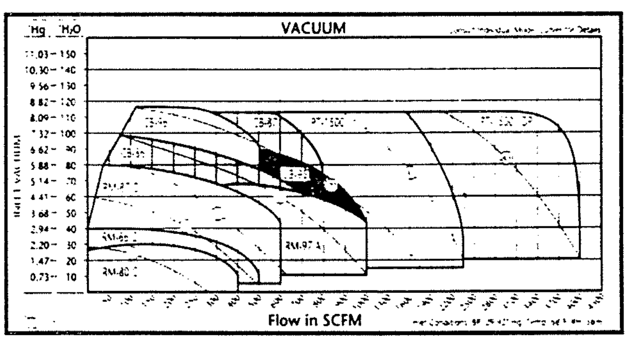
QUALITY

Blowers with gears and multiple impellers must be large and heavy to stand up. We've eliminated those restrictive elements from our blower design and have built a centrifugal blower out of aluminum and high-strength steels that is as strong as any other blower, no matter how large or heavy.
Each impeller and scroll are machined to a perfect fit. And, a complete, 100% operational, performance and vibration test is conducted on every blower prior to shipment.



HOT OR CORROSIVE GAS

Paxton blowers utilize a fluorocarbon seal that has been proven, under extreme conditions, to provide an oil-free gas stream over a wide range of gas conditions.
For special conditions we produce Paxton blowers in stainless steel, monel and hastelloy to withstand high temperatures or corrosive gases.



CALL OUR ENGINEERS FOR SPECIFICATIONS

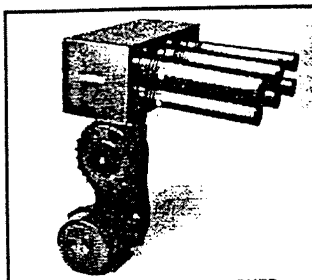
PAXTON CENTRIFUGAL BLOWERS, **929 Olympic Blvd., Santa Monica, CA 90404-3795**

PAXTON Centrifugal Blowers

The leading blower

LOW COST, EASY MAINTENANCE

The RM Series blowers are belt driven from the drive mechanism. The sealed bearing design and integral belt drive operate 15,000 - 20,000 hours between service. Should the blower fail it can be removed by one man in minutes and inexpensively shipped back to the factory for prompt, expert service. Many companies that use them extensively have a spare blower head assembly so that a unit can be replaced in a matter of minutes with virtually no down time.



A COMPLETE AIR KNIFE DRYER
Blower/Air Knife System is complete and self contained, ready to run.
- System is built to suit your needs.
- Ideal for conveyors 2 inches to 24 feet wide.
- Handles speeds 3 to 300 feet/minute.
- Reliable, quiet, compact and lightweight.
- Efficiently replaces most compressed air and multiple low pressure fan systems.
- Eliminates most heater banks.
- Great for PC boards, plastics, glass, metal strips, continuous plating, cable, bottles, cans and more.
- Quick delivery on standard units.

TYPICAL APPLICATIONS

DRYING/BLOW-OFF
- Printed circuit boards
- Steel, plastic, glass sheets
- Fruits, vegetables, other food products
- Plastic strand drier
- Dust removal - bearings, optic sensors, grinding & polishing
- Filter-belt dewatering systems

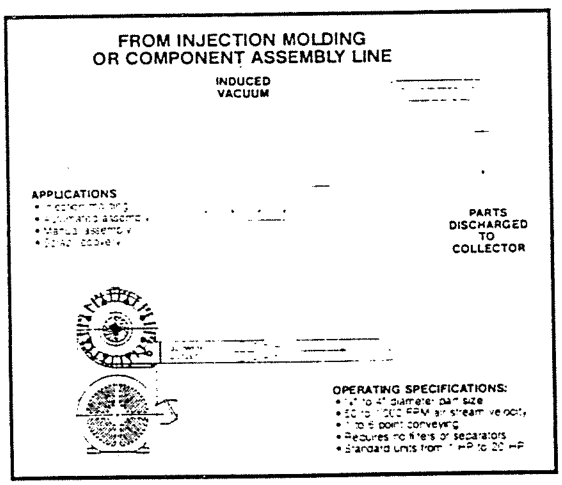
PROCESS AIR
- Flow bench testing
- Purge air
- Air curtains (furnaces, dusty environments)
- Air cushions (floating air pallets)
- Power take-off units (farm machinery)
- Air sampling (laboratory test equipment)
- Metal and plastic molds and extrusions

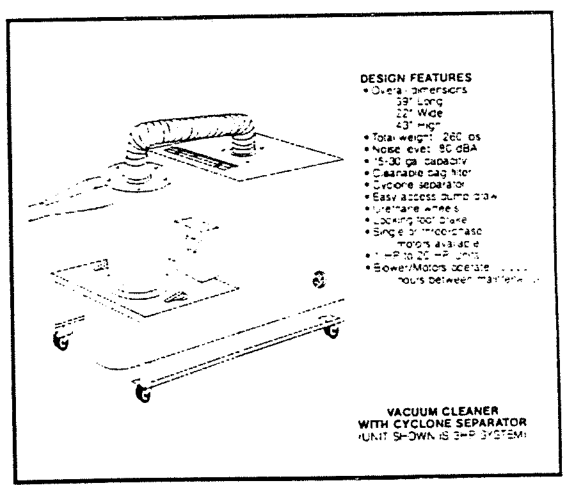
AERATION/AGITATION
- Plating tanks
- Large-scale film processing tanks
- Wastewater treatment tanks
- Fish ponds and other aquaculture tanks
- Investment casting (fluidizing sand beds)
- Fluidized resin (fiberglass, PVC powder, etc)

POLLUTION CONTROL AND COMBUSTIBLE GASES
- Exhaust and corrosive fumes – stainless steel, monel, hastelloy and other special blower materials available
- Vapor recovery (petroleum, chemical and other storage tanks)
- Exhaust tower/stack scrubbers and recyclers
- Exhaust emission analyzer systems
- Containment release blower systems (nuclear plants)
- Soil cleanup/fume recovery
- Landfill sites (methane gas recovery)
- Digester gas
- Combustion air

COOLING
- Supercomputer cooling
- Military aircraft ground support equipment, missle launchers, other mobile and airborne needs.
- Environmental test chambers

VACUUM/EXHAUST PROCESSES
- Complete portable vacuum systems
- Vacuum excavation - truck mounted
- Vacuum holding (packaging processes)
- Central vacuum (chips, dust, etc)
- Pneumatic conveying
- Air sampling (laboratory test equipment)





PAXTON Centrifugal Blowers

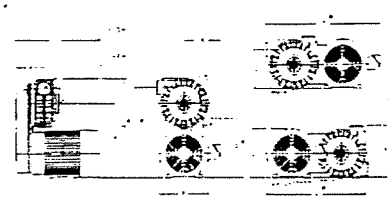
The leading blower

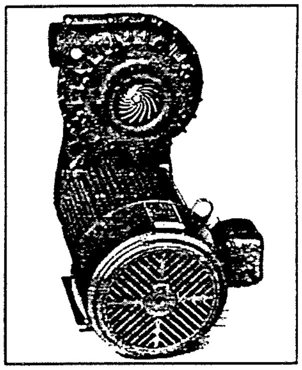
Paxton Centrifugal Blowers are performing vital roles for thousands of major food, metal, automotive, aviation, disposal and chemical companies, world-wide.

Paxton specializes in providing complete air knife, vacuum and conveying systems.

DIMENSIONS ARE IN INCHES. GENERAL TOLERANCE ± .06" EXCEPT WHERE SPECIFICED (* = .50" TOLERANCE). DH/EH = I.D. HOSE CONNECTIONS.

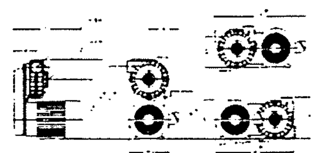
RM-80 SERIES

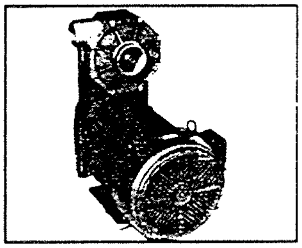




FRAME SIZE	H.P.	A	C	DH	EH	G*	H*	J*	K	P	Q	R*	S	T*	V*	X
145 TC	1.0/2.0/3.0	6.12	12.31	2.75	4.0	13	17.75	16	6.12	7.31	6.50	10	7.14	20.06	17.87	8.75
184 TC	5.0/7.5	6.12	16.43	2.75	4.0	14	18.75	17	7.03	9.56	7.50	11	9.28	20.75	19.00	9.75
213 TC	7.5	6.62	19.37	2.75	4.0	18	23.25	21	8.25	11.25	8.50	15	10.87	26.00	23.37	10.75
215 TC	10.0	6.62	20.87	2.75	4.0	18	23.25	21	8.25	11.25	8.50	15	10.87	26.00	23.37	10.75

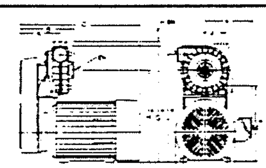
RM-90 SERIES

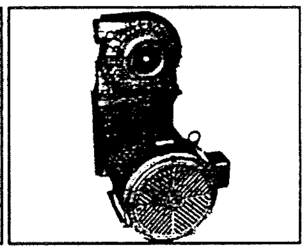




H.P.	A	C	DH	EH	G*	H*	J*	K	P	Q	R*	S	T*	V*	X
10.0	5.62	19.18	3.5	4.0	18.16	23.31	21.56	8.25	11.25	8.87	14.93	10.87	27.81	27.43	12.12
15.0	5.62	23.81	3.5	4.0	18.93	24.06	22.3	9.93	13.37	9.62	15.56	12.93	29.25	24.25	12.87

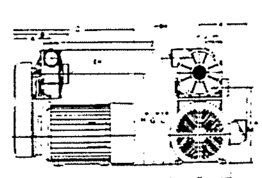
CB-80 SERIES





H.P.	A	B	C	DH	EH	F	G*	H*	J	K	L*	M*	N		
10.0	8.0	10.5	22.5	2.75	4.0	0.5	22.8	18.0	3.0	7.75	21.0	15.0	13.3		
15.0	8.0	10.5	25.6	2.75	4.0	0.5	23.8	19.0	3.0	10.0	22.0	16.0	13.3		

CB-90 SERIES



H.P.	A	B	C	DH	EH	F	G*	H*	J	K	L*	M*	N		
20.0	6.0	10.0	27.0	3.5	4.0	1.5	24.1	19.0	3.4	10.0	22.3	15.6	13.4		

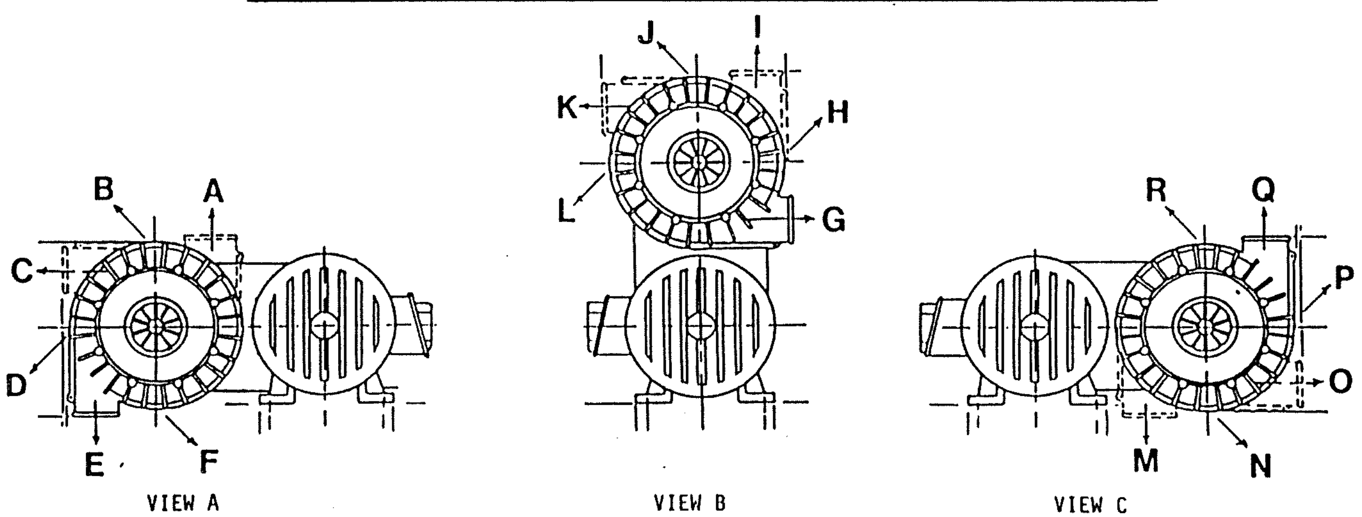
CALL OUR ENGINEERS ... **For costs and delivery information, to accurately specify optimum RPM, BHP and Accessories, or to help solve a problem, call or write our engineers with your requirements.**

Paxton Centrifugal Blowers, 929 Olympic Blvd., Santa Monica, CA 90404
Telephone (213) 450-4800 or FAX (213) 452-8093 ■ 7:00 am to 3:30 pm Pacific Time.

PAXTON PRODUCTS INC.
929 OLYMPIC BLVD.
SANTA MONICA, CAL. 90404
(213) 394-2751

BLOWER OUTLET ORIENTATION

PAXTON MODELS RM / CB / PT SERIES



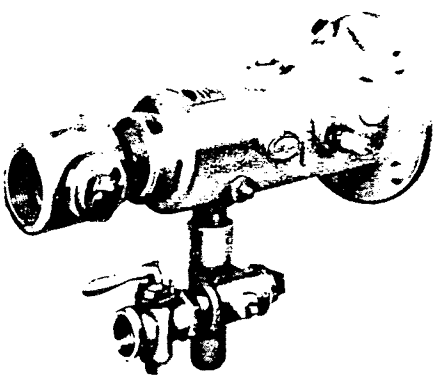
THIS DRAWING IS FOR GENERAL REFERENCE ONLY.
AVAILABILITY OF SPECIFIC ORIENTATION MAY BE LIMITED BY TYPE OF MOTOR ENCLOSURE AND JUNCTION BOX LOCATION.
AS CB & PT SERIES BLOWERS ARE BASE PLATE MOUNTED BLOWERS, THEY ARE NOT AVAILABLE IN ORIENTATION E.F.M.N. AND VIEW B.

8/20/84

H-44-3
Bulletin
9/83

ECLIPSE THERMAL BLAST AIR HEATERS

SERIES "TBH"



COMPLETE HEATER

Eclipse Thermal Blast Air Heaters are high temperature, high pressure, air heaters designed to produce 50 to 400 scfm of heated air with a temperature rise of 300° to 1600° F. at pressures up to 50 psi. They are suitable for a wide range of industrial heating and drying applications. These include: mold and core box heating, water dry-off, paper and fabric drying, plastic treating, food processing, air curtains, and aggregate drying.

OPERATION

Air piping upstream and downstream of the Thermal Blast Heater should be sized according to required air flow through the heater. See page 2 for recommended piping and transitions for various air flows. For normal operation, air is supplied to the burner at a constant pressure and volume, and gas flow only is controlled.

ADVANTAGES

- • • • Nozzle-mixing design
- • • • Single valve control
- • • • Exceptional flame stability
- • • • Broad range of discharge pressures
- • • • Broad range of discharge temperatures
- • • • Easy installation

IGNITION

Eclipse "TBH" heaters are furnished with an ignition plug which will light the burner anywhere within its operating range. The spark plug may be used in either of two openings provided on the heater (see Dimensions and Specifications, page 2).

FLAME MONITORING

Flame monitoring may be provided by using either a flame electrode or an ultra-violet scanner monitoring the flame. A tapped opening is provided on the heater for installing either flame rod or scanner (see Dimensions and Specifications, page 2).

DESIGN FEATURES

Eclipse "TBH" heaters have separate air and gas inlets and mixing takes place internally. No complex proportionating equipment is required. "TBH" heaters are designed to produce high discharge pressures with relatively low blower pressure. Air flows straight through the burner, minimizing pressure drops. The heater inlet is threaded and outlet is flanged for ease of installation.

ASSEMBLIES

Eclipse "TBH" heaters are available in either basic or complete assemblies. The *Basic Heater* consists of heater with ignition plus and peepsight. The *Complete Heater*, pictured above, includes the basic heater plus air butterfly valve, gas adjusting tee, gas cock, and necessary pipe nipples.

CAUTION: It is dangerous to use any fuel burning equipment unless it is equipped with suitable flame sensing device(s) and automatic fuel shut-off valve(s). Eclipse can supply such equipment or information on alternate sources.

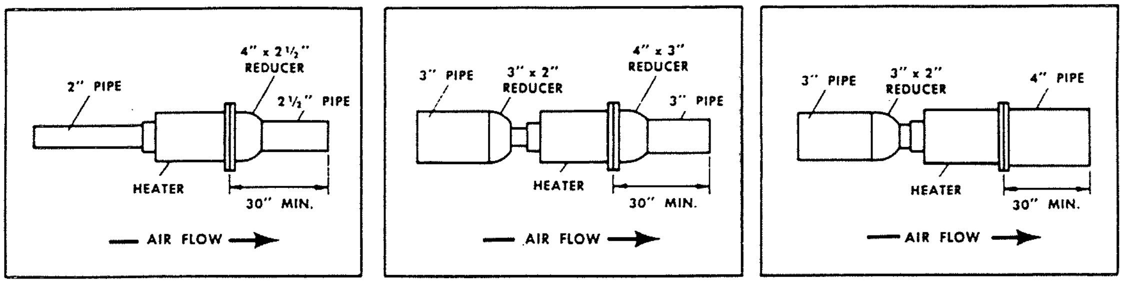
CAPACITIES

BURNER CATALOG NUMBER	SCFM HEATED AIR	MIN. GAS PRESS. IN "W.C. ABOVE DISCHARGE PRESS.	BTU/HR. 1600° F. TEMP. RISE*	BTU/HR. 800° F. TEMP. RISE*	BTU/HR. AT MIN. TEMP. RISE**	MINIMUM TEMP. RISE	MAXIMUM DISCHARGE PRESSURE*** IN "W.C. FOR VARIOUS BLOWER PRESSURES						
							8 oz.	12 oz.	16 oz.	20 oz.	24 oz.	32 oz.	48 oz.
84-10TBH	50	4.5	86,500	43,250	16,000	300° F	10	17	24	31	38	52	79
	100	5.5	173,000	86,500	32,000	300° F	8	15	22	29	36	50	77
	150	7.0	259,000	129,000	48,000	300° F	5	12	19	26	33	47	74
	200	9.5	345,000	172,500	64,000	300° F	--	8	15	22	29	43	70
84-14TBH	250	7.5	432,000	216,000	80,000	300° F	--	7	14	21	28	42	69
	300	9.0	518,000	259,000	110,000	340° F	--	3	10	16	23	38	65
	350	7.0	605,000	302,500	137,000	362° F	--	--	8	15	22	36	63
	400	8.5	692,000	396,000	166,000	384° F	--	--	3	10	17	31	58

*Inputs do not take into consideration manifold heat loss. Actual inputs will be higher by amount of heat loss.
**Temperature rise does not take into consideration manifold heat loss. Actual rise will be somewhat less.
*** Delivery pressure based on 10' of pipe between blower and burner. Loss in extra pipe length must be subtracted from delivery pressure. Loss through bell reducer has been considered in above table.

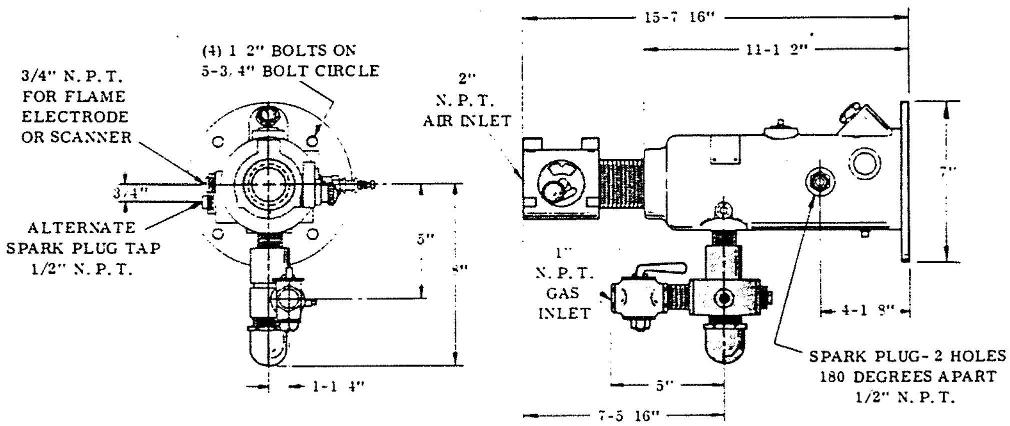
ECLIPSE COMBUSTION
A DIVISION OF ECLIPSE, INC.
ROCKFORD, ILLINOIS 61103 (815) 877-3031
IN CANADA ECLIPSE FUEL ENGINEERING CO OF CANADA, LTD. DON MILLS, ONTARIO

PREFERRED PIPING & TRANSITIONS



50 - 130 SCFM HEATED AIR | 131 - 300 SCFM HEATED AIR | 301 - 400 SCFM HEATED AIR

DIMENSIONS & SPECIFICATIONS



NOTE: Illustrates "Basic Heater."
Illustrates additional components included with "Complete Heater."

CATALOG NUMBER EXAMPLE

8 4 — 10 TBH

Air Inlet in ¼"
8 = 8 4 = 2

Gas Inlet in ¼"
4 = 4 4 = 1"

Gas Jet Dia. in 1 32"
10 = 10 32 = .076 Area Sq. In.

Thermal Blast Heater

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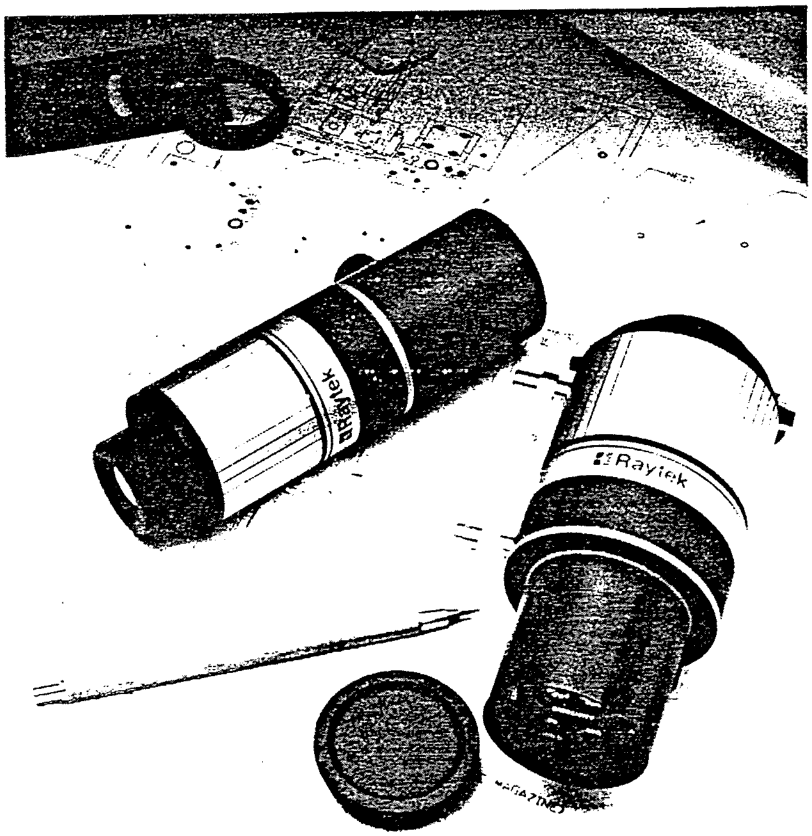
Litho in U S A

Thermalert ET noncontact temperature sensors for process monitoring and control



ET sensors measure temperature in film, paper and metal coaters, textiles, metal and print dryers, plastic, glass and metal forming and molding machines, food, glass and chemical processing equipment, and silicon wafers, magnetic media, and wave soldering devices.

Noncontact temperature sensors offer significant advantages over contact devices in many OEM applications.
ET sensors accurately measure the temperature of inaccessible objects, moving materials and webs. They have faster response times than thermocouples for better control of process heaters and indexing. This gives you better control of process quality and allows you to optimize throughput and yield.

Rugged, reliable and repeatable
The ET series combines sensor and electronics in a single rugged package. They're easy to install and simple to adjust. And ET sensors generally last longer and require far less service than contact devices.

ET sensors use digital logic circuitry to provide reliable, repeatable data over a wide temperature range.

Designed for continuous 24-hour operation, ET sensors are available in two basic configurations.

ET-II—Thermocouple Output
The ET-II provides simulated J, K, R or S type thermocouple output for use with any display, recording or control device requiring thermocouple input.

ET-III—Current Output
The ET-III provides a 4 to 20 mA current output for use with any display, recording or control device requiring a current input. The ET-III has four selectable temperature ranges.

Models are available for measuring glass, plastics, and higher temperature targets. All models include a mounting nut, fixed bracket and interconnecting cable for easy installation.

Both the ET-II and III can be customized to meet specific temperature applications.

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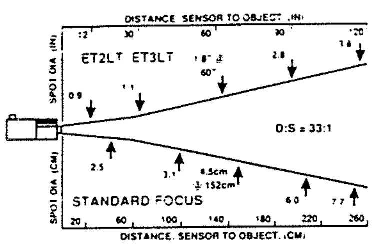

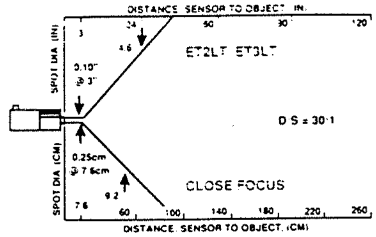

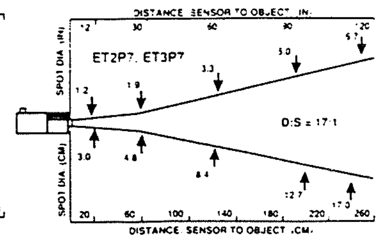

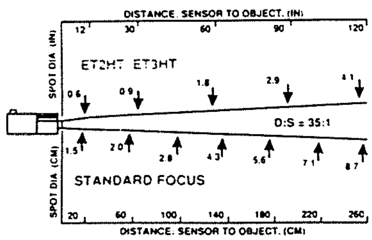

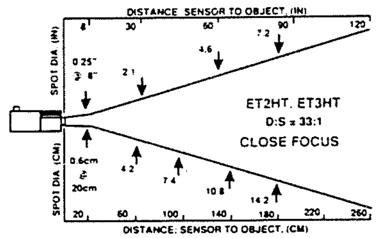

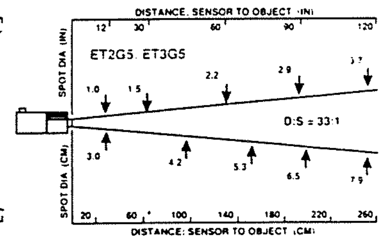

SPECIFICATIONS	ET2LT	ET3LT	ET2G5	ET3G5	ET2P7	ET3P7	ET2HT	ET3HT
Measurement ranges	Type J [illegible] Type K [illegible]	[illegible] (Range switchable)	500 to 3000 F 260 to 1650 C	[illegible] (Range switchable)	50 to 650 F 10 to 360 C	[illegible] (Range switchable)	[illegible]	[illegible] (Range switchable)
Data output	[illegible] Thermocouple [illegible] impedance	4 to 20mA Max Loop Resistance [illegible]	Type R Thermocouple 50 Ω impedance	4 to 20mA Max Loop Resistance 500 Ω	Type J Thermocouple [illegible] impedance	4 to 20mA Max Loop Resistance 500 Ω	Type R Thermocouple 50 Ω impedance	[illegible]
Spectral response	8 to 14 Microns (Low Temp)		Nominal 5.2 Microns (Glass)		Nominal 7.9 Microns (Plastic)		Nominal 2.2 Microns (High Temp)	
Accuracy	±1% of Reading (above 150 F (65 C)), 2.5 F (1.4 C) or better below 150 F (65 C)							
Repeatability	±0.5% of Reading, 1 digit, F or C							
Emissivity	0.10 to 1.0 digitally adjustable							
Response time	300 mSec (80 mSec option)						80 mSec standard	
Signal processing	Adjustable Peak Hold, Variable Averaging Filter							
Power	12 VAC nominal, 100 mA, 50 to 60 Hz							
Environmental rating	NEMA-4 (IEC529 IP65) with conduit & compression fitting							
Vibration	MIL STD 810D (IEC 68-2-6), 3G's, any axis, 11 to 200 Hz							
Shock	MIL STD 810D (IEC 68-2-27), 50G's, 11mSec, any axis							
Ambient operating range	32 to 120 F (0 to 50 C) without cooling, 32 to 350 F (0 to 177 C) with cooling							
Connection	Detachable 15 ft (4.5 m) cable standard							
Dimensions (L × Dia)	7.0 × 2.25 in (18 × 5.7 cm) Standard, 7.0 × 3.0 in (18 × 7.6cm) with cooling							
Weight	1.2 lbs (0.5 Kg) Standard, 1.7 lbs (0.8 Kg) with cooling							
Options (must be preordered)	Water/air cooled housing (includes air purge collar), 50 ft (15 m) cable, 100 ft (30 m), 200 ft (60 m) cable, N.I.S.T. Calibration Certification, K, ST C data output							
Accessories	Air purge collar, sighting viewer, right angle mirror, pipe adaptor, swivel bracket, 110/220 VAC to 12 VAC power supply							

Specifications subject to change without notice

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Raytek offers a full line of noncontact temperature measurement products for a wide range of applications. Both portable and online units are available. For additional information or a free product demonstration, contact Raytek at (800) 227-8074 in the Continental U.S. or (408) 458-1110 or your local Raytek representative.

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