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FABRICATION AND TESTING OF MAINTENANCE EQUIPMENT USED FOR PAVEMENT SURFACE REPAIRS

Final Report of Phase I

SHRP H-107A

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SECTION 1
FEASIBILITY ANALYSIS, MACHINE CONCEPTS AND COMPONENT DESIGNS

INTRODUCTION

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 rehabilitation.

The sealing and filling of cracks are tedious, labor-intensive operations. A typical operation to seal transverse 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 procedure is not standardized and there is a large distribution in the quality of the resultant seal. In addition, the crack sealing work team is exposed to a great deal of danger from moving traffic in adjacent lanes.

The ultimate goal of the SHRP H-107A project is to develop prototype automated machinery that will sense, prepare, and seal (or fill) cracks and joints on pavement. As such, the primary objectives of this 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. The cost effectiveness of such machinery comes from a combination of the increased speed and reduced manpower needs, in addition to the higher quality seal which will reduce the frequency of major highway rehabilitations.

In order to have the greatest impact, such machinery should satisfactorily perform the following functions automatically:

- Sense the occurrence and location of cracks in pavement.
- Adequately prepare the pavement surface for sealing/filling with the appropriate

methods; for example, any operation that is deemed necessary such as removing entrapped moisture and debris, preheating the road to ensure maximum sealant adhesion, refacing of reservoirs, etc.

- Prepare the sealant/filler for application; i.e., heat and mix the material, etc.
- Dispense the sealant/filler.
- Form the sealer/filler into the desired configuration.
- Finish the sealer/filler.

Additionally, as overall functional specifications, this machinery should be:

- Reasonable in cost,
- Easy to use,
- Reliable and fast,
- Rugged,
- Safe,
- Capable of being driven on the highway under its own power,
- Self-contained (contain all of the components necessary to perform task),
- Primarily powered by an internal combustion engine,
- Carry sufficient fuel supply for a normal day's operation,
- Provided with a heavy duty electrical system with sufficient capacity for safe operation of all components,
- Compatible with repair materials to be identified under SHRP H-106,
- Fabricated in such a manner that the eventual addition of safety lighting & appurtenances (arrow boards, etc.) is possible, and
- Compliant with any applicable OSHA standards.

Furthermore, the equipment prototypes may be derived from modifying existing equipment or from the development of new equipment, and each equipment design may include one or more pieces of equipment.

The purpose of this section of this report is to present findings of Phase I of SHRP H-107A, which has involved a feasibility study on the possible development of the automated pavement repair machinery discussed above, the design of first generation machine components, and the conceptual design of the prototype machinery. To follow in this section, we will provide our approach to the development of this machinery. We will first summarize the results of our extensive feasibility study of the numerous component elements of the machinery and the various related available technologies. This feasibility study is based on an extensive literature review, discussions with experts, and fundamental experiments and breadboard testing. We will then discuss the various sealing and filling operations that the machinery is expected to perform. This will lead directly toward a global machinery development plan. We will then present the machine system architecture, and the conceptual design of the integrated machinery. This will be followed by the specifications and designs of the first generation components to be tested during Phase II of this project. In subsequent sections, we will present performance specifications and a cost benefit analysis of the machinery.

FEASIBILITY STUDY

We will now discuss the feasibility for performing the required operations of the automated machinery. In general, this machinery should be able to sense, prepare, seal and finish in an automated fashion. We will later discuss additional details of the required sealing operations. Manually operated machinery exists capable of several of these tasks. As such, the automated sensing of cracks seems to be the major issue concerning feasibility and this area will be addressed first. We will then address surface preparation including routing, cleaning and pavement heating, and sealant dispensing and finishing. Finally, we will address positioning systems and system integration and control issues.

Automated Sensing of Pavement Cracks with Machine Vision

Clearly, a major aspect of the machinery to be developed concerns the automatic sensing and locating of cracks in pavement. There have been a number of studies that discuss automated pavement crack detection for purposes of categorizing pavement distress, and planning future maintenance activities (i.e., pavement management); see e.g., Bomar, et al. (1988); Butler (1989); Fukuhara, et al. (1990); Haas, et al. (1984,1985); Humplick & MacNeil (1988); Mahler (1985,1990a,1990b); Maser, et al. (1981,1988); Ritchie (1990); Ritchie, et al. (1991). Concerning crack sensing for automated pavement repair, Haas and Hendrickson (1990) have presented an algorithm for locating cracks that have been previously routed, and this algorithm has been demonstrated on a simulated roadway surface. Their algorithm has the potential to be quite useful for the pavement operations that they have concentrated upon, those being crack filling, patching, and spall repair.

The purpose of this section is to discuss details of a machine vision based crack sensing algorithm for sensing and accurately locating unprepared cracks between one-eighth and one inch in width in both Asphalt Concrete (AC) and Portland Cement Concrete (PCC) pavements. Preliminary results presented show the strength of the algorithm for sensing unprepared (and relatively dirty) cracks as small as one-eighth inch in actual AC pavement. The sensing of unprepared cracks is essential for the automated crack sealing machinery in which this algorithm will be used. In a later section, we will discuss the work required for the real-time implementation of this algorithm which is also essential for its intended use. We feel that the presentation of a detailed algorithm and its successful application to real pavement clearly shows the feasibility of the machine vision based approach.

Crack Sensing Algorithm

As noted above, many recent studies have applied digital image processing to the recognition of cracks in highway pavement in the interest of classifying crack type, severity, and extent as a basis for pavement management decisions. These "pavement-distress-survey" systems are expected to acquire data at a relatively high rate (e.g., on the order of 40 mph), as their primary purpose is to classify relatively large sections of highway. It is expected that maintenance workers would later be instructed as to the proper procedures for each section. Accordingly, such systems need to gather the following specific information (Mahler, 1990a):

- *Number* of cracks,
- *Length* of each crack,
- *Direction* of each crack, and
- *Width* of each crack.

Furthermore, the positional accuracy required is relatively low as the data will be used primarily to identify the distress type of these sections with descriptions such as: alligator cracking, longitudinal cracking, potholes, etc. These systems are intended to detect cracks as small as one-sixteenth inch wide.

In contrast to the requirements for pavement-distress-survey systems, automated crack sealing machinery must accurately locate individual crack segments so that they can be processed effectively. The required accuracy is highly dependent upon the details of the crack sealing operations to be performed and is inherently linked to both the configuration and the other components of the total machine. A recent paper by the same authors (Velinsky and Kirschke, 1991) has discussed the architecture of the automated crack sealing machine to be developed; this is additionally discussed in a later section. Of direct impact on the machine vision requirements are the following key aspects. A local laser range finder based sensing system (discussed below) will be used to verify the presence of cracks that the machine vision has identified. Additionally, through the development of crack machine end-effectors (e.g., sealant dispensers and shapers) that are tolerant to variations in crack width, detailed crack *Width* data will not be required from the machine vision system. As such, of the four pieces of information required of a pavement-distress-survey system, only *Length* and *Direction* information are required for our automated crack sealing machine. One additional piece of information is necessary, that being the starting *Location* of a given crack segment. Therefore, the following information, listed in order of importance, must be supplied by the vision system:

- *Location* of each crack segment,
- *Direction* of each crack segment, and

- *Length* of each crack segment.

Location is the most necessary information required to seal a crack. *Direction* and *Length* information is used for planning a path for the end effectors. *Length* information is primarily used for determining whether a crack should be sealed; i.e., unless a crack is longer than some critical value, it is not repaired. If the local range sensor could be located at the start of each crack segment by *Location* information only, it is possible that this local sensor could provide the information necessary to move the end effectors. However, this could result in a loss of efficiency, and for initial machine development, we have elected to path plan based on information from the vision based system and to use the local sensor for crack verification only.

In order to extract *Location*, *Direction*, and *Length* information, a histogram based algorithm has been developed and tested using approximately 400 digitized images consisting of both AC and PCC pavements. Pavement images were represented by at least two image-plane pixels per 1/8 inch of pavement in both horizontal and vertical directions. Fundamentally, the developed crack recognition algorithm performs the following four operations:

1. Divide the pavement image into a *grid* of which the mesh (tile size) depends on speed requirements, desired resolution, and acceptability of falsely recognized cracks.
2. Build a *histogram* representing each tile.
3. Compute a *statistical moment* of each histogram.
4. *Compare local values* of statistical moments to identify cracks.

We make note that the algorithm makes no attempt at obtaining a binary image in order to determine more specific qualities of crack segments through such methods as chain coding. That is, this algorithm works on more of a macroscale, representative of human perception methods (Crick, 1990). To follow is a more detailed description of these four steps.

Grid

A video image is first created of the pavement with a pixel resolution sufficient to resolve a 1/8 inch feature. In order to satisfy the Nyquist sampling frequency, this requires a pixel for at maximum every 1/16 inch of highway pavement. A grid of tiles is then created to carry information about pavement features contained within a finite area. This approach has been used previously in pavement-distress-survey systems, and Ritchie, et al. (1991) have discussed the evaluation of types of cracking within tiles.

In our approach, each tile within the grid is represented by 32x32 (1024) pixels. Through the building of a histogram and the computation of the statistical moment, the data

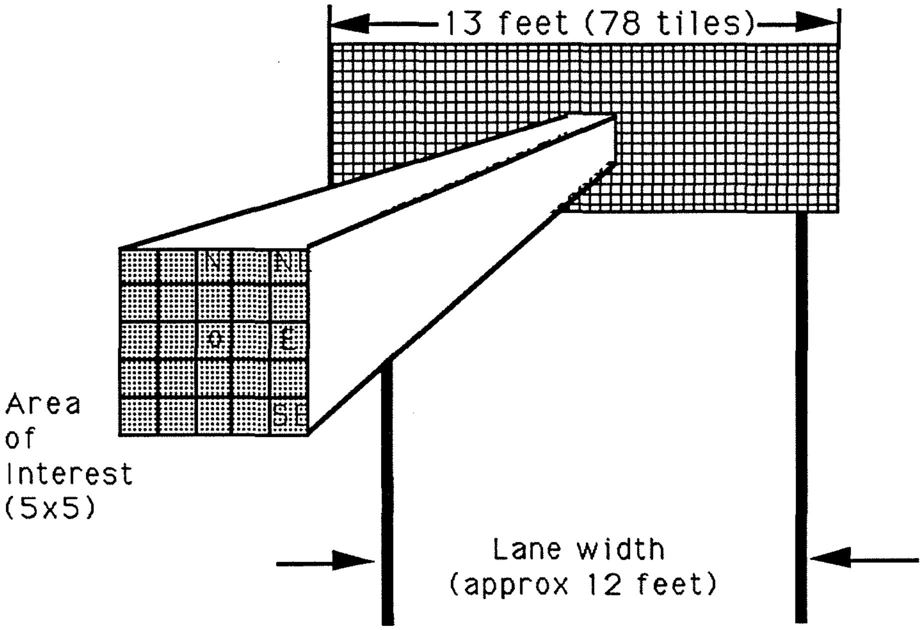


Figure 1.1 - Division of Field of View into Tiles and Four Crack Directions Within a 5x5 Area of Interest

representing each tile can be reduced from 1024 counts of 8 bit data (8192 bits) to one 32 bit integer (statistical moment). The use of statistical moment data to determine crack presence is described in the comparisons section. Figure 1.1 shows how the full lane width field of view will be divided into its component tiles.

Histogram

The first step in recognizing cracks within an area of interest is to develop a histogram for each tile. A histogram presents information on the number of pixels (digital picture elements) at particular grey levels within an image. Grey level values are a measure of the intensity of a pixel and range from black (grey level 0) to white (grey level 255 for an 8 bit image). In particular, the histogram that we use is a distribution of grey level values within a particular tile. Tiles which have cracks in them will have a greater number of darker grey level values than neighboring tiles. Figure 1.2 illustrates histograms of two specific tiles, one

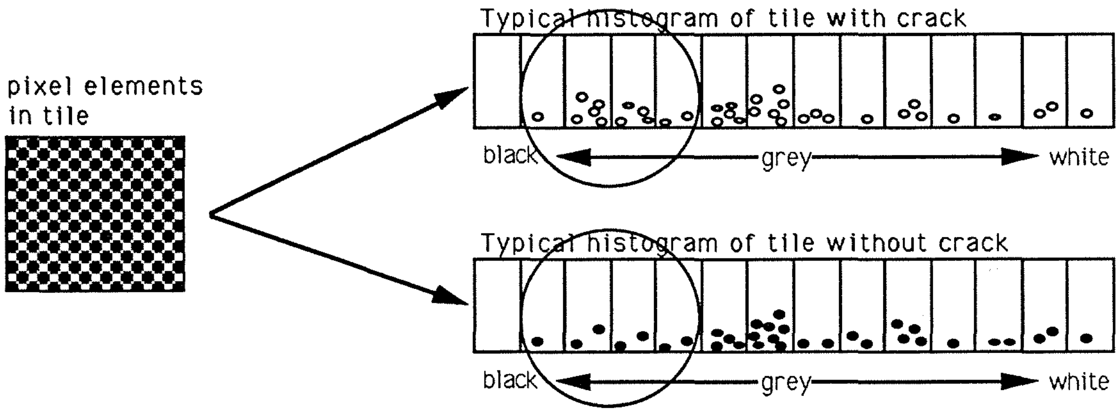


Figure 1.2 - Typical Histograms of Cracked and Non-cracked Tiles

with a crack and one without a crack. Histograms are widely used in image processing and they have been previously employed in pavement-distress-survey systems (see Bomar, 1988 and Mahler, 1990).

Statistical Moment

As shown in Fig. 1.2, there is a distinct difference between the histograms of tiles with and without cracks. The next task is to then represent these differences in a manner that can be easily interpreted automatically by a computer. Statistical moments have been widely used to provide abbreviated quantitative information on large sets of data, and there have been many engineering applications using this approach; e.g., see Vinh, et al. (1985) who use statistical moments to identify nonlinearities in structures.

In our algorithm, we use the mode of the histogram data, which is the most frequently occurring grey level value corresponding to the peak of the histogram. We then consider only pixels darker than each tile's mode and compute the statistical moment of this data relative to the mode for each tile. In general there are an infinite number of statistical moments. In this case, we represent m_e, the e'th statistical moment of our data, as:

$$m_e = \sum_{i=0}^{Mode} r_i^e \, n_i \qquad (1.1)$$

where i denotes the grey scale value, n_i denotes the number of pixels in the tile at that grey scale value, r_i represents the grey level distance from the mode to the i'th gray level, e is the power to which the r_i are raised, and we note that the sum includes only those grey level values less than the mode (darker). These parameters are depicted in Fig. 1.3.

By taking statistical moments relative to the mode, we are effectively developing a measure of deviation from the most common intensity. For this application, the mode represents the background (pavement) against which the cracks will be recognized. For uniform sections of pavement (i.e., those without cracks), we would expect a relatively narrow distribution of intensities regardless of the lighting. As such, the statistical moments of tiles with a crack will deviate from those for tiles without cracks with relatively minor sensitivity to type of pavement and lighting. That is, this approach has the potential to be extremely robust in comparison to the numerous methods that threshold data; i.e., select a particular pixel value above which data records are disposed of. Preliminary investigation has shown that the third statistical moment (corresponding to value of e=3) allows significant distinction between cracked and uncracked tiles for a variety of pavement types. This will be apparent in the results presented in a later section.

The tile size of 32x32 pixels allows for a minimal amount of variation in local* modes by reducing the effects of intensity changes within tiles due to differing shades of aggregate and surface defects. A small variation in local modes allows for a comparable measure of darker grey level values among adjacent tiles. This characteristic of local modes is what specifically allows for the recognition of cracks based on statistical moments about modes. If local modes varied substantially, local statistical moments would not be comparable. Reducing the variation of local modes with larger tile sizes must be weighed against the required accuracy to perform a sealing operation. Too large of a tile size may not provide the resolution required for a given operation.

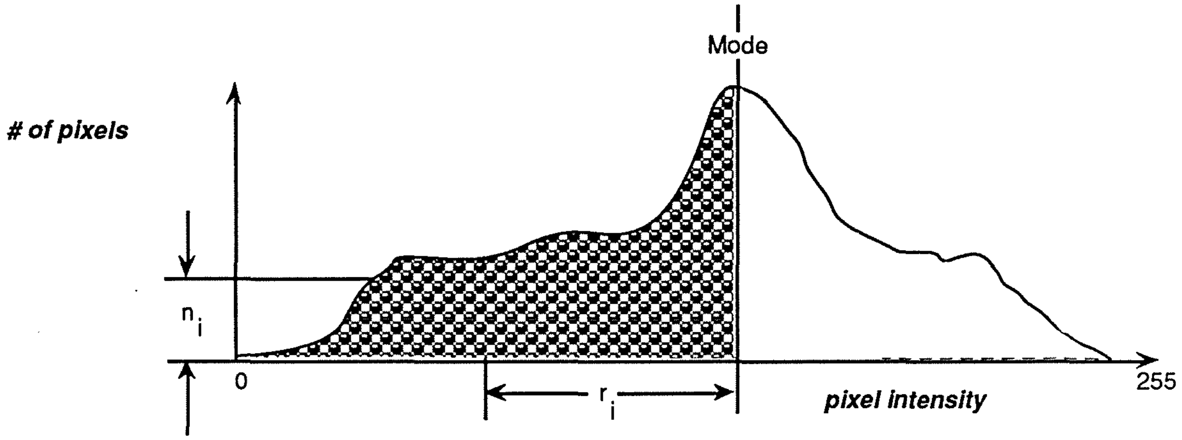


Figure 1.3 - Histogram Depicting the Parameters Employed in the Statistical Moment Computation

Comparisons

Once computed for each tile, the statistical moment values are compared within independent 5x5 tile areas. The function of our algorithm is to recognize a grouping of tiles which have a greater amount of contrast, which is represented by the statistical moment value, relative to neighboring tiles. Specifically, the steps of the algorithm are as follows:

- A set of 5x5 tile areas of interest is considered such that every tile in the grid (with the exception of the two columns of tiles on either end) is considered once as the center tile. Figure 1.1 denotes the center tile location as **o** and shows four of the possible eight directions for an individual 5x5 area of interest.
- For each individual 5x5 tile area, a set of conditions are invoked in order to determine both the presence of a crack and its preferred direction. The algorithm is best explained by referring to Fig. 1.4. In order for a crack to exist, all of the statistical moment values of the **D**irection tiles (labeled as **D**) as well as the moment value of center tile (**o**) must be greater than all of the statistical moment values of the **C**omparison tiles (labeled **C**) for that individual crack direction. The **D** tiles have been chosen to resolve the crack into eight possible directions. The **C** tiles have been selected based on much experimentation such that the possibility of a **C** tile sharing a crack with a **D** tile is minimized. While initial performance of the algorithm has been promising, the structure of these comparisons will be considered further in subsequent work.

C		D		C
C		D		C
C		o		C
C		D		C
C		D		C

N Comparisons

C	C		D	
C	C	D		C
C		o		C
C		D	C	C
	D		C	C

N_NE Comparisons

C	C	C		D
C	C		D	
C		o		C
	D		C	C
D		C	C	C

NE Comparisons

C	C	C	C	
C	C			D
	D	o	D	
D			C	C
	C	C	C	C

NE_E Comparisons

C	C	C	C	C
D	D	o	D	D
C	C	C	C	C

E Comparisons

	C	C	C	C
D			C	C
	D	o	D	
C	C			D
C	C	C	C	

E_SE Comparisons

D		C	C	C
	D		C	C
C		o		C
C	C		D	
C	C	C		D

SE Comparisons

	D		C	C
C		D	C	C
C		o		C
C	C	D		C
C	C		D	

SE_N Comparisons

Figure 1.4 - Summary of Comparisons for Crack Direction Determination

- The algorithm tests these conditions for the eight directions sequentially from North (N) to South East_North (SE_N), with the last recognized direction remaining as the recognized direction if more than one directional condition is met.
- If any condition is false, i.e., any **C >** (**D** or **o**) for a direction, it is determined that no crack exists along that direction.

We note that there is significant overlap from one 5x5 area to the next; i.e., since each tile is a center of a 5x5 area, there will be an overlap of four of the five columns between adjacent areas of interest. Thus, there is redundancy in capturing a crack along its length. The tile size employed in this algorithm is consistent with the scale of the defects to be recognized. While microscale (pixel) information is employed in establishing the characteristic of a tile (statistical moment), it is not necessary to retain all the microscale information and thus, real-time operation is feasible.

Preliminary Results and Discussion

The developed crack sensing algorithm has been tested on actual AC pavement. While the algorithm is intended to be used with PCC as well, the dark background of AC presents a more challenging crack recognition problem. As such, the successful application of this algorithm on AC pavement implies its feasibility for crack recognition on PCC (note that the algorithm was initially developed through the use of both AC and PCC images). Additionally, random crack sealing is more common on AC pavements.

Figure 1.5 shows sections of processed AC pavement images containing cracks varying in width from 1/8 to 1/4 inch. In this figure, the grid of tiles is shown overlaid on the pavement image. For each crack segment that has been recognized within a 5x5 local area, the center of each **D** and **o** tile has been marked.

Image 1 shows a typical and relatively clean transverse crack. The algorithm shows quite promising performance for such well defined cracking. Image 2 shows a crack which is both relatively clean (right fork) and unprepared (left fork). This crack, as well as the pavement failure that has occurred where the crack forks, is fully recognized. The relatively clean section of crack is typical of the cracking that would exist on a well traveled highway. The relatively dirty section of crack can be considered as worst case; this crack was located in a parking lot that experienced very little traffic. Clearly, the recognition of this crack shows the robustness and sensitivity of the algorithm.

The crack recognition algorithm does have its limitations. Image 3 shows a crack in a noisy environment. The bottom left of this image contains oil spots which have been improperly identified as cracking. This is a global problem of vision based systems that cannot distinguish distance. Based on the nature of our algorithm, an individual oil spot will not be identified as a crack due to the necessary continuation criteria; i.e., at least five tiles in a local area must include significant contrast for crack recognition. For the worst case such as that shown in which oil spots are consistent and in close proximity to cracks, the algorithm cannot distinguish between noise (oil) and signal (crack). However, a laser range finder based local sensor will be employed in the machinery to be developed for purposes of verifying the presence of identified cracks, and initial experimentation with such a local system has demonstrated the feasibility of this approach.

The algorithm has been initially developed in an off-line manner and with area scan

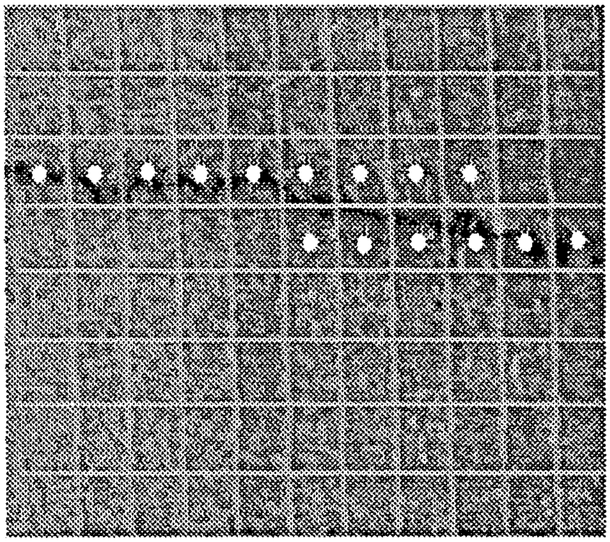


Image 1

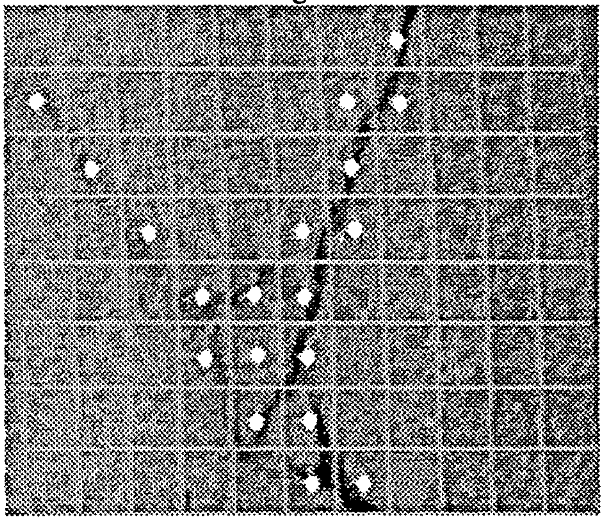


Image 2

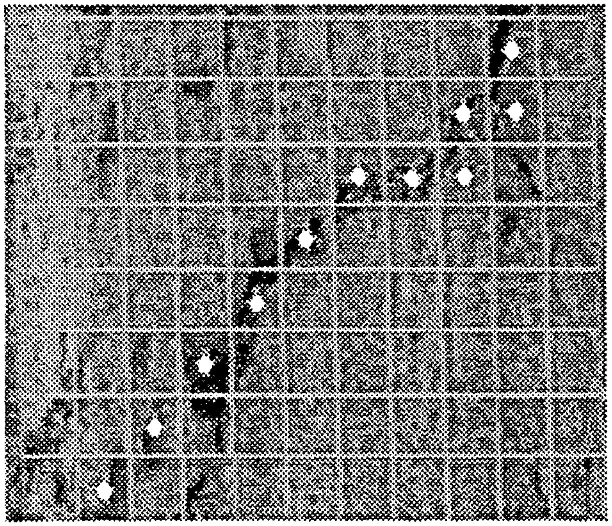


Image 3

Figure 1.5 - Processed Images

video camera technology. Future work will implement this algorithm with a line scan camera and a 68030 based vision system so that it can operate in real-time in automated crack sealing machinery moving at approximately two miles per hour. The development of this algorithm and its initial feasibility testing is just a start towards the automated sensing and sealing of pavement cracks. Later in this section, we will present the hardware design of the machine vision system, and in a later section, we will summarize efforts during Phase II of this project that will toward the further development and implementation of this system.

Automated Sensing of Pavement Cracks - Local Sensing Technologies

As noted above, local sensing will work in conjunction with the machine vision system to confirm the presence of a crack within a given area. The overall vision system will locate the position of a possible crack to within a given area. Local sensing will then scan a four inch area and confirm or reject the presence of the crack. Local sensing is necessary because the vision system cannot distinguish between oil spots, previously filled cracks, shadows, and actual cracks. The purpose of this section is to examine various local sensing technologies. Through breadboard testing it will be shown that local sensing can provide the range information necessary to accurately sense the presence of a crack in both AC and PCC pavements. However, in sealing meandering cracks, as opposed to strictly longitudinal, local sensing alone will not be adequate because the local sensor will require a planned path to scan.

Literature Review

The task of seam tracking during automated welding operations is highly comparable to the local sensing of cracks in pavements. That is, in automated welding operations, a global path is planned for the robot end effector, after which a localized sensor is then employed for fine positioning. This sensor must be rugged and operate in a relatively adverse environment. Numerous studies have been conducted on photoelectric, ultrasonic, and laser sensors that have been used for seam tracking during automated welding.

The use of both photoelectric and ultrasonic sensors were investigated by Tan and Lucas (1986). With the use of a modulated infrared sensor, they were able to remove unwanted noise and detect the seam in approximately 100 msec. Range information using this sensor was determined through intensity measurement of the reflected beam. The ultrasonic sensor, tested by the same authors, determined range information through a phase shift comparison between the receiver and transmitter. Results showed a longer time response, 500 msec, than the infrared sensor, yet produced a resolution of .1 mm and was less sensitive to variances in the measured surface. In each case it was necessary to physically sweep the sensor

In general, the following difficulties are associated with ultrasonic sensing for seam tracking: air movement, temperature fluctuations and noise. However, Siores, et al. (1987) believe that the added benefits of the wide frequency range and relatively slow velocities compensate for these problems. These authors transmit a continuously modulated frequency wave (as opposed to a single frequency), and determine range based on a measured frequency shift. This method, known as the echo principle, provides a method for determining range without calibration. Secondly, the sensor can be made insensitive to variant surface conditions with accuracies as high as .3 mm and time responses of 1 microsecond.

More research applying acoustic sensors to weld seam tracking was performed by Estochen, et al. (1984) who have also considered computer vision using a structured light source and triangulation. However, physical constraints of the light source and vision system coupled with the movement of the torch lead to problems with the computer vision approach. On the other hand, acoustic sensing does not require the computational support, nor does it have the corresponding time delay of the vision system.

In order to obtain sensor data for the cross section of the seam, two approaches were considered by Estochen, et al. First, a vector of sensors spanning the entire cross section was examined. This method allowed for the entire cross section to be scanned simultaneously. The second approach considered a single sensor which swept the cross section and sequentially processed the data. Due to its flexibility and ability to sample many surface features, the second approach was chosen. The sweeping motion was accomplished by rotating the sensor about its midpoint in the direction of the scan. Using this method, accuracy of the range information relied heavily on the ability to accurately sense the angular position. The authors specifically noted that the system can operate in real time only if the seam does not significantly deviate from its path during scanning.

Simmons (1987) has developed a computer vision approach using structured light to overcome the disadvantages of both acoustic sensing (necessity to accurately measure the transit time of the beam) and optical ranging (time requirements to construct a 3-dimensional image). In his alternative approach a thin line of laser light is directed on a surface. The contour of the object is then sensed with a camera mounted at a 45° angle from the laser line with the 3-dimensional image being constructed using the principle of triangulation. This image is constructed 200 times faster than other methods, at a rate of 240 points every 17 msec. The system can be configured to produce accuracies as small as .025 mm, and the sensor itself is miniature, measuring 6.1 x 6.7 x 2.5 inches and weighing 3.5 pounds. In one current application, seam tracking is performed at 40 in/sec.

Brunet, et al., (1986) use triangulation and scan a single point laser range finder to obtain 3-dimensional profiles of surfaces. This system uses a small He-Ne laser and a linear CCD array. In welding applications, accuracies to .2 mm were achieved at a velocity of 50 cm/minute.

A second approach to using laser range sensors uses a GaAlAs laser diode and a PIN-diode linear sensor chip rather than a CCD (Bamba, et al., 1984). The PIN-diode requires simpler image processing and electronic circuitry, and is less sensitive to external optical noise than a CCD. The use of a PIN-diode appears cost effective and suitable for the welding environment. Scanning is achieved by rotating the unit around the welding torch in order to create the 3-dimensional image. The laser range detecting approach determines distance regardless of the intensity of the beam and pulse-modulation can be employed to extract unwanted noise. This compact unit measuring 70 mm accross the cylinder diameter, achieves scanning rates of 2 Hz and a resolution of 0.2 mm.

A similar application of the laser range finding technology was developed by Ogilvie and Zemancheff (1983). Rather than a single laser light source as the preceding two examples, a linear emitter array was used to avoid the need to scan the cross section. The light from each emitter was labeled differently through modulation so that it may be distinguished, requiring a separate computer to manage and process detector outputs.

The "Optocator" probe is a commercially available laser range finder manufactured by the Swedish company Selcom. This sensor, chosen for one automated welding application (Smati, Smith, and Yapp, 1983), uses a narrow modulating laser beam that is projected, thus allowing unwanted noise to be distinguished. The scanning of the Optocator probe is accomplished using a stepper motor. The first step in acquiring data with this approach involves the use of a simple weighted recursive filter of first order to smooth the data, thereby increasing the signal to noise ratio. The resultant error is less than 5%. The next step is edge detection, and two methods were investigated. Scan rates of 2 Hz are achieved, and scan rates as high as 10 Hz seem possible through the use of mirrors, but this would limit the field of view and require that the sensor be mounted very close to the surface.

The Optocator is currently used by Swedenab Road Survey Technology (RST) for non-contact measurement of road surface conditions. The laser sensing system consists of eleven range finding sensors mounted across the front of the vehicle to measure rut depth, roughness, cracks, texture, crossfall, curvature, and hilliness. This "pavement-distress-survey" system vehicle can operate at speeds as high as 90 km/h.

Nayak, et al. (1987) have also developed a laser range finder, the Adaptive Real-time Intelligent Seam Tracker (ARTIST), which also uses a laser light source and a photosensitive device as a receiver to determine range information via triangulation. They were able to achieve welding speeds of 60 inches per minute.

The "Seampilot", a commercially available laser range finding sensor uses mirrors to create the scan (Appels, 1987). Again, a laser light source is transmitted and then received by a photosensitive device. Three-dimensional geometry is then determined by triangulation. This system is in use with speeds close to 3 m/min.

Another currently developed scanning laser range finder using mirrors is the LaserTrak by ASEA Robotics AB of Sweden (Edling, 1986). This sensor achieves a resolution of 0.02 mm and a typical accuracy of +/- 0.4 mm. Tracking speed is as high as 20 mm/s.

An inherent problem in using mirrors to create a scanning laser range finder has been identified and resolved (Rioux, 1984). The problem is associated with the fact that a large angular separation is necessary for good resolution and field of view. However, this large separation not only creates a larger sensing unit, but creates shadow effects, thereby making certain points undetectable by the sensor. Rioux's solution to this problem is to synchronize the light spot projection with its detection. This is accomplished by using two mirror scanners rather than one mirror. The first mirror, as in the previously mentioned examples, causes the beam to scan the cross section. The second mirror is used so that the receiving sensor can follow the spot. In doing this, a more compact sensor can be achieved. Furthermore, by using synchronization, an increased resolution can be achieved without reducing the field of view.

Many additional sensors have been considered for the general crack detection and tracking problem over the last two years; see Jing, et al. (1990). These include those listed in Table 1.1.

TACTILE	microswitches time domain reflectrometry
NON-TACTILE	visible array infrared spectral analysis capacitive inductive acoustic laser pneumatic radar ultrasonic ultraviolet

Table 1.1 - Sensor Types Considered

Initial Feasibility

Tactile sensing was eliminated as a possible sensor due to the high amounts of wear associated with its use. Of the non-tactile sensing systems, spectral analysis was eliminated because no sensor of this type currently exists. Acoustic sensing was eliminated due to its inadequate resolution and time response. Capacitive and inductive sensors are not appropriate for this application because asphalt is non-conducting. Far infrared temperature sensing does not provide adequate response time. Pneumatic sensing proved to be very non-linear and unstable, and was eliminated. No comparable work has been done using radar or ultraviolet sensors to detect cracks, so these choices were also eliminated. Of the remaining sensors, visible arrays do not provide the additional third dimension of depth necessary to distinguish between previously filled cracks, oil spots, shadows, and actual cracks. Finally, ultrasonic, laser, and near infrared photoelectric sensors appeared promising for local sensing tasks, and further investigation and a literature search has been performed to aid in choosing the best sensor.

Based on the literature search, the following three types of sensors were considered for the local crack detecting application: photoelectric, ultrasonic, and laser vision using triangulation. The latter encompasses both single point laser range finders and vision systems using structured light. It is believed that the literature search has adequately demonstrated these four sensor's ability to track a seam in automated welding, and therefore it may be possible to adapt the same technologies for crack detection.

The first sensor considered is a diffuse photoelectric sensor which determines range information by measuring the intensity of diffusely reflected light. It is economical and commercially available. Photoelectric sensors are widely used in the comparable task of detecting seams for automated welding as previously described. However, the sensor performance would be significantly affected if the lens were to become dusty, thereby reducing the amount of reflected light being sensed. Furthermore, this type of sensor does not perform well on surfaces which vary in color or reflectivity, such as pavement.

The second sensor considered was an ultrasonic range finding sensor. This type of sensor determines distance by measuring the phase lag between the source and reflected signals. Again, this sensor is economical, commercially available, and commonly used for seam detection in automated welding. However, no sensors on the market were found to have small enough beam diameters to provide the required resolution; due to the resolution required to detect 1/8" cracks, a sensor with a 1/16" beam is necessary. Furthermore, these sensors are sensitive to the air temperature through which the beam passes, and this is of considerable concern for pavement that will be exposed to the sun or other forms of heat (such as that from the surface preparation heater).

The third sensor considered involves laser vision using triangulation. One method of using laser light to extract a 3-dimensional surface profile is structured light. A 3-dimensional surface profile is determined by projecting a laser pattern in a plane perpendicular to the surface being measured. The line of light is then observed by a CCD camera at an angle, and, using triangulation, the surface features can be found. This sensing method is more expensive than either ultrasonic sensors or photoelectric sensors. There are a few systems which are commercially available, but customized software for this application would be required. However, the commercially available systems including the software comprise a turn key system, and a CPU with the necessary information for crack detection is provided. This technique is widely used in automated welding with much success. It is believed that structured light could provide all the information that is needed for local sensing.

Another type of laser vision system considered was the single point laser range finding sensor. The sensor transmits a laser light source and then focuses the diffusely reflected laser light onto a photosensitive device (PSD). The current flow through the PSD varies depending on where the reflected light hits the PSD. Using triangulation, the distance to the surface is then determined by measuring this current. This type of sensor is also more expensive than the previously mentioned ultrasonic and infrared sensors, yet it is also commercially available and widely used for welding seam detection.

Both types of laser triangulation sensors are impervious to color variations, so either structured light or a laser range finding sensor should work well on all pavements. Furthermore, since they measure the location where light is reflected rather than the amount of light being reflected, laser sensors are less sensitive to a dusty environment. Laser triangulation is also insensitive to lighting conditions because the sensor provides its own lighting conditions via the laser. Overall, laser triangulation is a proven reliable technique for extracting three-dimensional surface characteristics.

Breadboard Testing

In order to determine whether vision systems using laser triangulation will detect cracks on both PCC and AC, a representative laser range finder without an incorporated scanning ability has been thoroughly tested at slower scan speeds. Two comparable laser range finding sensors were considered for this test, those being manufactured by Aromat and Keyance. Their specifications are listed in Table 1.2. The Keyance sensor was selected for testing.

MANUFACTURER	Keyance	Aromat
MEASURABLE RANGE	60-140 mm	100-200 mm
TIME RESPONSE (90%)	.7 ms	2 ms
FREQUENCY RESPONSE	700 Hz	1 KHz
LINEARITY	1% full scale	+/- 150 um
RESOLUTION	180 um	100 um
VIBRATION	10 - 55 Hz	10 - 55 Hz
SHOCK	10 G	10 G
TEMP FLUCTUATION	0.02% F.S./deg C	+/- 3 mV/degC
ILLUMINATION	4000 lux max	3000 lux max
OPERATING TEMP	0 - 50 deg C	10 - 40 deg C
HUMIDITY	35 - 85%	35 - 85%
RECOMMENDED ANGLE	+/- 30 deg	+/- 10 deg
OUTPUT	+/- 4 V	+/- 5 V
COST	$1500	$2500

Table 1.2 - Commercial Laser Range Finder Specifications

A test apparatus was built such that the range finding sensor scanned a section of pavement. The apparatus provided a physical constraint through gearing relating the x position (forward motion) of the sensor and the y position (direction of scan) of the sensor. For this experiment, the x and y positions were constrained such that:

$$y = 2 \sin[(8)(\pi)(x)]; \quad \text{where } x \text{ \& } y \text{ are in inches.} \qquad (1.2)$$

From this relationship it is apparent that the sensor scanned in the y direction a total of 4" inches, and one cycle of sweep corresponded to 1/4" movement in the x direction.

In order to determine crack coordinates, the x position was measured through the use of a rotary encoder attached to the system drive and the y coordinate calculated from eqn. (1.2). One revolution of the encoder shaft corresponded to one complete scan cycle. The pulse from the encoder was input into the counter of the I/O board. The x-position was therefore determined by reading the counter. A schematic of the test hardware is shown in Figure 1.6.

This testing required the development of computer code to process the raw data and translate it into actual crack coordinates in real time. The developed software includes routines to acquire data from the sensor, perform A/D conversion and scale the data, detect crack edges, and determine crack coordinates.

Sensor output in initial testing was clean and thus it was not necessary to incorporate digital filtering as originally expected. Some filtering was provided in that cracks detected which were less than some minimum width were ignored. This prevented unwanted spikes due to noise aliasing as cracks. To detect crack edges, the currently sampled sensor to surface distance was compared to the average of the previously measured distances compensating for varying surface profiles and normal height deviations in pavement. When the current value varied from the averaged values by more than an acceptable tolerance, the sensor located the edge of a crack, and the tolerance used was iteratively varied until the best performance was achieved.

When the leading edge of a crack was detected, a flag was set, and the coordinates were stored. This flag remained set until the trailing edge of the crack was located. While the flag was set, the new distance measurements did not affect the averaged distance. When the trailing edge of the crack was located, these coordinates were stored and another flag was set. The midpoint of the crack is easily determined by averaging the leading edge and trailing edge coordinates.

Feasibility Test Results and Conclusions

The sensor was tested on sample cracks in both AC and PCC pavements. Figure 1.7 shows a plot of crack coordinates sensed on PCC while Figure 1.8 shows a plot of crack coordinates sensed on AC. The uppermost and lowest lines represent raw data of the

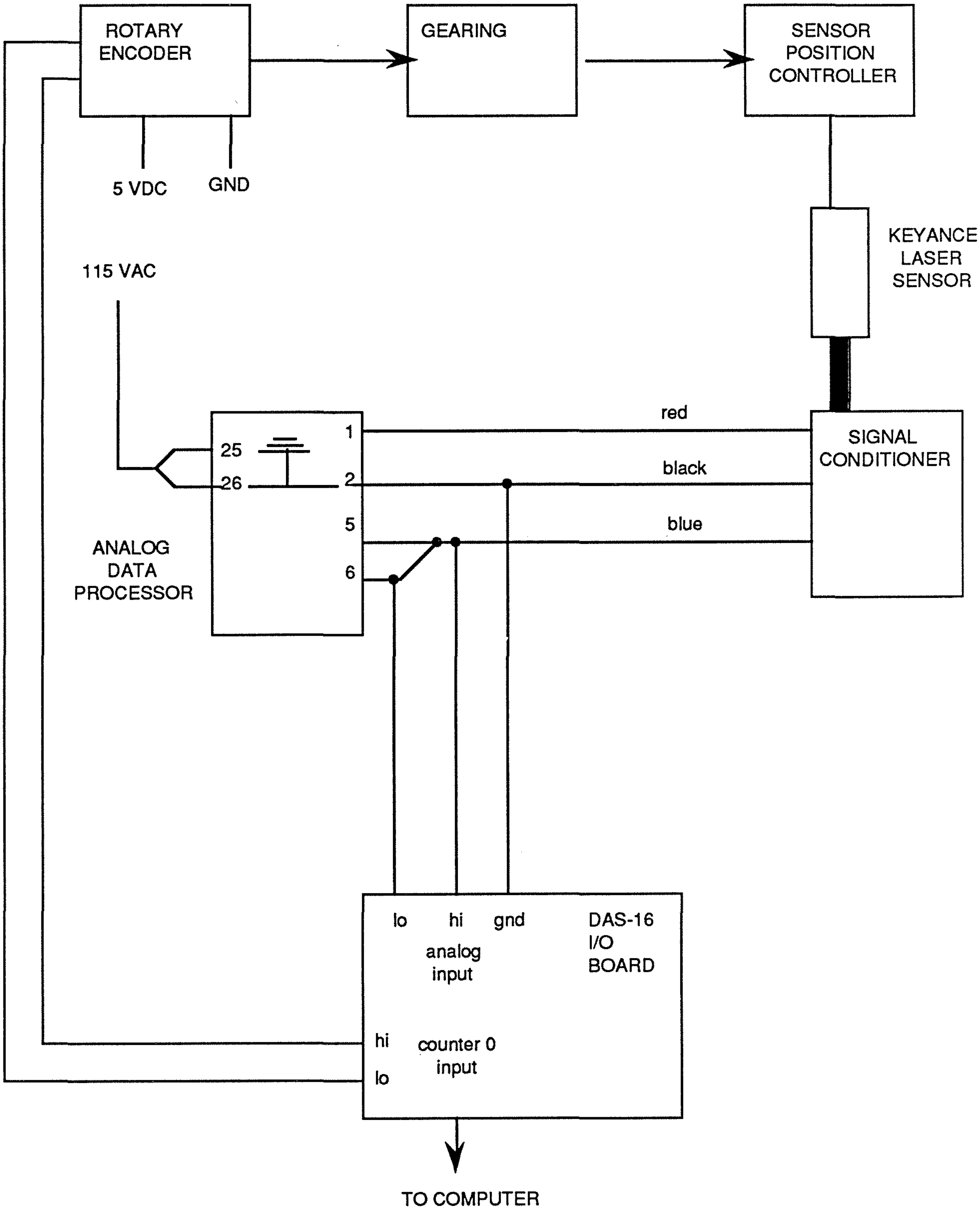


Figure 1.6 - Schematic of Local Sensor Test Hardware

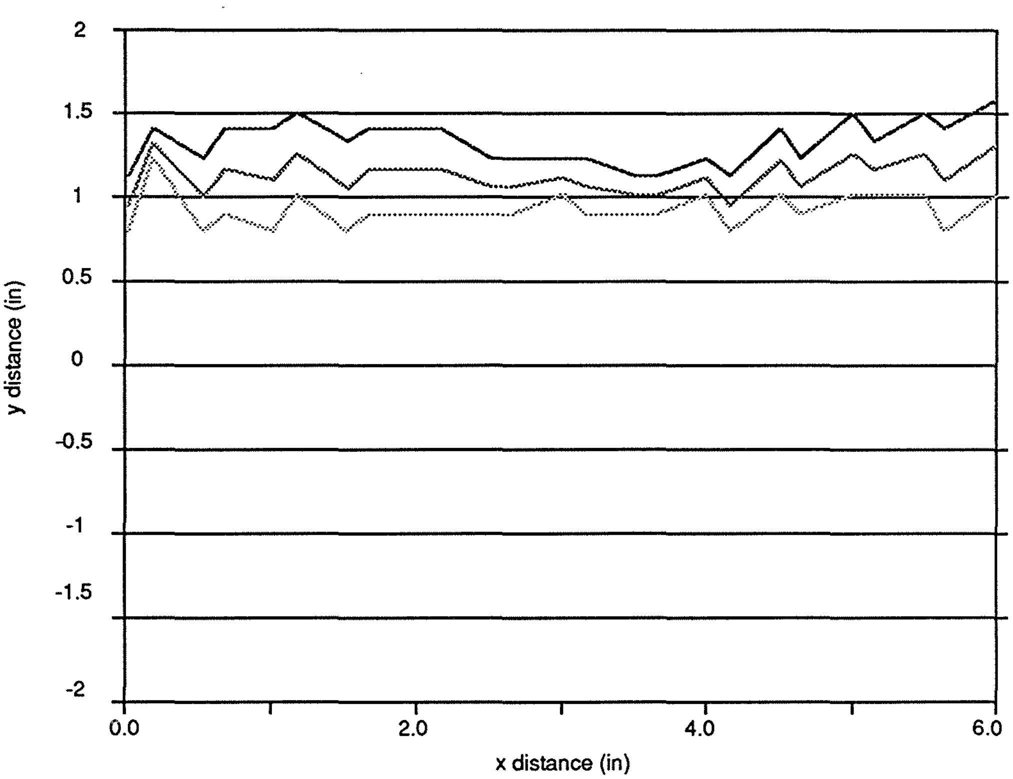


Figure 1.7 - Sample Crack Data from Breadboard Testing of the Laser Range Finding Sensor on PCC Pavement

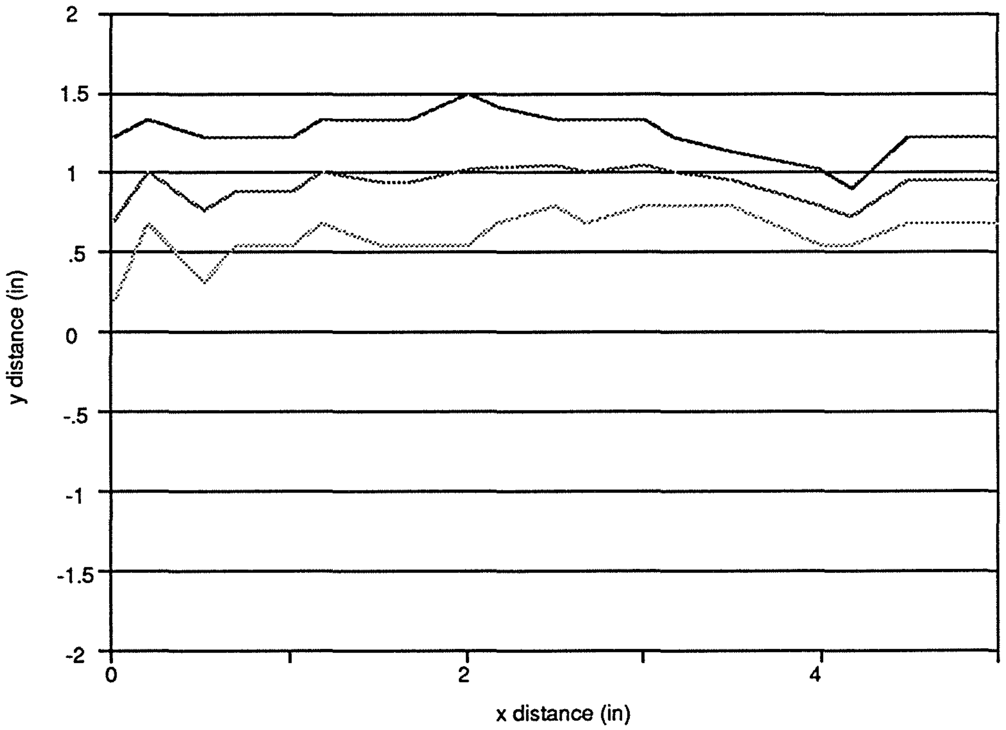


Figure 1.8 - Sample Crack Data from Breadboard Testing of the Laser Range Finding Sensor on AC Pavement

detected crack edges, whereas the center curve is the calculated crack centerline. This simple breadboard test has proven that vision systems based on laser triangulation can accurately measure surface characteristics of both AC and PCC pavements. Furthermore, from the surface profile data, the algorithm used was able to recognize cracks and determine crack coordinates. Thus, this technology has the potential to verify the presence of cracks, and additionally can be employed to supplement the machine vision to more accurately locate the cracks. The proposed local range finder system design will be discussed later in this section of the report.

It should be noted that the limiting factor on the accuracy of the test data was in the test apparatus rather than in the sensor. The encoder used generated a pulse every three degrees. When this angle was converted to the y distance, a maximum error of 0.06" occurred. This error was observed by scanning a wood board with a straight route. The y coordinates showed a maximum variance of 0.06", which indicates no additional errors in the sensing system. This was expected based on the manufacturer's specifications.

Preparation of the Pavement Prior to Sealing - Routing and Sawing

In order for the formed-in-place sealant to adhere adequately to the pavement, and to ensure maximum seal longevity, the crack or joint must be prepared in a manner that provides intact bonding surfaces that are free of moisture and other contaminants (Chehovits and Manning, 1984). Currently various methods are employed by highway agencies to clean cracks and joints; a wide variety of cleaning approaches will be discussed later in this section. However, many do not remove all or most contaminants. Routing and sawing though are two methods for establishing an uncontaminated surface for the sealant to properly bond. The composition of the road surface considered for repair dictates the appropriateness of either a routing or sawing operation.

Routing and sawing operations can also be used to form a sealant reservoir with a functional shape factor (width-to-depth ratio of the in-place sealant) to minimize the strain on the extreme fiber of the sealant during thermal expansion (Bugler, 1984). As such, the utilization of a proper shape factor is considered essential to poured sealant longevity. However, there is currently no definitive recommended optimal shape factor. When the ratio is small (a narrow width and large depth), the stress on the sealant will be high. Generally under these conditions adhesion failure will occur. Shape factor is critical in the ability of the sealant to withstand extension as the pavement contracts. Peterson (1982) recommend a shape factor of 1:1 (with a minimum of 1:2) width to depth.

Prior to 1980, the Ontario, Canada, Ministry of Transportation used the 19 x 19 mm rout configuration as standard for PCC pavement joint sealing. This same standard was also used for AC pavement joints and cracks (Chong and Phang, 1988). Since the extensibility and adhesion requirements at low temperature are not the same for PCC and AC pavement, in the early 1980's, studies were initiated to identify the most efficient route configurations from various combinations of width and depth. The result was that the new configuration of 10 mm deep by 40 mm wide was put into the Ministry Maintenance Operation Instruction Guide as an option to the standard 19 x 19 mm configuration for asphalt concrete pavement route-and-seal guidelines. The stated benefits of this configuration include:

1. Under low temperature, the extensibility required of the sealant materials with the 1:4 shape factor induced much less strain on the sealant and minimized the cohesion failure in the material.
2. The shape factor provides a greater bonding area horizontally instead of the vertical bond faces for the standard square configuration. Thus, extension forces will induce smaller adhesion stress on the sealant material reducing the chance of bond failure.
3. The wider route width can accommodate sharp directional changes in the crack enabling the operator to more effectively cover the course of the crack.
4. Less stress results on the routing machine and router bits meaning higher productivity at less cost.

Although this configuration is optional, Chong and Phang (1988) reported that the majority of the in-house and contractual work were done using this 10 x 40 mm route. Chong and Phang also noted that well executed and timely route-and-seal operations can prolong pavement life by up to 5 years for AC pavement.

Within the United States there is no consenesus on the use of sawing and/or routing, and of the states that do perform these procedures, there is considerable variation in equipment used, vessel size and configuration (Rossman, et al., 1990). Rossman, et al. note that there is no conclusive evidence that sawing and/or routing produces any significant benefit, and furthermore, there is some belief that routing may produce secondary cracking.

Belangie (1989) has pointed out one specific disadvantage of sawing or routing. He noted that concrete is a permeable material whose moisture level tends to follow the humidity of the surrounding environment, and that sawing operations saturate the area surrounding the joint. Under hot weather conditions this additional moisture apparently has little adverse effect on sealing operations, but if the weather is cool or it is desired to quickly seal a crack that has been sawed or routed, the wet road surface could create a problem.

As in Canada, the most widespread use of routing of cracks exists in cold regions where underbody plows or graders will be used for snow removal. Thus, following the completion of the survey of states and study of Rossman, et al. (1990), the value engineering team recommended the elimination of routing/sawing of cracks in AC pavements prior to sealing, except in areas where underbody plows or graders will be used for snow removal. It was noted that this will eliminate one person per sealing crew, which amounts to one-half person year per crew, and that the savings from this recommendation should conservatively amount to $33.5 million per year nationally. This estimate did not include the cost of the router or saw, and its maintenance.

The resealing of Portland Concrete Cement (PCC) joints involves the removal of old sealant and the refacing of the joint walls prior to applying the new sealant. To prepare PCC joints in this manner SHRP H-105 (Smith, et al., 1991) has determined that ninety one percent of highway agencies surveyed use concrete saws to perform this task. There are several products available on the market to saw PCC, the most common of which rotate one or more wet diamond saw blades about a horizontal arbor parallel to the road, that together are slightly wider than the original joint. As the diamond saw blade(s) pass through the joint, a fresh surface is generated on the joint walls, any old sealant is cleaned out, and the desired reservoir depth is established. Accurately guiding the cutters along the joint is an important consideration to minimize the amount that the joint is widened each time it is repaired. Also, this guarantees that both sides of the joint are refaced. Currently, concrete saws are guided along the joint with an arm sliding through the joint in front of the saw and by the operator during the last few feet.

While there is controversy concerning the use of routers/saws for AC pavements, since a number of states do use this approach, the H-107A will develop machinery that can accomodate the routing or sawing operation. There are several different methodologies concerning the resealing of Asphalt Concrete (AC) cracks which may involve a routing or sawing operation (Rossman, et al., 1990). According to SHRP H-105 (Smith, et al., 1991), of the highway agencies that use crack cutting preparation methods, sixty three percent use routers, the horizontal spindle impact router being their most common choice. Routing provides a clean bonding surface for the formed-in-place sealant to adhere as well as a sealant reservoir with a known functional shape factor. The typical, commercially available impact router, consists of a motor driving the rotation of a circular tooling plate at approximately two to three thousand revolutions per minute. Six to eight impact cutters are allowed to spin freely about arbors rigidly attached to the tooling plate. Each cutter has five to eight carbide tipped cutting teeth that chip away at the AC pavement producing a fresh intact groove to seal. Usually the cutters are rotated in the direction such that the resulting cutting force (the force generated by the shear forces between the cutter and the material being cut) tends to lift the cutters up and out of the road and toward the direction of cut. Therefore, impact routers are designed to have the center of weight of the entire unit directly over the cutting area to provid the needed weight to keep the cutters into the roadway. The advantages of this type of cutter are that the impact router can be maneuvered to follow meandering AC cracks and, the nature of the cutting procedure precludes the need for a liquid coolant to remove excess heat from the cutting area. This is advantageous since liquid coolant would contaminate the clean surface prior to applying the sealant.

Testing performed at the University of California, Davis on impact routing equipment used by highway agencies has led us to the conclusion that common routers are specifically designed to satisfy the ability and capabilities of their human controllers. The current production rates of these routers are not limited by mechanical or cutting considerations, rather they are limited by how fast the human operator can guide the cutters along a crack. The result of routing inaccuracies along the crack leads to either an improperly prepared crack, limiting the seal life, or even worse, missing the crack entirely and creating another distress next to the pre-existing unprepared crack. The computer controlled positioning system that will be part of our automated machinery will relieve the guidance limitations of human controlled positioning. A quicker guidance system would unleash the full potential of current routing and sawing equipment and can lead to the development of a router with a greater production rate. Details of the componet designs to be tested in Phase II will be discussed later in this section.

Preparation of the Pavement Prior to Sealing - Crack Cleaning

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. While it is known that crack cleanliness is essential for proper bonding of the sealant, one primary difficulty in obtaining an "adequate level-of-cleanliness" is that there are no current standards to evaluate crack cleanliness nor are there accepted cleaning procedures (Belangie, 1990).

In order to develop crack sealing machinery, it is necessary to determine a method of efficiently and effectively cleaning the road surface cracks prior to sealant application. Various possible methods for cleaning road surfaces are discussed below and the purpose of this portion of the project is to select the cleaning method(s) that best meet the goals of this project in terms of effectiveness, efficiency, and project time schedule requirements.

A number of methods exist for cleaning cracks in road surfaces. Cleaning with a hot compressed air (HCA) lance, compressed air only, low pressure-high volume blowing, abrasive blasting, wire brushing, sweeping, and water jet blasting, are all methods that can be used individually or in some combination (Rossman, et al., 1990; Chehovits and Manning, 1984; Peterson, 1982). Rossman, et al. (1990) conducted a survey of States to determine the methods of crack cleaning and found that the principle equipment used is the HCA lance or compressed air. This fact does not mean that either of these methods is necessarily effective. However, it can be inferred from this survey that crack sealing machinery which uses a hot air lance (with compressed air exiting from the nozzle tip) to clean the road surface would probably be accepted by the majority of end users.

In a related study, an attempt was made to determine the relative cost-effectiveness of various surface-preparation and paint stripe removal methods (Davidson and Callahan, 1987). It was noted that due to the constantly changing surface conditions of pavements, there is no single surface-preparation method better than the rest and that the selection of a method of (paint) stripe removal is contingent on the material to be removed, the condition of the old marking material, its adherence to the pavement, and several other factors. Unfortunately, due to the brevity of the report, it does not allow for the selection of a method for our application. As such, we will address a variety of possible cleaning methods noting information from many sources including experiments conducted as part of SHRP-107A.

Compressed Air Jets

Compressed air is widely used as a primary method for cleaning cracks and pavement surfaces. Its acceptance seems due mainly to its ease of use and relatively low cost. While compressed air jets are useful and are capable of removing debris from cracks, it is doubtful that in many cases the air jet can remove all unacceptable crack contamination. The literature varies somewhat in its assessment of the effectiveness of the compressed air jet for cleaning road surfaces. These discrepancies seem to exist primarily because there is no widely accepted standard as to the “acceptable level-of-cleanliness” of cracks and road surfaces prior to sealing.

A study of roadway crack debris removal using high pressure air jets was conducted by the UC-Davis/Caltrans engineering team (Schultheis and Smith, 1990). The purpose of the experiments was to gain a better understanding of the effectiveness of using a high pressure air jet to remove debris (e.g. dirt, sand, small gravel, and weeds) from road surface cracks. The objectives of the experiment were achieved through a series of controlled laboratory tests as well as field tests under actual working conditions. Air pressures up to approximately 80 psi and air flow rates up to approximately 75 cfm were used for this experiment. These values are roughly equivalent to those of the lance portion of an existing HCA lance.

Conclusions from these experiments follow:

- The air jet can satisfactorily remove loose debris from cracks at slow speeds. At speeds greater than approximately 5 mph, it may be necessary to employ alternatives such as additional air jets, higher air flow rates, mechanical cleaners, sandblasting, steam cleaning, water jets, etc.
- The air jet was unsuccessful in removing live vegetation and “dirt film” from cracks. Therefore, other methods of vegetation and dirt film removal were recommended for further study. These included high pressure water jets, propane burners, sand blasting, steam cleaning, brushes, etc. It should also be noted that the air jet was able to remove some dead vegetation provided that the roots of the vegetation

were sufficiently deteriorated.

- Nozzle eccentricities greater than approximately 1/2" clean the crack relatively poorly as compared with eccentricities less than approximately 1/2". Nozzle eccentricity is defined as the offset distance between the path of the device and the path of the crack when these paths are parallel. The cause of this was not determined conclusively. It may be a function of crack width, nozzle size, etc. Further study may be useful.
- For optimum air jet performance, it is preferable for the nozzle to be continuously centered above the crack.

HCA Lances

It is known that heating of the crack and local road surface prior to sealant application improves sealant adhesion. It is usually explained that sealant adhesion improves as the temperature gradient between the local road surface temperature and the sealant temperature decreases. In addition to heating the pavement, heat lances usually produce high velocity air jets which tend to clean the surrounding area of debris. However, it is doubtful that the heat by itself actually removes significant debris from the road surface since road films are generally composed of inert materials that do not burn (Davidson and Callahan, 1987).

Rossman, et al. (1990) recommend the hand held HCA lance as the preferred tool of highway crews for crack cleaning since they are capable of producing exhaust temperautres 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 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). The ability of current HCA lances to transfer enough heat though, at a faster speed, remains to be addressed later in this section. However, as mentioned above and assuming that the same would be true for the air lance portion of an HCA lance, at speeds greater than 5 mph and with crack eccentricity greater than 1/2" inch, compressed air jet cleaning effetiveness decreases. Other methods were therefore examined.

Low Pressure-High Volume Air Blowers

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 "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. As just mentioned, an existing HCA lance's compressed air line does not effectively remove debris outside of an approximate 1 inch wide strip (+-1/2 inch) and at speeds greater than 5 mph. A centrifugal blower operates at only 4 psi (based on vendor discussions) and therefore, the air does not expand significantly after leaving the exit. Thus, a blower may be the best choice for implementing the crack cleaning and heating system. Compressors are currently used in highway heating operations because they are readily available and crack eccentricity is not a major concern using a hand held HCA lance. Nor is speed of much concern. However, on a crack sealing machine travelling much faster, the robot end-effector can perform best by allowing the most tolerance.

The space savings by using a blower would be significant. A large 185 cfm compressor requires roughly 72 cubic feet of space, whereas a hydraulic blower, which can tie into existing hydraulics, requires only about 2 cubic feet of space. Furthermore, the blower intake is available to be used as a vacuum source, possibly to catch and suck up router debris. Since the router propels debris back with a high velocity, a "catcher" with a vacuum line could be attached just behind the router. The vacuum line could then be plumbed through a dust collector where the AC chunks and road dust could be removed prior to entering the blower face for recirculation.

Preliminary sizing of such a system indicates that a 5 HP hydraulic motor, as opposed to a 100 HP compressor engine, outfitted with a 7/8 inch nozzle could provide the needed air power to clean out a crack and the path cut by a router.

Abrasive Blasting and Abrasive Vacuum Blasting

Sandblasting can be a very effective means of cleaning cracks in road surfaces. Sandblasting has been found to be effective as a surface-preparation method and as a stripe-removal method for traffic paint, thermoplastic markings and epoxy markings (Davidson and Callahan, 1987). Additionally, sandblasting is an extremely economical method to remove rust and to clean bare metal prior to bridge painting (Perkins, 1990).

Vacuum blasting has been found to perform well also but is relatively slow, and expensive in terms of paint preparation (Perkins, 1990). Vacuum blasting employs a device which encloses the blast nozzle and uses negative pressure (vacuum) in the local area to collect the blast media (sand, aluminum oxide, steel shot, etc.) for disposal and possible refiltration and reuse of the blast media. Although this process is not yet ideal for paint preparation, since a road surface is relatively flat and uniform, it may be suggested that an abrasive blast operation could be more appropriate for crack preparation. Other work related to the use of vacuum blasting for lead-based paint removal has noted its benefits. In particular, Culp (1989) has reported on the effectiveness of using a water scrubber to remove collected dust and on the long life of steel shot blast media.

With respect to joint resealing, through studies in New York State, it was recognized that a sandblasted joint face has a much greater surface area for bonding when compared with a sawcut joint face, and that a sandblasted joint face enables a properly constituted formed-in-place sealant to achieve a significant increase in net bonding force at the joint face (Bugler, 1984). Although sandblasting was an effective crack cleaning method when performed properly, in some instances incomplete sandblasting of the joint face led to 2-4 inch intermittent bond adhesion failures for the full depth of the seal. The author went on to note that operator error is common and that for a properly sandblasted joint face it is necessary to hold the sandblast nozzle in very close proximity to the pavement. Other problems with sandblasting include: the mass of equipment necessary, the logistics of handling dried sand, stray and deflected sand contact with passing vehicles, and the need to remove sand from the roadway after blasting. Additionally, dry blasting has been restricted in recent years because of health hazards from silica dust inhalation, air quality concerns with visibility, suspended particulates, fugitive or nuisance dust, and dust contamination of machinery or equipment. If proper containment procedures are taken and respirators are used (when necessary), these problems can be eliminated. It would also be beneficial to employ a blast media such as steel shot or aluminum oxide since these media do not pose the health problems associated with the use of sand. The above subjects have been discussed by Medford (1990), Perkins (1990), and Culp (1989).

It is apparent from literature that abrasive blasting is a very good method of surface preparation, if the operation is conducted properly. If this method is to be used in the future, it may be helpful to produce standard procedures for the blasting operation and to possibly automate or improve the process so that the problems associated with improper blasting could be overcome. Separation and reuse of the spent blast media from the debris would also reduce the problem associated with the logistics of supply and disposal of the blast media, and the combination of automation and containment should eliminate most other concerns.

In addition to the literature search, a study was conducted by the UC-Davis/Caltrans engineering team to determine the effectiveness of the general sandblasting method and the more sophisticated abrasive vacuum blasting method (Schultheis, 1991). It was concluded from this study that the abrasive blasting method is highly effective in removing all loose debris, vegetation, and dirt film from the road surface. In addition, the abrasive blasting method (without vacuum recovery of the abrasive media and debris) was generally quite efficient in that it could clean the road surface at a reasonable rate of speed. However, this method left the debris and blast media as waste on the road surface. This would not be acceptable for a commercial machine. The abrasive vacuum blasting method was slightly less effective, although it shows much promise; the particular machine used had operational difficulties at the time of the experiment. However, even if peak performance was achieved from the machine, the cleaning operation would still be considerably slower since the vacuum blast head was both cleaning the road surface and vacuuming the blast media and debris from the road surface. In addition to the slower cleaning rate, the vacuuming process required a large portion of the total power requirements for the system.

Based on information gathered from the literature search and the field studies, it is concluded that abrasive vacuum blasting using a blast media of either aluminum oxide, steel shot, or cut steel wire could produce the best results. In addition to providing a very clean road surface and crack, the pavement surface is left dry and free of all loose debris, dirt film, and oil film. The blast media is immediately vacuumed from the road surface following the blasting operation, cleaned of debris, and reused as blast media. Currently, the major drawbacks of this method include high power requirements to vacuum the debris and blast media from the road surface, relatively slow speed of the operation, and considerably higher equipment costs. Although abrasive vacuum blasting shows great promise, considerable development would be required to make it commercially feasible for an automatic crack sealing machine, and this is deemed beyond the scope of the H-107A project.

Wire Brushing

Chehovits and Manning (1984) have noted that a power brushing operation can aid in cleaning and removing relatively loose deteriorated asphalt concrete from cracks and greatly improve the adhesion of the sealant in the pavement. Other studies have noted the benefits of wire brushing for pavement surface preparation, although it is not effective for paint stripe removal (Davidson and Callahan, 1987).

In general, wire brushing is relatively easy to use, it works well over irregular surfaces, it does not damage the road surface, it has no logistics or time-lapse problems, it removes road film and scratches the surface, and generally improves paint stripe adhesion. However, unless there is gross contamination, wire brushing is not particularly effective (Davidson and Callahan, 1987). A minimal amount of feasibility testing was performed at UC-Davis with wire brushing, and it was not found to be effective for crack surface preparation.

Wet Blasting

It was initially believed that high pressure-low volume water blasting may prove feasible in crack sealing if water flow could be kept to a minimum as pavement drying would have to occur either naturally or though the use of the heater. Therefore, a variety of wet blast methods in general use including water blasting, hydroblasting, air abrasive wet blasting, air/water abrasive blasting, pressurized water abrasive blasting with high and low pressure water, and ultra high pressure water jetting were examined for possible incorporation into this generation and future generation crack sealing machinery.

In short, various types of wet blasting systems showed much promise in surface preparation and may prove valueable to future generation crack sealing machinery. However, since it currently desireable to apply a non-emulsion based sealant to very dry pavement and to the perform crack sealing in a single pass operation, wet blasting is unfeasible. Other drawbacks are the large support equipment needed and their associated cost. The development of wet blasting for crack and joint preparation is far beyond the scope of the SHRP H-107A project, and it will not be pursued further. Much information regarding wet blasting is available on request.

Cleaning with Chemicals

Chemicals have also been considered to remove paint stripes and clean the road surface. In particular, etching with 3% hydrofluoric acid would improve the life of traffic-marking materials. The problem with its use is one of logistics and expense. Although effective, the steps involved in the use of acid and the hazards involved make its use unattractive (Davidson and Callahan, 1987).

Comparisons of the Various Cleaning Methods

It is concluded from the literature search and independent experiments conducted as part of this research that proper cleaning of road cracks and surfaces is essential if crack sealants are to adhere properly to the road surfaces. To summarize the information that was gathered and better evaluate the various cleaning methods, the problem of road surface cleaning will be separated into three separate tasks, those being: vegetation removal, loose debris removal, and dirt film removal. Each of these tasks must be completed satisfactorily for optimum seal adhesion to be achieved. In order to lead towards the desired cleaning method(s) for each task a set of method selection criteria have been developed. See Table 1.3.

Each of the road surface cleaning tasks are addressed in Tables 1-3 of Appendix 6.1. Every attempt has been made to include all reasonable cleaning methods which could be used to complete the particular task. The advantages and disadvantages of each potential method are also presented. A comparison of the cleaning methods, based on the method selection criteria, will be performed to determine the best method(s) to accomplish each of the tasks.

1) EFFECTIVENESS
The cleaning method must accomplish the task satisfactorily either by itself or in combination with one or more other methods.

2) SAFETY
The cleaning method must not be a significant hazard to the machine operators, motorists, or the environment.

3) SIZE & MANEUVERABILITY
The "business end" of the cleaning system/systems must be mounted as a robot end-effector and should have a small mass, small physical size, and be flexible and maneuverable.

4) LOGISTICS
It is desired to employ the least number of cleaning methods to complete the entire job of vegetation removal, loose debris removal, and dirt film removal. The ideal would be for one cleaning method to be used for all of the tasks. This should reduce the complexity of the machine, thus improving the logistics of supplying cleaning materials, fuel and other power requirements, replacement parts, skilled maintenance personnel, etc. for the cleaning operation.

It is desired that the chosen system employ a minimum number of total parts and a maximum number of identical parts. Parts inventory is generally reduced in this situation.

5) COST
It is desired for the cleaning method to accomplish the task at a minimum fixed and operational cost.

It is desired to employ the least number of cleaning methods to complete the entire job of vegetation removal, loose debris removal, and dirt film removal. The ideal would be for one cleaning method to be used for all of the tasks. This should reduce the overall fixed costs and operational costs of the machine.

It is desired that the chosen system employ a minimum number of total parts and a maximum number of identical parts. Operational costs are generally reduced in this situation.

6) EQUIPMENT MAINTENANCE AND RELIABILITY
It is desired to employ the least number of cleaning methods to complete the entire job of vegetation removal, loose debris removal, and dirt film removal. The ideal would be for one cleaning method to be used for all of the tasks. This should reduce the complexity of the machine, thus providing for less complicated and less time consuming maintenance procedures.

It is desired that a cleaning method be employed such that machinery wear is minimized. Machinery wear may include such things as undesirable contact of the cleaning head with the road surface, deterioration of abrasive blast nozzles (and related equipment) caused by the blast media, damage and deterioration of associated equipment (such as sensors) caused by flying debris or heat effects, etc.

It is desired for the cleaning method to employ as few moving parts as possible. As the number of moving parts per system increases, failure rate, downtime and maintenance also tend to increase.

It is desired that the chosen system employ a minimum number of total parts and a maximum number of identical parts. Maintenance requirements are generally reduced and machine reliability is generally increased given this situation.

7) POSITIONING
It is desired to employ cleaning methods which do not require a high degree of positioning accuracy (both lateral and rotational) of the end effector.

8) POWER REQUIREMENTS
It is desired that the cleaning method accomplish the task with minimum power requirements.

9) MOISTURE REMOVAL
It is desired for the cleaning method to accomplish the task without the addition of moisture to the road surface. All road surface moisture must be removed prior to crack sealing.

10) AREA COVERAGE (of the cleaning head)
The cleaning head should be capable of preparing a broad area (approximately 2 1/2" either side of the crack) surrounding the crack.

11) RECYCLING
It is desired that cleaning media (if any) be recycled and reused for the cleaning process. This will reduce operational and environmental costs.

12) EQUIPMENT AVAILABILITY
It is desired to utilize cleaning equipment that is readily available from commercial sources. The use of readily available commercial equipment will reduce equipment development time and costs, machine development risks, and involves private companies in the development of the crack sealing machine.

Table 1.3 - Method Selection Criteria

Summary of Results

Literature and experiments concerning the various cleaning methods are not entirely conclusive and are sometimes conflicting. Even so, it seems reasonable to conclude from the available information that a centrifugal blower/vacuum system will do a satisfactory job in removing most loose debris from the road surface and cracks. Should this system prove to be ineffective in Phase II testing though, as a contingency, a compressed air jet(s) can easily be implemented. However, it cannot be expected that either of these methods will be effective in removing *all* loose debris or any live vegetation or dirt film. It would be necessary to employ a more sophisticated cleaning method if a cleaner road surface is required.

It is concluded (from the surveys of State practices) that by far an HCA lance is the most common method employed for cleaning road surfaces today, even though the cleaning performance of a compressed air jet via an HCA lance is somewhat limited. It is usually chosen by crews primarily because the equipment is readily available (DOTs already own compressors), easy to use, and the operation is relatively inexpensive in terms of both labor and equipment costs as compared to other methods. However, as was mentioned ealier, at speeds greater than 5 mph and with positional inaccuracies greater than 1/2 inch, the compressed air jet present in an HCA lance will not adequately clean a crack or its routed path.

A centrifugal blower, similar to those being used in street sweepers, on the other hand produces high volume-low pressure air to blow an area clean. Longer effective "reach" is achieved by a blower since after exiting the nozzle the air does not expand so rapidly. A wide routed path can therefore be blown clear more reliably. Since a blower system is easy to use, quieter, smaller and less costly (a compressor is not required), crack sealing machinery which uses a blower as its primary method of road surface cleaning should therefore be widely accepted by the majority of end users. Once a machine of this type is operational, further development of the road surface cleaning system (possibly employing other or additional cleaning methods) could enable a more thorough cleaning of the road surface. Later in this section additional discussion will center on the feasibility of various heating methods. Also, first generation component designs will be presented later.

As noted in the preceding paragraph, high pressure air jets, blowers and HCA lances were not found to be the *most* effective in terms of cleaning road surface adequately. Based on information gathered, it is concluded that abrasive vacuum blasting using a blast media of either aluminum oxide, steel shot, or cut steel wire has the potential of producing the best results. This method does a very acceptable job of cleaning the road surface and the crack. After the cleaning operation, the pavement surface is left dry and clean of all loose debris, dirt film, and oil film. The blast media is immediately vacuumed from the road surface following the blasting operation. It is cleaned of debris and reused as blast media. The major drawbacks of this method include high power requirements to vacuum the debris and blast media from the road surface, relatively slow speed of the operation, and considerably higher equipment costs. Although abrasive vacuum blasting shows great promise, considerable development would be required to make it commercially feasible for an automatic crack sealing machine and this is beyond the scope of this project.

Preparation of the Pavement Prior to Sealing - Pavement Heating

The automated crack sealing machine requires that the roadway is heated prior to crack sealant dispensing to insure that the pavement is dry and to allow ample time for the hot-pour sealant to flow into the crack before cooling. It is generally accepted that an off-the-shelf HCA lance is the preferred method of crack cleaning and heating among the manual road crews today. However, typical existing HCA lances were built under different design criteria. They were designed to be hand held, to be simple to operate at slower than walking speeds, and to utilize a compressor as a means of supplying hot air to blow out the crack. These design criteria differ significantly from those of the automated crack sealing machine. Since the machine must be designed for speeds greater than the current walking speeds, the heat output must be appropriately increased. 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 heat lances. Also, the air flow must be powerful enough to blow out a crack and/or its routed path. For these reasons this report presents the finding from the feasibility study on various alternate methods of crack heating and provides recommendations for the machine component design.

There are primarily two methods of pavement heating, those being radiant and convective heating. 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 is used presently in some crack sealing operations. 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. Therefore, in order to assess the feasibility of using currently available heating equipment, computer models were constructed to aid in determining the relative differences between the two types of heating. Both models output the temperature of the asphalt surface as a function of exposure time. Findings from the literature search are presented here followed by the analysis and technique used to construct each computer model. Generally, radiant heat as a method of surface heating is more efficient than convective heating so it is presented first.

Radiant Heating

There is a large body of literature available concerning radiant heat transfer to AC pavement. Much research has been conducted related to the prediction of temperature distribution within pavement as it relates to daily heating cycles and climatic variations. Although a full review of it is not necessary for this report, some basic findings are presented.

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 asphaltic 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). The values presented are generally widely accepted and form the basis of many verified computer models. It should be noted however, that the thermal properties of a nonhomogeneous 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 radiative 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.

Radiant Pavement Heating Analysis

During recycling operations, crews are primarily interested in heating the asphalt from 1 1/2 to 3 inches in depth to temperatures of 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). To maximize the effectiveness of the "rework", i.e., to heat the 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 (Osborne, 1988). During crack sealing operations however, the conditions for the heat transfer drastically differ.

The primary goal of the UCD team is to automate the sealing of pavement cracks. Based on initial crack sealing machinery speed goals, heater speeds upwards of 2 mph are required. Given any reasonably sized radiant heater, this speed means that less than 5 seconds of heater exposure time, rather than 2-5 minutes, is available for crack sealing. However, 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. Any excess heat which penetrates down into the pavement is incidental. During recycling operations, it is important though, to heat the pavement to a significant depth and much research has been done as to how this heat penetration can be enhanced. The short heater exposure time and shallow depth required for the sealing of highway cracks coupled with the nonhomogeneous, rough surface of pavement make the accurate prediction of the surface temperature difficult.

As noted, 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. Our approach includes the modification of the Carmichael et al. model, which is more indicative of the types of heaters that can be used for crack sealing operations, and its verification with Corlew and Dickson's experimental data. The resulting model will be used to predict pavement surface temperatures and times of interest to 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:

$$\frac{\delta T}{\delta t} = \alpha \frac{\delta^2 T}{\delta z^2} \tag{1.3}$$

or incrementally as:

$$T_i^{j+1} = T_i^j + \alpha \frac{dt}{dz^2} * (T_{i+1}^j + T_{i-1}^j + 2T_i^j) \tag{1.4}$$

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

$$\frac{(T_i^{j+1} - T_{i-1}^{j})}{dz} = \frac{(T_i^{j+1} - T_S)}{(\frac{k}{h})} \tag{1.5}$$

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:

$$T_1^{j+1} = \frac{dbx^*T_2^{j} + dx^*T_S}{dbx+dx} \tag{1.6}$$

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:

$$Q = \frac{\sigma(T_1^3 + T_1^2T_2 + T_1T_2^2 + T_2^3)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F} + \frac{1-\varepsilon_2}{\varepsilon_2}} {}^* A(T_1 - T_2) \tag{1.7}$$

The large product on the right side of Eqn. (1.7) 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 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•ft^2•F. In Eqn. (1.7) above, T_1 and T_2 represent the temperature of the surface of the heater and asphalt, respectively, e_1 and e_2 are the heater and asphalt emissivity 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 our needs, this model was first modified to account for the free convective heating coefficient, h_{conv}. Second, a calculation of the radiant shape factor (as opposed to an estimation) was added. For their experiment, Corlew and Dickson used a simple direct-fired propane heater to heat a 4 inch diameter asphalt core insulated on its sides. 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:

$$F = 0.5\left[X - (X^2 - 4Z_2^2/Z_1^2)^{1/2}\right] \tag{1.8}$$

$$\text{where } X = 1 + (1 + Z_2^2)/Z_1^2 \quad \text{and } Z_1 = R_1/D \text{ and } Z_2 = R_2/D$$

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 to be 2 inches and 1/2 inch, respectively.

Lastly, since the Corlew and Dickson experiments were based on a constant heat flux rather than a constant temperature source, it was necessary to use the experimental information provided to solve for the heating source temperature for input into the new 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 runs of the new 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 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). As one final 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} found above and the source temperature became inputs to the constant heat flux model. With these changes complete, the Corlew and Dickson experimental and theoretical data was then compared to the data provided by the new constant temperature model and the modified constant heat flux model. Results were plotted for AC depths ranging from 1/4 inch to 2 inches verifying the model to within 15% error. 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 data, and the nonhomogenious structure of asphalt. Certainly a model with this accuracy should provide adequate information to determine the feasibility of this heating approach.

In order to make the verified program useful to the crack sealing project, it had to be modified to account for the rectangular shape factor consistent with typical radiant heaters. 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):

$$F = \frac{2}{\pi XY}\left[\ln\left[\frac{(1+X^2)(1+Y^2)}{1+X^2+Y^2} \right]^{1/2} + Y\sqrt{1+X^2}\,\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + X\sqrt{1+Y^2}\,\tan^{-1}\frac{X}{\sqrt{1+Y^2}} - X\tan^{-1}X - Y\tan^{-1}Y \right] \tag{1.9}$$

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. Eq. (1.9) 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 verified model was altered to account for the cooling of the pavement. Accurate modelling 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:

$$\Delta x \, \rho \, C_v \frac{\delta T}{\delta t} = k \frac{\delta T}{\delta x} - \varepsilon_2 \, \sigma \, T_2^4 - h_{conv} (T_2 - T_{amb}) \qquad (1.10)$$

The resulting FORTRAN model code is available upon request.

Radiant Heating Results and Recommendations

The resulting computer program was then 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 our application. Results from our pre-contract testing showed that AC pavement begins to darken and smoke at temperatures above 280°F. Thus, a conservative 250 °F was selected as the surface design temperature goal for the system. A plot of the temperature/depth history is presented below (see Figure 1.9). Because of the nonhomogeneous substance structure of AC and its rough surface texture, data is plotted ranging from the surface to one-tenth of an inch deep. The temperature of the asphalt changes dramatically with depth increments as small as .01 inches, which is due primarily to the thermodynamic properties of aggregate. Thus, the nonhomogeneous substance structure of asphalt and the fact that it is not a perfectly smooth surface causes difficulty in accurate modelling of individual points on the pavement surface. However, the model should give a reasonable estimate of the average surface temperature and is quite useful for our purposes.

Based on our simulations of commercially available heaters, the Maxon Corp. heater with a face temperature of 2100°F seems to provide the best results. This heater produces 132,000 BTU/hr/linear foot of heater. By trial and error a heater length of 6 ft. was determined as necessary to reach a surface temperature of 250°F while travelling at 10 mph; i.e., approx. 792,000 Btu/hr of radiant heat. While a radiant heater of this length would appear feasible for a machine that addresses straight, long cracks, it is apparent that it would be quite difficult to employ such a heater on a machine that addresses random, meandering cracks. Thus, we will now examine convective heating which has the potential for a much

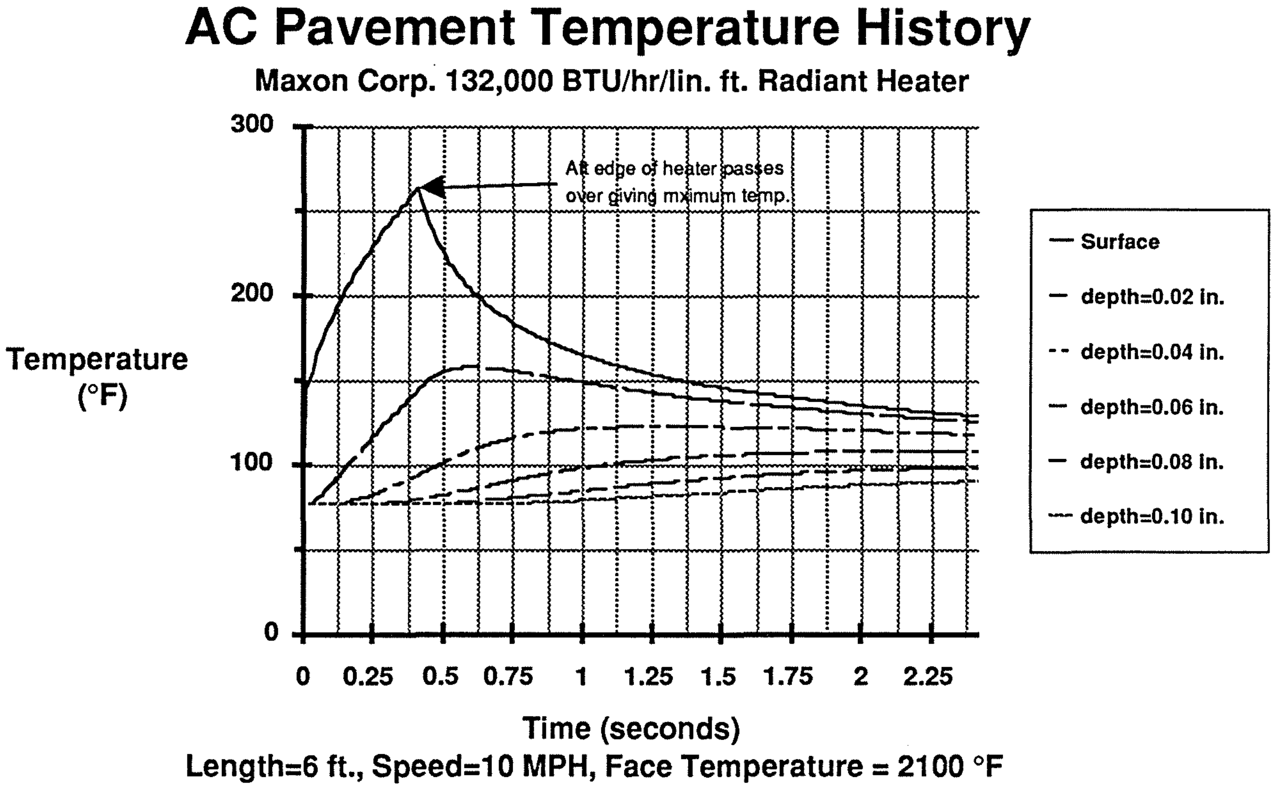


Figure 1.9 - Pavement Temperature History

more compact design based on existing equipment.

Convective Heating

As cited previously, a recent value engineering study surveyed Departments of Transportation from 23 states and concluded that a heat 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 heat lance to heat pavement is effective in lengthening the life span of pavement, there is not available analysis with an estimate of the local heat transfer coefficient which could lead toward the optimization of the heater exit velocity, temperature, and heating time. Such information is necessary to examine the feasibility of using existing heat 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 heat lance systems. Prior to discussion of related literature and the developed model, we will present some background on existing HCA lances.

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 inch diameter stainless steel tube onto the crack to be heated. In doing so, the moisture formed 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 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 speeds on the order of 10 mph. Alternate means of heating must therefore be examined.

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:

$$Nu_D = \frac{h_{conv} D}{k} \tag{1.11}$$

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 burner 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 distance away from the stagnation point on the surface of the material, r/D were studied, and results indicate that maximum heat transfer occurs for a jet-to-plate distance of approximately 6. At any height greater than Z/D of 6, entrainment effects of the surrounding air start to become significant . A plot of the Nusselt number as a function of r/D, the number of diameters down stream from the stagnation point (parallel to the surface), at a Reynolds number, Re_D, of 23,750 was presented. The plot shows the general trend of the Nusselt number which starts at Nu_D=160 at r/D=0 (the stagnation point) and gradually descends to Nu_D=30 at r/D=14. 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. This can be quite a significant issue when modeling pavements.

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, $\Delta T=60°C$ (140°F), the effective heat transfer is significantly decreased. 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 a heat 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 states though, that for large temperature differences, on the order of those sought by use of a heat lance, density changes of the air may play a large role in affecting the energy transfer.

Goldstein and Behbanhani (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:

$$\overline{Nu} = \frac{Re_D^{.6}}{3.329 + 0.273(r/D)^{1.3}} \tag{1.12}$$

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.

Convective Pavement Heating Analysis:

It was desirable to use a model similar to that constructed for the radiant heating to size a burner/heat lance system that can bring the surface up to 250°F with a travel speed of 10 mph. This was accomplished by using Eqn. (1.12) to modify the existing model in order to find the convective heat transfer coefficient, h_{conv}. Due to end-effector space limitations it was assumed that heat transfer effects are only valid out to approximately 5 diameters. It is believed that the extreme mixing that takes place immediately after exiting the burner tube imposes this limitation. Also, blast shields and safety skirts will be placed adjacent to the burner to help contain the heat thereby further limiting the flow. Eqn. (1.12) requires the input of Reynolds number which is expressed as: $Re_D=D^*v/\mu$ where D is the pipe diameter, v is the exit velocity, and μ is the exit gas viscosity. The pipe diameter is known and the viscosity at the average wall temperature can be estimated to be that of nitrogen at 1000°F (the main component of propane exhaust). The velocity however, must be found by combining the rated heater output in BTU/hr, dividing it by the heat of combustion for propane, 21,591 Btu/lbm, and converting it to cubic feet per hour using the ideal gas law to find the density, 0.3519 lbm/cu. ft. (62°F, 30 psi) (Baumeister and Marks, 1967). This number represents the volume flow of the propane exiting the line and entering the burner. Approximately 24 times as much volume of air is needed to completely combust the propane and, since during combustion of propane (C_3H_8), the gases expand twofold (Baumeister and Marks, 1967), the resultant burner exit tube volume flow is estimated as 50 times that of the propane. The velocity is found be dividing the volume flow by the burner tube exit area.

With the Reynold's number for a given burner system then known, the Nusselt number, Nu_D can be determined along the approach and departure of the burner over a specific point on the roadway surface. With Nu_D known, the heat transfer coefficient can be immediately determined from Eqn. (1.11). The surface temperature is then determined from Eqns. (1.4), (1.5), and (1.6) neglecting radiant effects (this is necessary since the emmisivity of a gas is negligible). The resulting model predicts AC pavement temperature as a function of time. Again, FORTRAN code is available upon request.

It is important to again point out that data produced by the model may be in significant error due to pavement non-homogeniety, surface roughness, expansion effects, and ideal combustion estimates. Thus, detailed testing of components is necessary in Phase II of this project.

Results and Recommendations

In order to better understand how burner heat is transferred and to provide a testing facility for Phase II work, a test apparatus was constructed to analyze the surface heating of burner systems. A sample of AC pavement was outfitted with thermocouples and connected to a PC based data-acquisition unit. The lance was then moved across the pavement at constant speeds varying from .3 to .6 ft/s in an effort to ascertain surface heating effectiveness. Preliminary data verified that the HCA lance will not provide the necessary heat at crack sealing speeds necessary for automated machinery.

The developed heat transfer model was then used to size a burner system able to heat the roadway to be as hot as possible while travelling at speeds between 2 and 10 mph. Vendors were contacted and various burner configurations were examined.

It is noted that merely increasing the burner size proportional to the desired speed increase will not solve the problem. This is because heat can only be transferred to the surface via the heat transfer coefficient which is a function of Reynolds number. And, since Reynolds number is a function of diameter, the exit area is important. Thus, a large BTU rating coupled with a small exit area provides the fastest heat transfer.

It is desired to minimize the size and weight as much as possible while maximizing the heat transfer and automation of the process. Commercially available burners and burner control systems were researched resulting in the choice to use a 1.8 million BTU burner by Sur-Lite in Phase II testing. This burner uses high velocity air from a 600 cfm blower mounted on the burner itself to produce a high exit velocity. A flame tube diameter of 5 inches may be used giving the burner the high Reynolds number needed for increased heat transfer. Figure 1.10 illustrates the difference in surface heating temperatures achieveable between a typical off-the-shelf HCA lance and the Sur-Lite burner system.

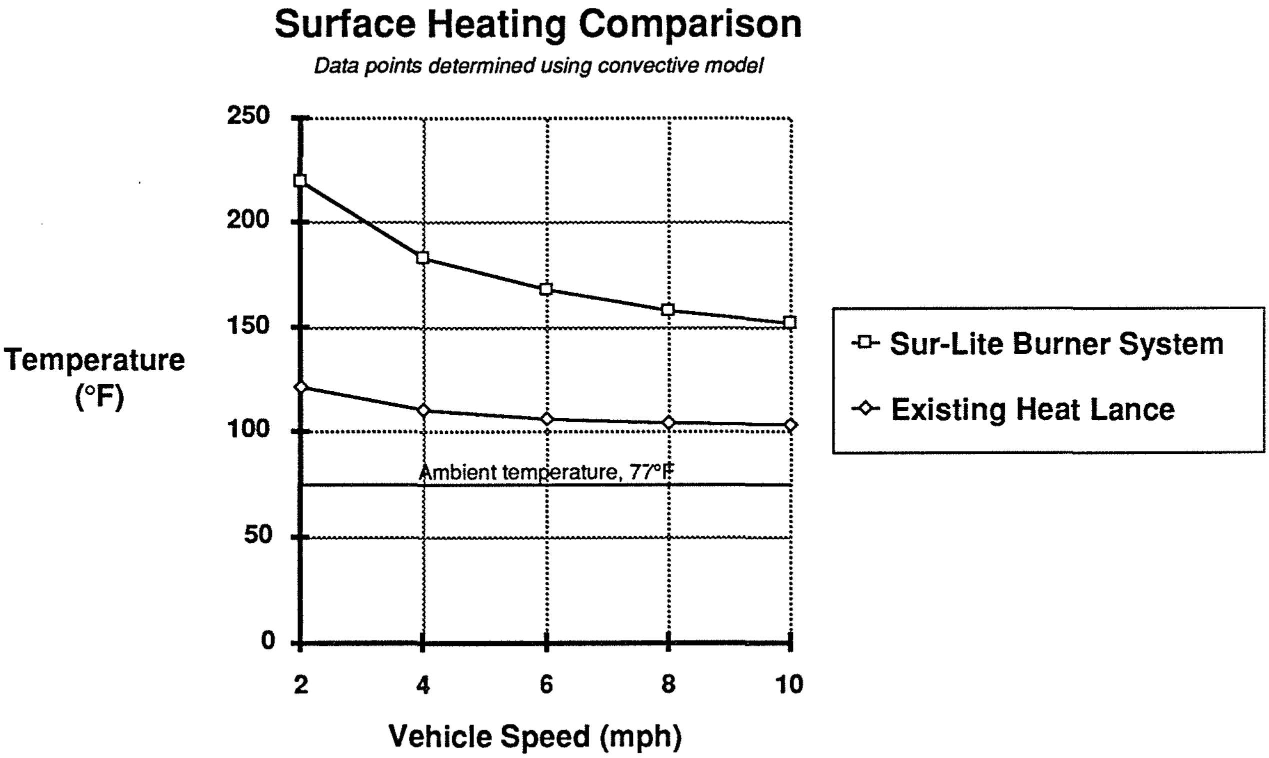


Figure 1.10

Clearly a heater/blower system appears much more feasible for the machinery to be developed than an HCA lance. Thus, in Phase II, we will test a Sur-Lite 1.8 million BTU burner with its own onboard 600 cfm blower. Much additional design details are discussed later in this section.

Sealant Dispensing and Finishing

The SHRP H-106 project is looking at the performance of various materials and procedures used for crack sealing in both AC and PCC pavements. It is obviously beyond the scope of this project to duplicate the efforts of H-106. Unfortunately, recommendations from H-106 will not be made until the machinery development of this project is well underway. As a result, we will continue to stay in close contact with the H-106 contractor (ERES Consultants, Inc.), and we are already employing their expertise in devising our development plan to be discussed later in this section. Every attempt will be made to develop flexible machinery capable of providing a variety of sealing procedures.

There are two broad types of sealant materials that are commonly used for crack sealing. These are thermoplastic materials that can be applied hot or cold and thermosetting materials, that are applied cold. The most commonly applied materials are hot-applied thermoplastics. Materials in this category are representative of materials that have average or above average performance and can be expected to provide three to five years of sealing, if properly applied. The best surface configuration for the sealant on AC is still of major concern. The choices to be investigated in H-106 are a recessed sealant, a flush sealant and an overbanded sealant. Each approach has its advantages and disadvantages and all have been discussed in detail in the literature.

The standard method of sealant material application involves a highway worker walking along the highway dispensing sealant into pavement cracks, usually following another worker who is performing a surface preparation operation (Rossman, et al., 1990). The worker dispenses the sealant in the crack by operating a flow valve attached to the applicator wand of a sealant melter system. This method of sealant application is further complicated by the fact that since the cross-sectional area of pavement cracks are continuously changing, so must the sealant flow rate. Dispensing the proper quantity of sealant is important; enough sealant has to be dispensed to completely seal the crack without overfilling it and wasting material. A secondary tooling operation, generally a type of squeegee, is used to trowel the sealant into the crack and relieve the possibility of over or under filling. However, squeegee's tend to develop a puddle of extra sealant at the end of the crack which is then just methodically spread over the roadway. If the sealant is to be shaped into a desired sealant configuration, this secondary tooling operation is performed before the sealant cools. Depending upon how the squeegee is used and/or shaped, it can produce either a flush sealant configuration or an overband. Flush configurations are easily created by pushing the squeegee flat along the pavement, whereas an overband configuration will result from either tilting the squeegee forward or trimming the rubber sides of the squeegee up from the pavement.

Automatic sealing equipment moving at considerably higher speeds than manual operations will correspondingly need to dispense sealant at flow rates far greater than the current practices. Research has been performed by the UC-Davis/Caltrans Advanced Highway Maintenance Technology (AHMT) program to evaluate the feasibility of a high speed dispensing devise for the application of reflective roadway markers. The main goals of the experiment was to evaluate the forces required to dispense viscous materials (sealant) and to determine the maximum material dispensing velocity without splashing. A rapid delivery sealant pump testing fixture was designed and fabricated at UCD to verify the analytical models. Details of this device were presented in a previous quarterly report. Information gained from this research will be quite useful for sizing piping, valves, and pump horsepower for the SHRP H-107A sealant dispenser. Figures 1.11 and 1.12 illustrate the relationship between nozzle diameter and the required sealant velocity for two popular routed sealant configurations (.2" deep by 1.5" wide, and 1.0" deep by 1.0" wide).

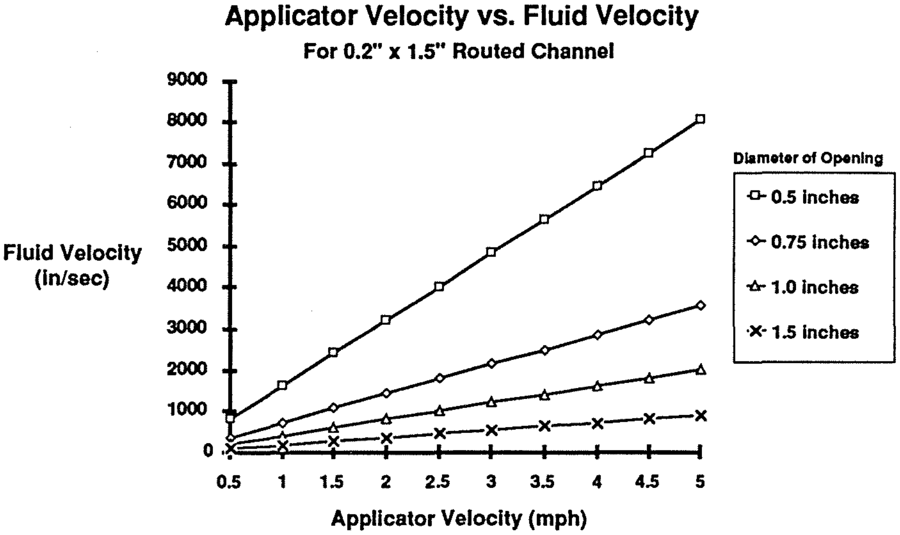


Figure 1.11

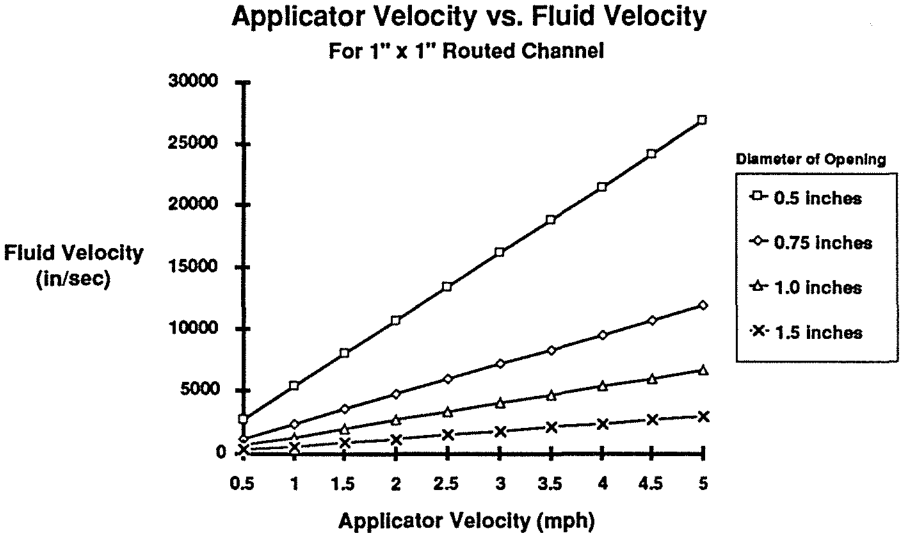


Figure 1.12

Splashing occurred when the sealant was applied to the pavement at velocities between 600 and 750 in/sec. The specifics of the actual sealant viscosity, which ranged between 30 and 60 poise, and geometry of the nozzle resulted in a range of critical splashing velocities. Appropriate sealant pump sizes were evaluated to determine the force required to dispense the viscous sealant according to the following expression:

$$F = (32 \text{ m L n } A_p) / d_o^2 \qquad (1.13)$$

where: F = Required force [lb],
m = Material viscosity [lb-sec/in^2],
L = Length of applicator tube [in],
n = Bead feed-out velocity [in/sec],
A_p = Cross sectional area of plunger [in^2], and
d_o = Applicator tube diameter [in].

One of the goals of the SHRP-107A automated applicator system is to increase the sealing rate which can be obtained by increasing the applicator surface speed. This increase in surface speed will require higher sealant flow rates. Therefore, calculations were performed to determine reasonable surface speeds based upon reasonable sealant flow rates. Figure 1.13 shows the sealant flow requirements as the surface speed of the applicator is increased for the two routed sealant configurations used in the above calculations. Most common sealant melters supply about 5 to 10 gallons per minute of sealant at the applicator nozzle. Examination of the figure clearly illustrates the advantage of the 0.2 inch deep routed channel due to the realistic sealant flow rates at higher surface speeds.

The results of this testing in addition to communication with vendors of a variety of pump related equipment were used in developing the sealant application system to be discussed later in this report.

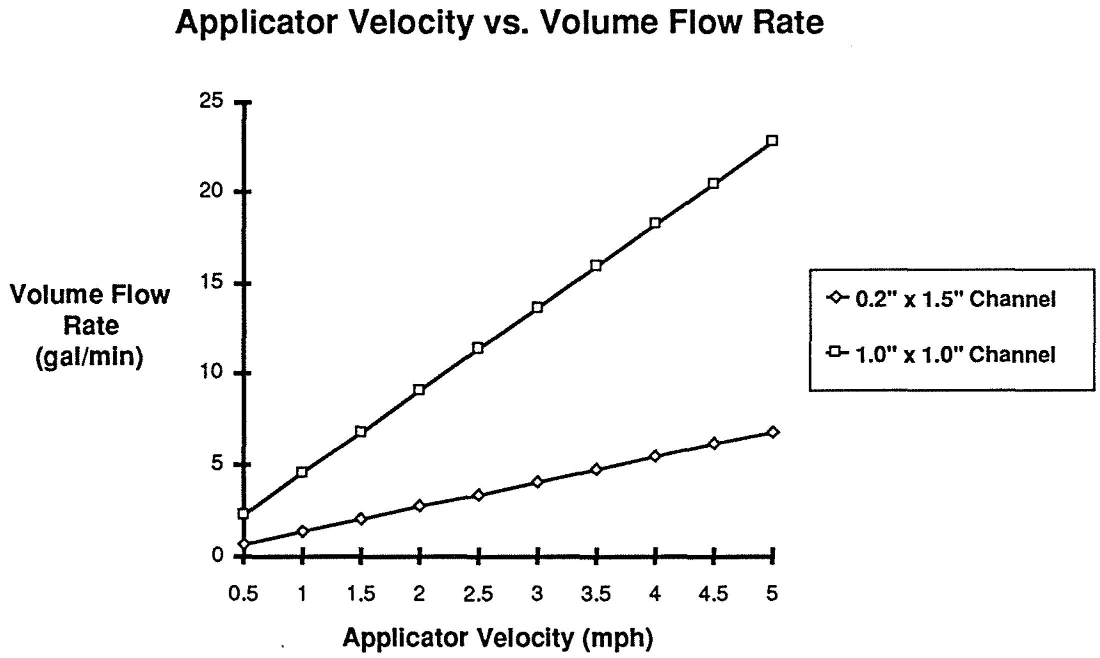


Figure 1.13

Applicator Positioning Feasibility

In order to seal cracks in the pavement, it will be necessary to position the various machine components relative to the roadway, and it is desirable to do so in an automated fashion. Rather than point to individual studies to ascertain feasibility, we note that robotic positioning is widely used in a tremendous variety of industries and applications, and that entire conferences and journals exist for purposes of disseminating information in this area; e.g., IEEE Journal of Robotics and Automation, International Journal of Robotics Research. Additionally, several of the personnel have considerable experience on both basic robotic research and practical application of robotic and automated machinery as discussed in the original proposal. As such, in this subsection, we will note some of the developed criteria for the choice of a robot postioning concept for the automated crack sealing application. In a later section, we will discuss our choice and the positioning system concept.

The design goals of the positioning system are summarized to follow:

- For sealing/filling of random and transverse cracks/joints, the positioning system shall provide the capability to operate on one lane width (approximately 13 feet as there are actually a significant number of lanes with greater than 12 foot width) of road surface.
- In general, the system shall allow for motion with at least the two degrees of freedom of the road plane in order to follow random and transverse cracks.
- A goal of the designed positoning system should be its capability to operate on the road surface with the support vehicle operating in both batch (stop) and continuous (go) modes.
- The positioning system shall provide the capability to perform concurrent parallel operations on an individual crack. That is, it is undesireable, and would greatly reduce the machine's productivity, to have a portion of the machine sitting idle (e.g., dispenser) waiting for another component to complete its task (e.g., router).
- For longitudinal sealing/filling, the positioning system shall provide the capability to operate on the road surface at speeds on the order of approximately 10 to 15 miles per hour. While this exceeds the specifications provided through the SHRP Equipment Development Plan, we feel that such speeds are possibly attainable for the simpler operations (e.g., unrouted sealing).
- The positioning system shall be flexible and allow for crack/joint preparation methods as specified by H-106, in addition to the seal/fill types of configurations specified by H-106.
- The machine shall be rugged and stable. It shall also be capable of properly maintaining the position of the variety of components that it will move while being subjected to physical disturbances (i.e. road bumps and curves, vibration, speed fluctuations, etc.).

- The machine shall have the capability of converting from the "road travel" configuration to the "crack/joint sealing" configuration in a minimum amount of time.
- In the event that the machine has two positioning systems, one to address random and transverse cracks/joints and the other to address longitudinal cracks/joints, the two positioning systems should be compatible in that components could be mountable on either system. Furthermore, they should be compatible in that they could both be mounted on the same platform.
- The machine shall be comprised of as many commercially available elements as possible.
- The positioning system shall be capable of being mounted on a common commercially available platform.
- It would be desirable to have a single self-contained machine; i.e., a trailer mounted positioning system is undesirable.

Integration and Control Feasibility

All operations of the automated crack sealing machine will need to be integrated and managed by some form of control system. This control system needs to coordinate, and sometimes initiate information and control flow between the separate systems of the machine. The control unit, therefore, acts as a liaison between all subsystems of the machine which otherwise would act independently. In addition, the control system must perform in an efficient manner such that the machine will operate at its intended speed.

It is apparent that a centralized control system is a necessity and this system will henceforth be referred to as the Integration and Control Unit (ICU). Specifically, the ICU will be required take crack location information from the vision subsystem and translate that information into a usable path configuration based on the changing orientation of the vehicle. Thus, the ICU will execute path planning and updating algorithms necessary for accurate crack/joint sealing/filling. The Control System will also interact with the components that position the various machine end-effectors such as routers, sealant dispensors, etc. This system will also need to synchronize the motions and timing of the various components to maximize speed and avoid interference.

Before a discussion of general requirements is initiated, a note on the ICU development philosophy is in order. The most common remark made by research managers, researchers and vendors questioned about the ICU requirements for this project was that "it's good to see the integration of all subsystems considered at the beginning, rather than at the end of a project". The second most common remark suggested that the acquisition of the most robust, flexible development system at the beginning of the project would save a lot of trouble at the end of the project, once all project tasks are actually revealed. This seemingly over specified system is commonly referred to as the "Mother System" and offers true flexibility throughout the duration of the project. In addition, Stankovic (1988) recommends flexible development and target systems for any real-time project. Since making the application fit the system causes integration problems, it is necessary to obtain a flexible system that matches the application. Each real-time application is specialized and the control system architecture needs to be similarly specific; e.g., see Arnold, et al. (1982), Bemmerl (1989); Bromley (1990), Civera, et al. (1985); Conte, et al. (1985); Eck (1989); Evesham (1990); Stankovic (1988); Zalewski, et al. (1989); Zimmerman (1990). These noted references include examples of various bus-types, operating systems, number, type and location of processors, and software approaches available. Conte, et al. (1985) conclusively show that multiprocessor systems have advantages over high speed and high power monoprocessor systems. Multiprocessor systems, then, require compatible bus structures. Analyzable and modular operating system and software approaches are similarly necessary for efficient implementation. The use of embedded or real-time controllers in such complex projects as the Space Shuttle primary avionics system and advanced control (Carlow, 1984) of thermal power plants led to well documented and tested application-specific pros and cons of each of the above system variables.

With these comments in mind, the ICU team went on to assess, recommend and purchase a "mother system" for the crack sealing machine. The recommended system is considered by many in the industry as a standard for real-time integration and control development.

General Requirements

In order for the ICU to complete the previously mentioned tasks, as well as other undefined tasks, in a manner that allows for reliable operation of the entire crack sealing operation, the following general requirements need to be fulfilled. These requirements are based on information gathered in an extensive literature review as well as many discussions with researchers pursuing similar projects and vendors who manufacture and distribute integration and control equipment.

The ICU should be computationally fast and efficient. For an application such as automated crack sealing, where almost all subsystems are dependent upon the action of other subsystems, an immediate response to unfolding processes is essential. In addition, there is a need for the ICU to be able to recognize and process prioritized interrupts, as each subsystem is assigned a level of importance. There is also a need for rapid processing of concurrent information, for which the operating system must be capable of handling concurrent multiple tasks. This feature is called multi-tasking.

The ICU should have sufficient spare capacity to provide for flexibility to expand during all phases of SHRP H-107A. As the selection of the ICU will precede the final definition of some subsystems and their relationship with the ICU, the chosen system will need the flexibility to expand in order to accommodate any unforeseen computing tasks. To this end, the system should support multiple processors which would allow functionally separate parts of the software to either run concurrently on the same processor or move to separate processors if processing constraints become critical. In addition, an expandable backplane is necessary to accommodate increases in hardware needs.

The ICU will need to be modular in both hardware and software design. Modularity is of paramount concern when integrated and controlling many subsystems. The interdependences of each subsystem and the overall system complexity increases rapidly with the addition of each new subsystem.

The application software should be developed in an environment that is user friendly and common to many programmers. The environment consists of both the operating system and the platform in which the operating system resides. This software development environment can be different from the ICU environment, as many programming features are typically eliminated from the latter in order to attain faster processing speed. In addition, the code that controls the machine operation should be developed in a high level language which is also common to many users and can be ported to a variety of different development environments. Additionally, the complete system software should be ROMable to enable an embedded application. In other words, the ICU operating system and developed code should be stored and operated from an integrated memory circuit or chip on the target hardware (the environment that resides on the machine) rather than the hard disk drive that was used during the software development.

The vehicle mounted ICU needs to be rugged enough to operate in a hostile environment including the shocks and vibrations typical in heavy equipment, ranges of operational temperatures and rapid changes in humidity. The selected hardware will need to be reliable during the extreme conditions encountered during the crack sealing operation. Placing code in ROM will contribute to the ruggedness of the ICU.

Finally, compatibility with other Caltrans/UCD in-house development efforts and expertise is an important consideration. Caltrans is investing considerable time and effort in the development of advanced traffic surveillance and information systems, both of which have most of the requirements listed previously; i.e., large amounts of information from many different sources processed very quickly in a very hostile environment. The AHMT program at UCD also has two similar projects under development by subcontractors that deal with the acquisition of information from the highway. Both projects utilize very fast integration systems to conduct quick processing of large amounts of information in order to control other tasks.

System Recommendations

Definitive control of a real-world, real-time environment is best done with a real-time operating system running on an embedded controller. A real-time operating system is a computer operating system which has the capability to handle time-critical processes with a minimum response time. In addition to being efficient, the real-time operating system can be priority-driven for process scheduling, (differing subsystems maintain differing priorities), and can process concurrent multiple tasks or multi-task. Dedicated embedded controllers are involved in the monitoring and control of real world systems, processes, or other information systems, in an on-going basis.

From the general requirements, a suitable ICU computer architecture might consist of a real-time operating system running on a backplane composed of a modular bus system with ruggedized connectors. This target hardware should be linked to a development environment consisting of a workstation. The workstation will be used to develop code that the target hardware executes.

The wide variety of available dynamic systems that satisfied this general recommendation prompted the Integration and Control team to systematically evaluate seven options, ranging from the well known and utilized PC/AT bus system to the very high-speed VME Bus or MultiBus system. Each system was evaluated in terms of twenty-two individual criteria. These criteria included items such as bus transfer rate and size, number of interrupt levels, whether or not the system had multi-master arbitration, backplane capacity, system ruggedness, system costs, and delivery dates. Compatibility with other defined subsystems and other AHMT projects was also a very important consideration in selecting the final system design.

The VME system bus architecture utilizing a real-time operating system was selected as the most desirable based on all considerations and requirements. Based on compatibility with other subsystems, ruggedness, bus transfer rate, multi-processing capability, and compatibility with other AHMT projects, the Single Board, Smart I/O, STD Bus, PC/AT, and MultiBus options were eliminated. The VME Bus and PLC configuration were the most competitive. The PLC configuration falls short of providing real-time processing at the current time and was thus also eliminated. In addition, the vision subsystem currently utilizes the VME bus Architecture with a real-time operating system.

The VME system bus option appears to be the only solution to the strict requirements of this real-time system. The VME bus is also the only system to satisfy all requirements developed for the Integration and Control Unit. The VME bus provides the highest bus transfer rate, is rugged enough to perform in the maintenance vehicle environment and is a truly flexible system. The VME bus provides the flexibility, compatibility, modularity, and multi-processing necessary for the efficient operation of the ACSM. Based on this assessment, the ICU team recommends the use of a VME bus architecture with a real-time operating system.

Several real-time operating systems currently exist and can run on the VME bus. The global vision subsystem (to be discussed later) utilizes the OS-9 operating system, considered a real-time multi-tasking standard. OS-9 is recommended as the operating system for the VME bus because it is increasingly accepted as a standard, and complies with the requirement to be compatible with other ACSM subsystems and other AHMT and Caltrans projects.

The OS-9 operating system available on the target hardware sacrifices tools and programming 'friendliness' for fast execution. Other operating systems include all the programming "bells and whistles" at the cost of speed. The best of both worlds can be achieved by linking a friendly development platform to the fast OS-9-based target system. A UNIX-based operating system on an Apollo workstation for example, allows for easier and faster program development and debugging and provides function libraries. Also, a workstation would allow multiple programmers to work simultaneously. The finished code developed on the workstation would then be downloaded to the target hardware (the VME-based system) via a cross compiler. This cross compiler interfaces the UNIX-based.system with the OS-9 system on the target hardware. Again, based on much discussion with experts on real-time software development, the ICU team recommends the UNIX operating system to reside on a workstation as the software development platform. A cross compiler will be needed with his configuration.

It is also recommended that the application software be written in the "C" language. This high-level language generates very efficient code and allows access to the machine hardware. Also, "C" offers the most flexibility to move from one development platform to another and is an industry standard for real-time system implementation. "C" is also a common language for most computer programmers.

Specification for the central processing unit (CPU), system memory including ROM and RAM, flexible, hard and tape drives and all input and output will follow the program philosophy for the "Mother System". These are critical specifications, as system capacity and capability rely on the selection of correctly sized components. During the specification process for the aforementioned items, attention was given to perceived needs and system costs, as well as incremental costs for stepped up components which would allow more flexibility. The following list of component requirements were then generated and currently stand as recommendations.

CPU

Processor:	Motorola 68030, 50 Mhz
RAM:	4 MBytes DRAM, 128 Bytes non-volatile RAM
ROM:	2 MBytes ROM
Other:	VSB compatible bus interface, SCSI interface

INPUT / OUTPUT

Analog:	12 bit A/D, D/A conversion, 16 channel input, 4 channel output
Digital:	48 bit: 4 bidirectional 8 bit ports and 2 unidirectional 16 bit ports

Comm: Ethernet communication card, 4 RS232 ports, 1 parallel port

SOFTWARE

Real-time Operating System:
OS9 Professional, system state debugger, source level debugger
Device Drivers: M6800 Industrial I/O routines to control I/O modules

MEMORY

Hard drive: 60 MByte embedded SCSI drive
Floppy drive: 2 MByte 3.5 inch drive
Tape drive: 150 MByte 1/4 inch archive streamer

ENCLOSURE

Type: Rackmount
Height: 17.5 inch
Card Cage: 12 slot
Power Supply: 500 Watts
Bus: VME

CABLING & CONECTORS

Ethernet cabling package including:
Ethernet transceiver
Transceiver cable
10 feet Thinnet cable
T-connector and terminators

As a final note, most contacts stressed the importance of finding a reputable systems-house to incorporate the target hardware and operating system, and to deliver a "turn key system". The preceding recommendations for both hardware and software should be integrated by the systems-house and delivered with full warranty on individual components as well as the complete system. All software drivers should be written and each component integrated much the same way a systems-house puts together a personal computer. This will eliminate considerable development time, as there are many considerations when integrating various computer boards, some of which are developed by different manufacturers.

DEVELOPMENT PLAN

The objective of this project is to develop, fabricate, test and demonstrate prototype equipment that will perform joint and crack sealing/filling in concrete and asphalt pavements. Desirable improvements would be in the direction of enhanced speed, efficiency, quality, and safety. It is believed that the development of an automated crack/joint sealer with the above-noted improvements is feasible. Such a machine would operate at least at the speed for currently available more labor-intensive methods, and would perform to the quality level widely obtainable by such methods. Because the equipment would be self-contained and automated, it would reduce the exposure of maintenance crews to traffic, thereby also resulting in enhanced safety.

While the feasibility study presented above has examined many of the current practices, it is not an objective of SHRP H-107A to identify whether sealing cracks or joints makes sense, nor what the best method is of performing these maintenance operations. These issues have been addressed in the past, and two other SHRP projects are also addressing these issues. In SHRP H-101, the *effectiveness* of crack sealing in asphalt concrete (AC) pavements is being studied to see if sealing cracks improves the performance of the pavement in comparison to similar pavements without sealed cracks. SHRP H-101 is using more or less standard materials and procedures to seal these cracks. SHRP H-106 does not address effectiveness of crack sealing at all, but looks at the *performance* of various materials and procedures used for crack sealing in AC pavements and joint resealing in PCC pavements.

Therefore, between H-101 and H-106, it may be determined whether or not crack sealing is an effective maintenance technique and what materials and procedures work best in sealing a pavement. These two projects are field experiments, however, whose results may not fully be known or analyzed in the next 3 years. This is long after H-107A will be completed. How can H-107A proceed, then, to ensure that it speaks to the issues of the RFP while avoiding built-in obsolescence should the results from the other SHRP research efforts point in a different direction? This portion of this report suggests a development plan that simultaneously addresses the objectives of this project and avoids obsolescence of the resulting product. While some of the material is repetitious, this part of the report also summarizes the findings of the earlier feasibility study. While H-107A is not directly evaluating the crack sealing operation, we have elected to examine the currently used machinery and techniques, which are inherently linked, in order to develop the best, and most versatile, machine. As such, in the above feasibility study, we have recommended existing devices that we feel are suitable for an automated machine, and additionally, we have discussed specific developments that would enhance performance.

Assumptions

The developments in H-107A are based upon several key assumptions that bear discussion. Because of the state of flux of pavement sealing technology, it has been assumed that it is inappropriate to try to develop from the start a piece of equipment that is able to use the most innovative materials and procedures to seal cracks and joints. Instead, a modular approach is being taken to the development of the equipment that will allow, without excessive cost or rebuilding, the addition or substitution of different elements of the equipment, each of which represent different activities in the sealing process. The modular approach is central to the success of the project. It removes the emphasis from guessing what the most successful materials and procedures will be and allows the focus of this project to shift toward the general operations, the automated sensing of cracks, and the mechanical operations.

In discussions with SHRP staff, it has been confirmed that the crack sealing vision system need not be able to identify when to seal cracks. This type of information would likely come from an automated distress survey, and it might be in the form of "crack sealing needed between MP xx.x and xxx.x." Thus, it is likely that a decision would already be made based on the existence of the right type of cracks, and the machine itself would not have to differentiate between alligator cracking, fine transverse cracking, and/or other conditions that might not be appropriate. What remains to be determined then, is the type of decision system that would be used to identify the suitability of a section of pavement for this type of equipment. It also must be determined whether the vision system would need to identify localized areas that should not be sealed in a general section that is being sealed.

There are perhaps five types of pavement sealing that must be addressed by the prototype equipment developed in this project. These are:

- AC/PCC longitudinal crack sealing.
- PCC longitudinal joint sealing.
- PCC transverse joint sealing.
- AC transverse crack sealing.
- PCC transverse crack sealing.

The longitudinal sealing operation is perhaps the easiest and fastest to perform. Longitudinal cracks and joints tend to be uniform, occurring as reflective cracks above longitudinal joints in PCC pavements, as cold joints between separate passes of an AC paver, as a longitudinal joint itself in a PCC pavement, or as the longitudinal joint between a mainline PCC pavement and the adjacent shoulder. The area to be sealed in these cases is very straight over a comparatively long distance, and locating and sealing the joint/crack are simple activities. Preparation consists of either sawing or routing to form a reservoir and cleaning out the reservoir prior to application of the sealant. With only a few exceptions, very little movement is expected at these joints, which makes sealing them well an easier task than other sealing activities. The longitudinal sealing operations, when performed using current practices, is the fastest of the five.

PCC transverse joint resealing is only slightly more difficult. In PCC joint resealing, a straight reservoir is located at regular intervals or in a regular, repeated pattern. These are easily identified, are found in known locations, and are expected to be straight. Preparation prior to resealing can include routing, sawing, and plowing to remove debris and old sealant, and water blasting, sand blasting, or air blasting to prepare the joint for new sealant. Prior to placement of the sealant, the placement of a backer rod may be specified in order to achieve a desired shape factor. The sealant, when placed, may require tooling at the surface or the material can be self-leveling.

Because joints are built into the pavement and are not a defect, expectations for sealant performance are greater here than in other applications. Typically, these will be more highly engineered and thus more care is taken in the design, selection of materials, and construction of resealed PCC joints. It is assumed that a project would be identified as a suitable candidate for joint resealing by some other means.

AC crack sealing is the most complex operation of the five to be addressed in this project. PCC crack sealing is similar, but it is performed much less frequently. There are many different types of cracks that are present on a pavement surface. They are rarely uniform in width or spacing, follow random patterns, and can change in nature (e.g. from tight to wide or from clean to spalled) from one location to the next. Because of the many variables associated with AC crack sealing, we will devote a significant part of our initial research efforts of towards this method. Additionally, since longitudinal operations are the fastest and simplest, we will concurrently address this operation. By employing many of the same components for these two operations, we will clearly show the modularity of our machine, and the potential to address all other types of sealing which fall in between in terms of difficulty. It is believed that adaptation of automated crack sealing equipment to the other operations is a trivial event in comparison to the challenge associated with the automated sealing of cracks in AC pavements. The rest of this document more narrowly defines characteristics of the AC crack sealing operation that are believed to be important in defining the abilities of the prototype equipment.

Crack Sealing Approach

There has been a significant amount of research time and effort spent on identifying the appropriate means of sealing cracks; e.g., Blais, 1984; Belangie & Anderson, 1985; Chehovits & Manning, 1984; Chong & Phong, 1984, 1987; Turgeon, 1989; Smith, et al. 1991; Wolters, 1973. The following discussion applies some of the findings of the above-referenced research studies, concentrating on those portions that apply to the sealing of cracks in bituminous pavements. It should be noted that the greatest body of research on this topic has been conducted, with a few exceptions, in regions subjected to fairly harsh winters (Utah, Minnesota, Ontario, Delaware, Georgia, Montana, and Tennessee) and, in most cases, excessive moisture. Their findings must be considered as representative of conditions in which the environment has the most severe effect on pavement performance.

Causes and Development of Cracks

Cracks in AC pavements are caused by many different factors. In general, causes can be divided into load-related cracks, environment-related cracks (temperature, moisture), pavement materials problems, and cracks caused by failures associated with the existing subgrade. While the causes are certainly of interest, the types of cracks that should not be sealed are adequately identified through the specification of other criteria, such as crack width, orientation, volume, and density.

If there are too many cracks, it is both uneconomical to seal them, and unsound from an engineering standpoint. Generally speaking, too many cracks are indicative of a pavement in an advanced state of deterioration. At that point, the pavement is more likely a candidate for major rehabilitation or reconstruction. This approach eliminates from consideration a pavement with fatigue or alligator cracking, or one with serious block cracking. Even a pavement that exhibits primarily transverse cracking may be ruled out as a candidate for sealing if the cracks are too closely spaced or excessively wide. One study recommended that pavements with cracks closer than 25 ft should not be considered for crack routing and sealing because that would indicate a later stage of deterioration in which crack sealing would not be effective in prolonging pavement life (Chong and Phang, 1984).

Crack width

It is generally recognized that there is a range of crack widths within which crack sealing is practical. Extremely narrow cracks are not considered suitable candidates for several reasons. Generally, they are not a major source of moisture infiltration for a pavement. Also, substantial routing or sawing would be required in order to make narrow cracks wide enough to place sealant material within the crack. Such routing would unduly damage the pavement when the cracks are so narrow. Very narrow cracks are also difficult to track on a pavement surface, further supporting the contention that they are not yet candidates for sealing.

On the other hand, cracks that are too wide tend to be indicative of more serious problems. They most likely extend through to the bottom of the pavement and will have significant movement associated with them. With such movement, most available sealants will not last very long. Furthermore, by the time such a crack is found, distresses associated with the presence of excess moisture may have started to develop.

Studies which specifically addressed crack width as a sealing criterion were fairly consistent in their recommendations. Chong and Phang recommended that cracks between 6 and 12 mm (approximately 0.25 to 0.5 in) were candidates for routing and sealing; narrower cracks were to be left alone and wider cracks were simply to be cleaned and sealed (Chong and Phang, 1984). The Value Engineering study of crack sealing recommended that cracks wider than 0.19 to 0.25 in were to be sealed, although no upper limit was recommended (Belangie and Anderson, 1985). Utah recommended that cracks between 0.19 and 1.0 in wide were candidates for crack sealing (Blais, 1984). A review of the available literature on the topic suggests that cracks between 0.20 and 0.60 in wide be considered as suitable for sealing by the automated sealant equipment.

Crack Length

Cracks should be of sufficient length to justify sealing. For transverse cracks, this means that they will run most of the width of the pavement. Interconnecting cracks, such as primarily longitudinal-diagonal or longitudinal cracks, will also be sealed if sufficiently long. In combination with the crack width criteria, it is believed that a minimum length of 3 to 6 ft is appropriate. Shorter cracks should be avoided because they are either in the process of becoming longer cracks or because they will most likely be narrower and have associated with them less movement. Sealing will not stop the further development of a crack that is not fully formed. The crack will continue to develop and the sealing effort will have been wasted, as a crack that is only partially sealed will not keep moisture out of a pavement.

Random Crack Orientation

It is believed that most of the cracks for which automated crack sealing is a viable alternative will run primarily transverse to the direction of travel. There may be some diagonal cracking or longitudinal cracking (other than those located at seams and joints), but generally transverse cracks occur several years sooner than other cracks and would therefore need to be sealed sooner. Thermal cracks, with which are associated the greatest amount of movement, also generally run in a transverse direction.

Reservoir Dimensions

The shape of the reservoir has a large effect on sealant performance. The shape is characterized through the ratio of the sealant depth to reservoir width, also known as the shape factor. The desired shape factor is a function of the type of sealant selected and the expected movement at the crack. A variety of approaches are used for both rubberized asphalt sealants as well as for silicone sealants. Low profile channels have received increased attention with popular dimensions being 10 mm deep by 40 mm wide and 0.2" deep by 1.5" wide.

Crack Preparation

Most studies have recognized and emphasized the importance of the proper preparation of the crack. The first step in the preparation of the crack calls for the removal of loose materials from the crack and the creation of the properly-dimensioned reservoir to accept the sealant. Routers are probably the most commonly used equipment to perform this function for cracks in AC pavements.

Routers are relatively quick and very maneuverable, which allows them to be able to closely follow a meandering crack. Routers will produce some spalling along the edges of the crack, but generally not enough to create any problems for the application of the sealant. While saws provide a more uniform and perpendicular cut, routers are generally preferred for cracks because of their maneuverability. Vertical spindle routers cause less spalling than rotary impact routers, but are much slower than the rotary routers. The use of carbide-tipped bits on the rotary impact router helps to mitigate the spalling.

We should note that some controversy exists relative to the use of routers for reservoir creation and this has been discussed earlier. While we do not expect to resolve this issue, the modularity of our machine will allow operations with or without the use of routing. Additionally, the automation of the operation may have a significantly positive effect on the cost-effectiveness of routing.

Reservoir Cleaning

The crack reservoir must be clean and dry prior to placement of the sealant. A number of methods have been used to clean cracks in a sealing operation. Air blasting can be used to clean the reservoir faces, but is not successful in removing any laitance or material bonded to the reservoir face. A hot compressed air (HCA) lance, or heat lance, not only delivers air under pressure, the air is also hot enough to dry out moisture in the crack and the adjacent pavement.

As noted earlier, there are several other methods that are available for crack preparation. Sand blasting and shot blasting have the advantage of being abrasive enough to remove laitance on the reservoir face. Compressed air blasting is still required after their use, however, to remove the dirt and material left by those cleaning methods. In the use of sand or shot blasting, there are additional safety precautions that must be followed.

Water blasting has seen some use, but is not really appropriate for AC pavements. While it may be useful to prepare concrete pavements, it also leaves the pavement wet, and most sealants cannot be applied until the pavement is dry. Safety is also a major concern when using water blasting. Crack saws have seen increasing use for reservoir preparation. The technology has not been totally successfully applied to cracks because of the difficulty in following their meandering path.

The HCA lance is probably the best compromise of existing devices for cleaning out the material from the crack since it also serves the dual purpose of drying out the crack and adjacent pavement. To automate the use of existing hot-air lances would require extensive modifications, and thus, a new form of heat lance will be proposed as part of this project. With the use of a heat lance, it is essential that the pavement not be overheated, and care should be taken not to burn the pavement, nor to drive off too much of the light fractions of the asphalt.

Material Type

There are two broad types of sealant materials that are commonly used for crack sealing. These are thermoplastic materials that can be applied either hot or cold, and thermosetting materials, that are applied cold. The most commonly applied materials are hot-applied thermoplastics. Materials in this category are representative of those that have average or above performance and can be expected to provide 3 to 5 years of sealing if properly applied.

Sealing Configuration

A major issue in crack sealing for asphalt pavements is the surface configuration of the sealant. The choices are a recessed sealant, a flush sealant, and an overbanded sealant. Each approach has its advantages and disadvantages and these have been discussed in detail in the literature.

Summary and Plan

The sealing of cracks and joints in both AC and PCC pavements has been extensively researched in the past, and it is not within the scope of H-107A to try to ascertain the best method to seal pavements. For the purposes of this project, the automated equipment should incorporate sealing methods and materials that are in widespread use and have been shown to be effective. The developed equipment should enable the prototype to be fairly adaptable, so that findings from H-106 and perhaps other research can be used to modify the equipment should that be deemed necessary.

As such, we have developed a hierarchy of crack sealing operations in terms of difficulty in order to limit the functional requirements of the prototype machinery. The easiest and most difficult operations are longitudinal AC/PCC sealing and transverse crack sealing, respectively. These two operations have been chosen as those that the prototype machinery should address. Furthermore, due to their many unique features and the fact that they are sealed much more frequently, we have elected to address AC transverse crack sealing initially. By developing machinery to address the "upper" and "lower" bounds in terms of difficulty, we feel that the modifications necessary to address other types of crack repair will be relatively minor involving such things as providing different types of end-effectors. By developing machinery to address the "easiest" and "most difficult" operations, the feasibility of the machinery to address any other operations should be clearly established. Finally, the two operations noted are quite common and thus, such machinery has the potential to find widespread application.

Along these lines, the following list summarizes the initial functional requirements of the prototype machinery to be developed under SHRP H-107A:

- The machine shall operate on cracks that are between 0.2 and 0.6 inches wide.
- The machine shall operate on cracks that are at least 3 feet long.
- The machine shall have the ability to prepare a crack reservoir with a router.
- The machine shall clean and heat the reservoir with some form of a hot air lance.
- The sealant material will be a hot-applied thermoplastic.
- The sealant should be placed approximately flush with the surface of the pavement.

MACHINE SYSTEM ARCHITECTURE

With consideration of the range of activities required of an automated crack sealing machine, a general machine system architecture has been devised. In addition to the support vehicle itself, the total machine includes seven systems. A block diagram of the total machine architecture including block diagrams of the individual systems is included in the following pages after a short description of each system.

Integration and Control Unit (ICU): The ICU will act as a clearing house for all information flow. Many of its functions are listed in the block diagram. Fundamentally, this unit includes the ability to communicate with all the systems and the ability to process the information. The ICU oversees the entire operation and coordinates the activities of the other subsystems. The information forwarded from the Vision Sensing System (VSS) will be translated into a planned path for the Applicator and Peripherals System (APS) components (crack/joint preparation equipment, etc.). Thus, the ICU will include the necessary algorithms to plan a crack/joint sealing path. If multiple end-effectors are employed, the ICU will need to first allocate cracks to the individual applicators and will do so in a manner to maximize speed and avoid interference. This system will keep account of the actual position of the total machine and its components by interacting with sensors on the Robot Positioning System (RPS). It will additionally monitor the APS to ensure adequate volume and temperature of sealant/filler, air, etc. Following the planning of the appropriate path(s), the ICU will control the motion of the applicator(s) with the interaction of the Local Sensing System (LSS) and it will additionally control the individual applicator functions.

System Display Unit (SDU): The SDU provides for any interactions with the machinery operator. It will provide information on the machinery status, and it will allow for the operator's inputs to the ICU. It is unrealistic to expect that the integrated machine will work with no operator involvement. As such, this system will offer the operator a convenient means for inteacting with the machine.

Vision Sensing System (VSS): This machine vision based sensing system will be capable of viewing the entire width of the roadway and providing crack information (location and orientation) to the ICU in sufficient detail so that crack preparation, sealant/filler application, and shaping can be performed automatically. This system includes camera, image processing equipment, and necessary supplemental lighting. The VSS will be provided vehicle position and speed information from the Vehicle Orientation and Control System (VOC). This will be necessary in order to accurately determine relative crack positions. Information from this system will be used to plan the path of the APS's end-effectors in the ICU.

Robot Positioning System (RPS): The RPS will position the APS end-effectors according to the path planning information provided by the ICU. The path dictated by the ICU will include both positional and speed information. The RPS will have sensors that will feed back actual speed and position information based on joint coordinates and velocities in order to modify trajectories in the ICU according to additional information including vehicle speed, etc. The RPS also positions the Local Sensing System.

Local Sensing System (LSS): The LSS will be a laser range finder based system, and it will be initially used to verify the presence of cracks identified by the VSS. During Phase II of the project, we will experiment at integrating the LSS in an alternative system architecture that will allow for the LSS to particpiate in the APS path. Such an approach has the potential to increase machine accuracy and speed. The LSS includes both the actual sensor and the support processor. The LSS has the potential to provide infomation on crack depth and width in addition to extremely accurate postional information.

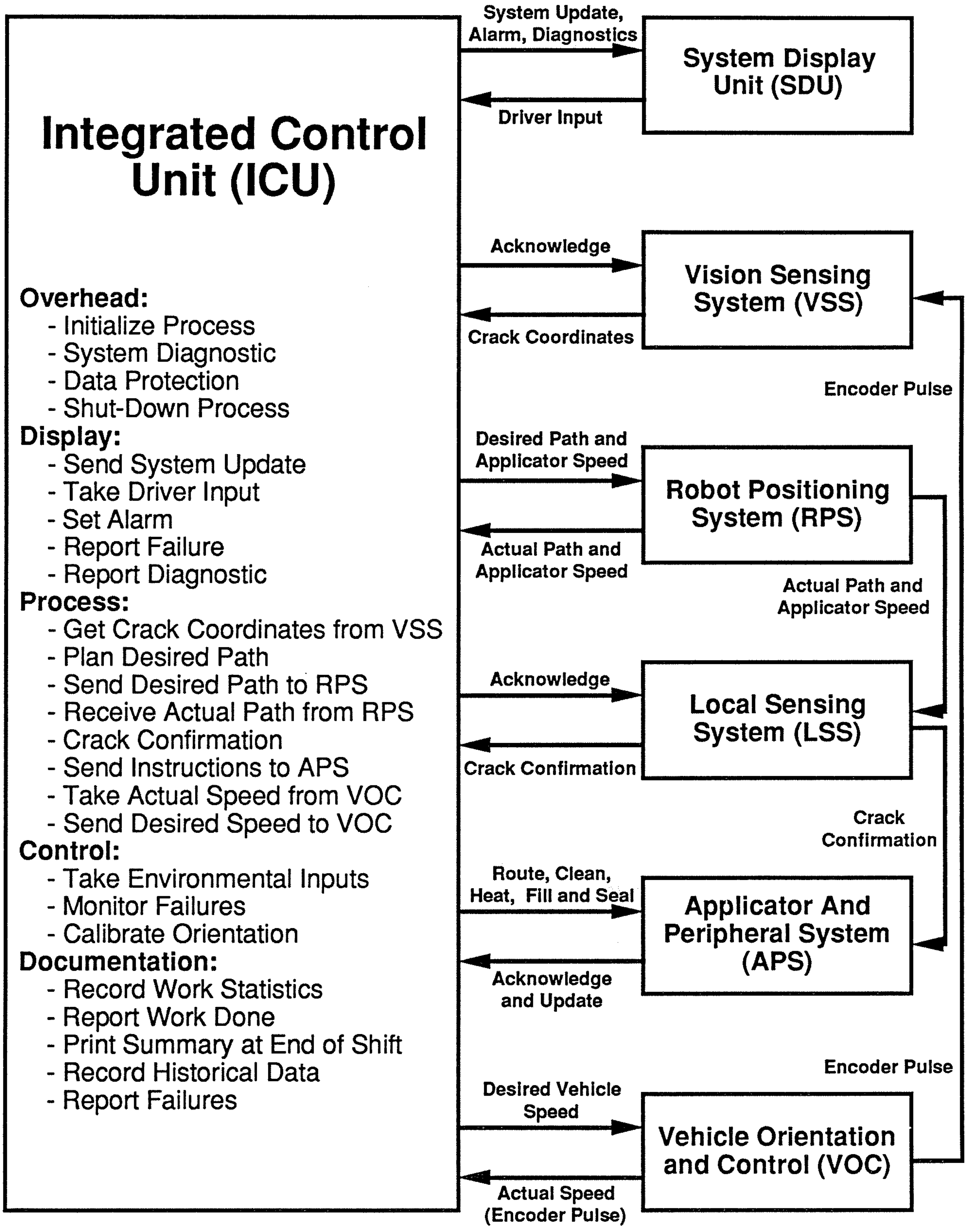
Applicator and Peripherals System (APS): The APS includes all the components that actually operate on the roadway and all the peripheral hardware such as air compressors, melter, propane tanks, etc. The APS end-effector components will be positioned by the RPS and all components will be instructed by the ICU. The APS includes a wide assortment of sensors that will provide information on each of its components to the ICU for instructions. The ICU will in turn provide APS status information to the operator through the SDU for his information and possible attention; i.e., notification of empty sealant tank, etc.

Vehicle Orientation and Control (VOC): The VOC controls the motion of the support vehicle based on instructions from the ICU and it provides vehicle motion measurements to the ICU and VSS. The VOC includes all necessary hardware to measure vehicle speed and orientation as well as the hardware to implement control action such as throttle position servomotors, etc. Additionally, the VOC will have the necessary sensors to monitor actual control inputs.

Alternative Machine System Architecture

As noted above, the LSS will initially be used for crack verification only. However, the LSS is capable of providing much additional information. The block diagram shows an alternative machine system architecture that will begin being developed during Phase II of this project. In the alternative machine system architecture, the LSS provides additional information on the location of the crack to allow fine positioning of the RPS; it will still be necessary to plan the global path based on VSS supplied information.

CRACK MACHINE SYSTEM ARCHITECTURE



Integrated Control Unit (ICU)

Overhead:
- Initialize Process
- System Diagnostic
- Data Protection
- Shut-Down Process

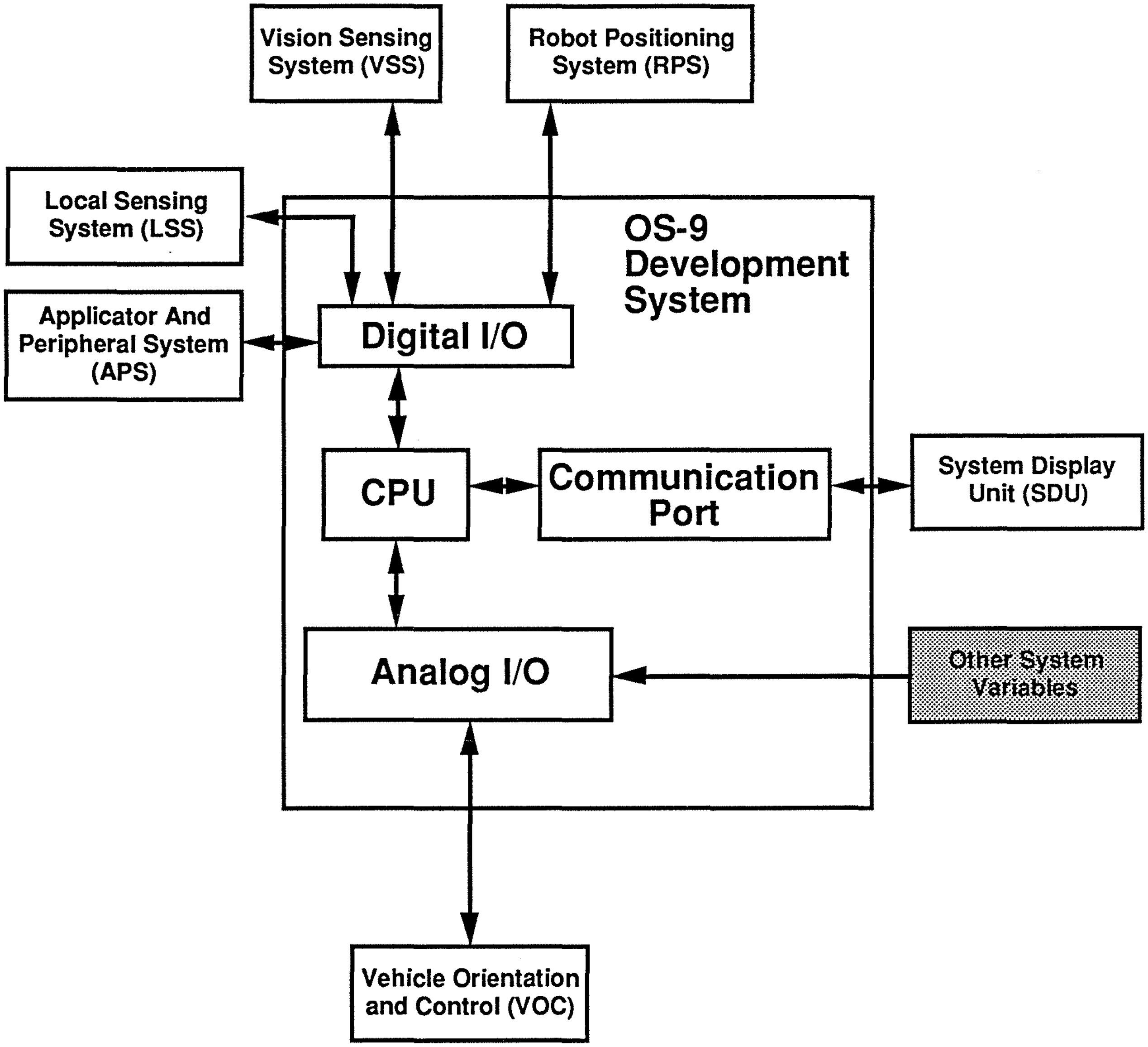
Display:
- Send System Update
- Take Driver Input
- Set Alarm
- Report Failure
- Report Diagnostic

Process:
- Get Crack Coordinates from VSS
- Plan Desired Path
- Send Desired Path to RPS
- Receive Actual Path from RPS
- Crack Confirmation
- Send Instructions to APS
- Take Actual Speed from VOC
- Send Desired Speed to VOC

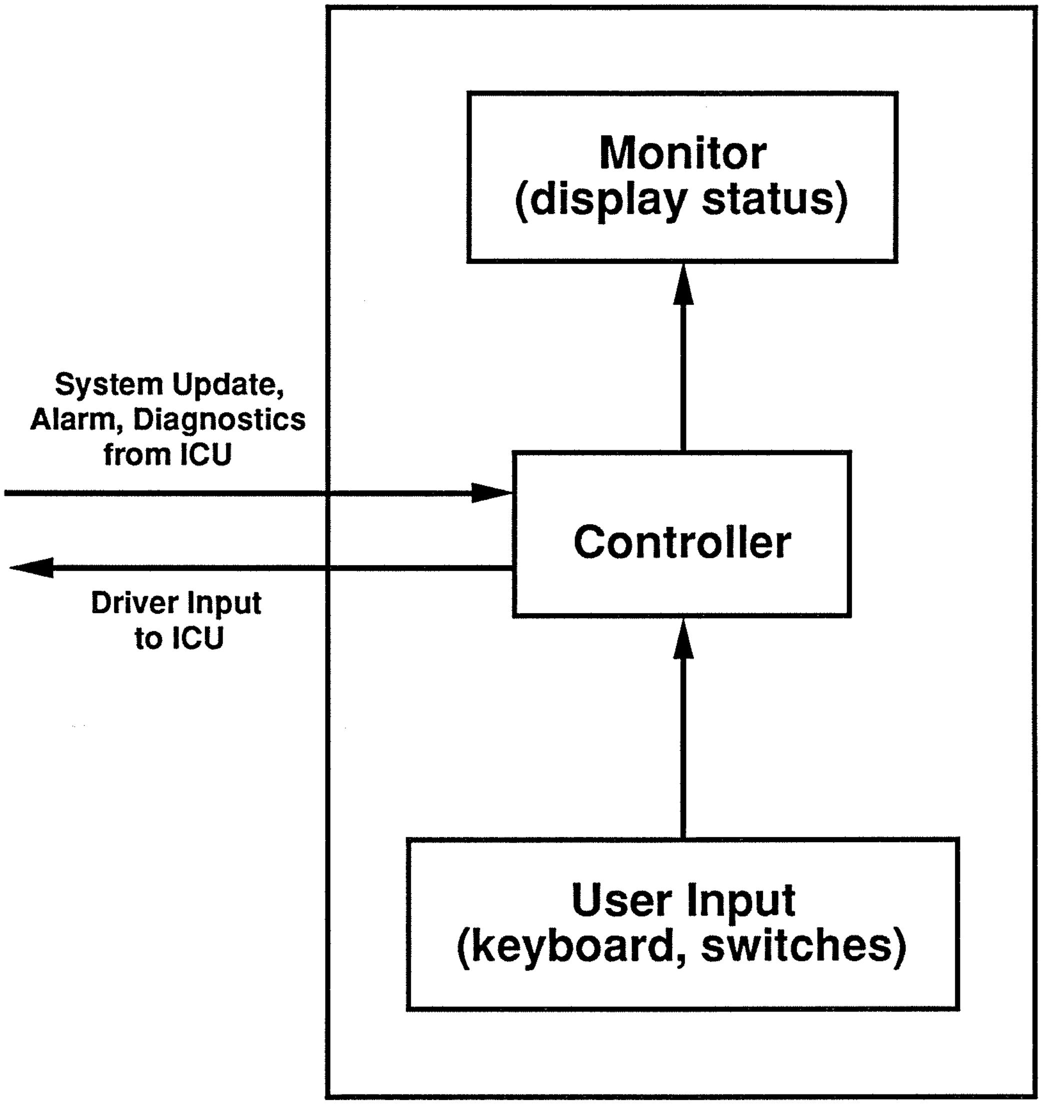
Control:
- Take Environmental Inputs
- Monitor Failures
- Calibrate Orientation

Documentation:
- Record Work Statistics
- Report Work Done
- Print Summary at End of Shift
- Record Historical Data
- Report Failures

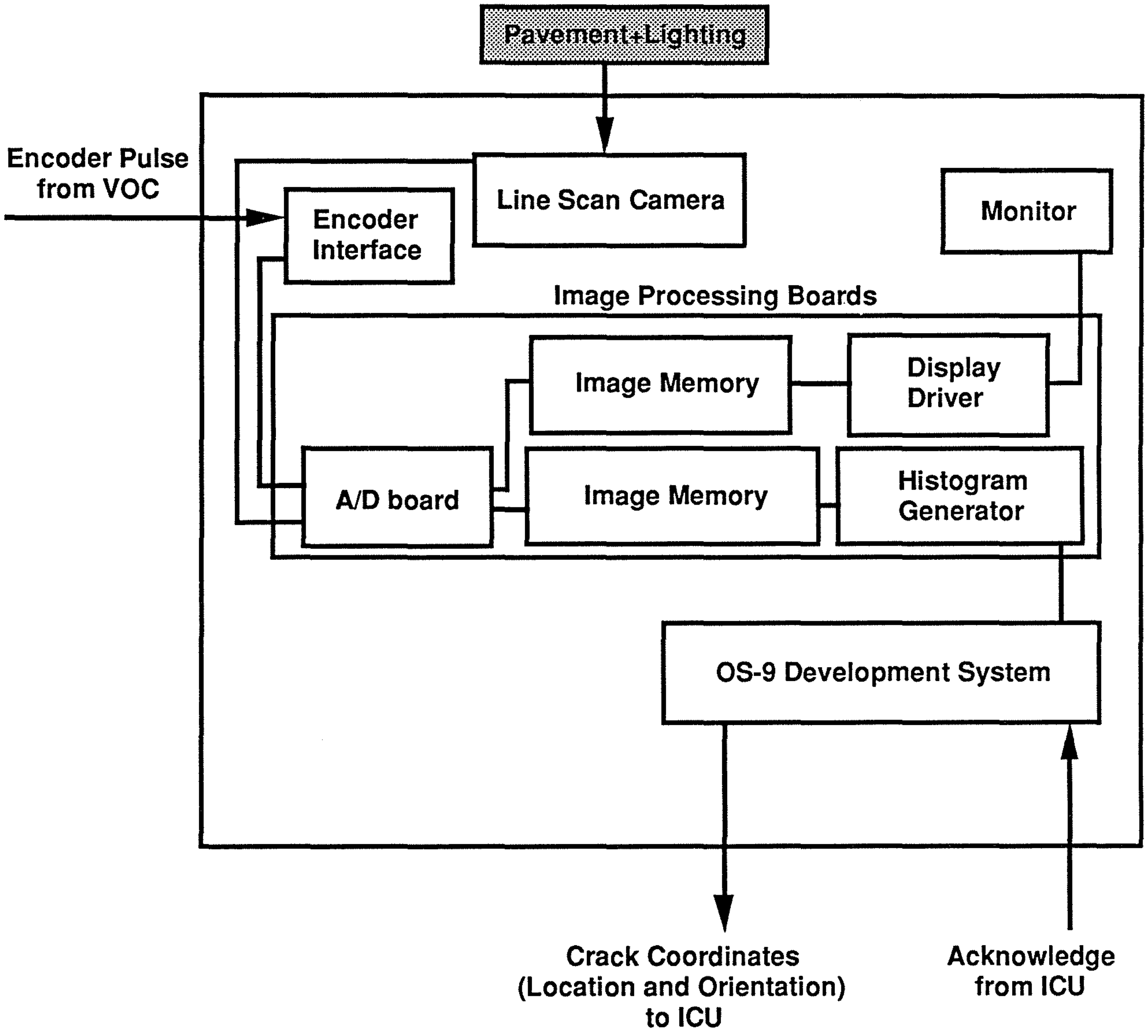
INTEGRATED CONTROL UNIT
BLOCK DIAGRAM



SYSTEM DISPLAY UNIT
BLOCK DIAGRAM

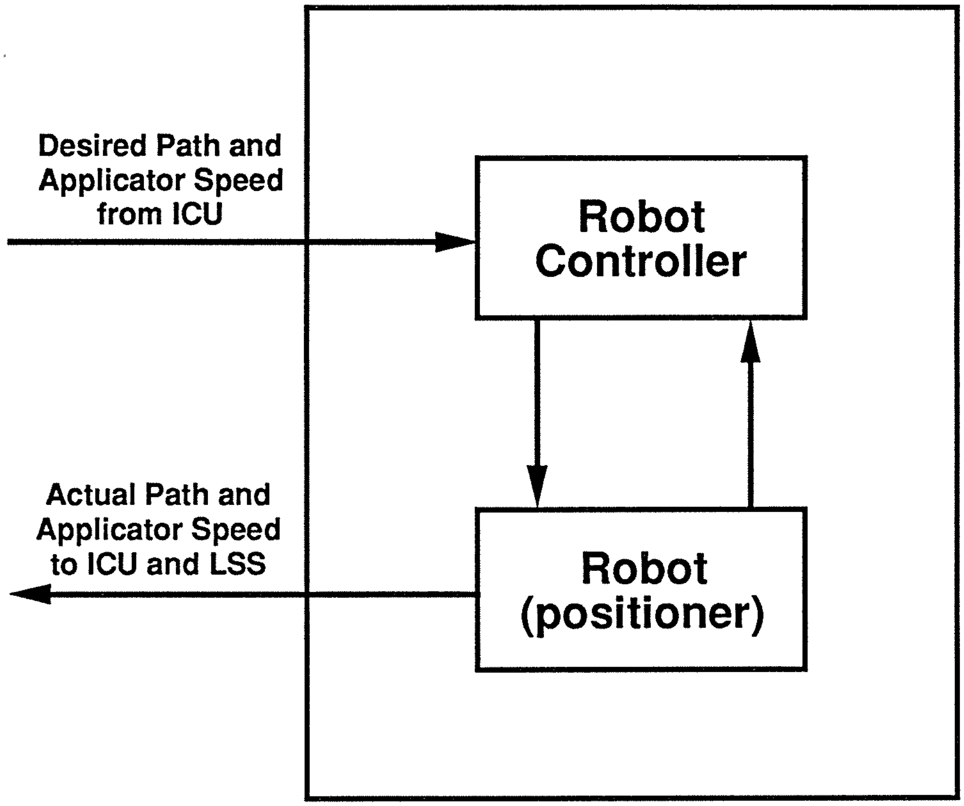


VISION SENSING SYSTEM
BLOCK DIAGRAM

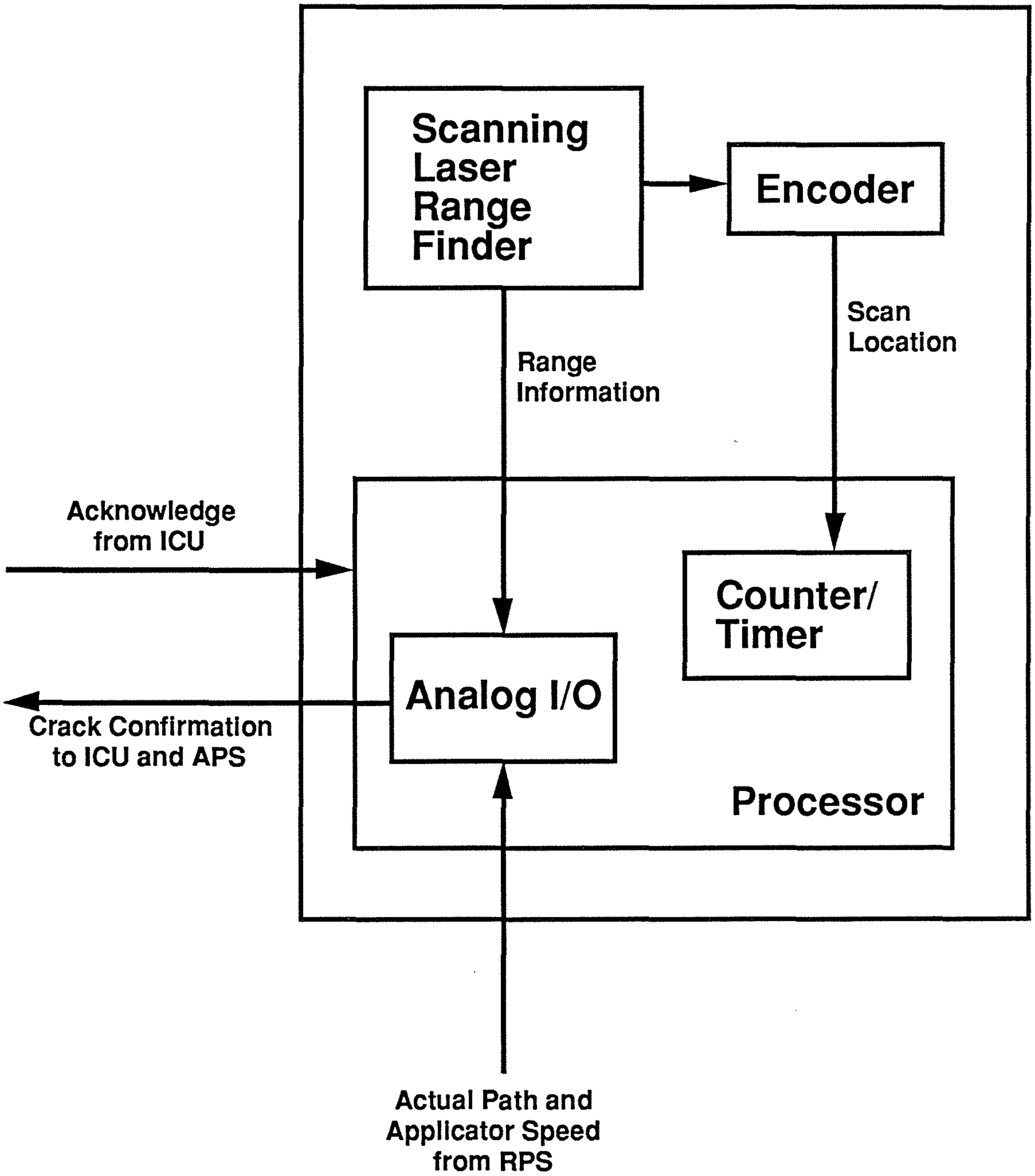


ROBOT POSITIONING SYSTEM

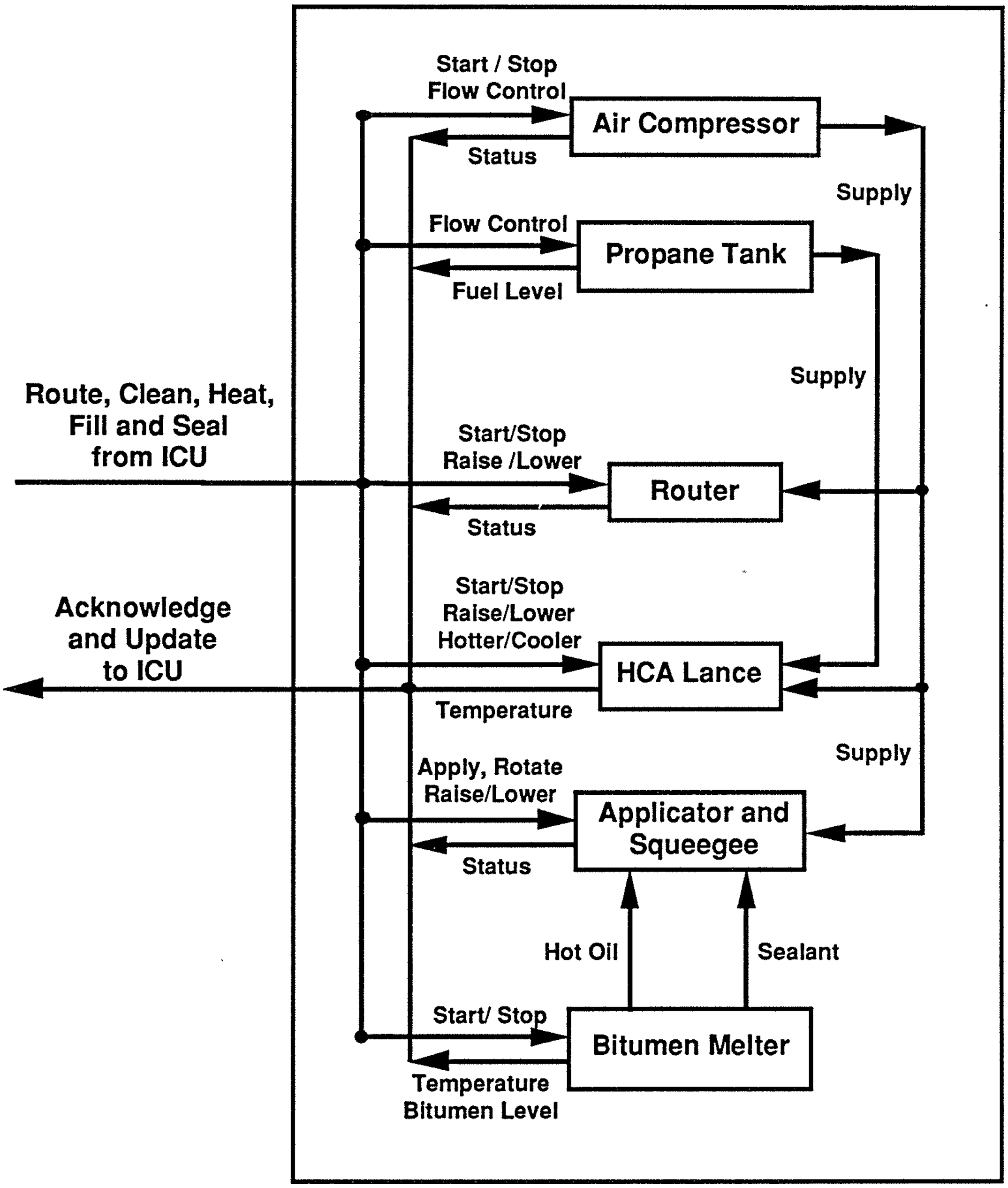
BLOCK DIAGRAM



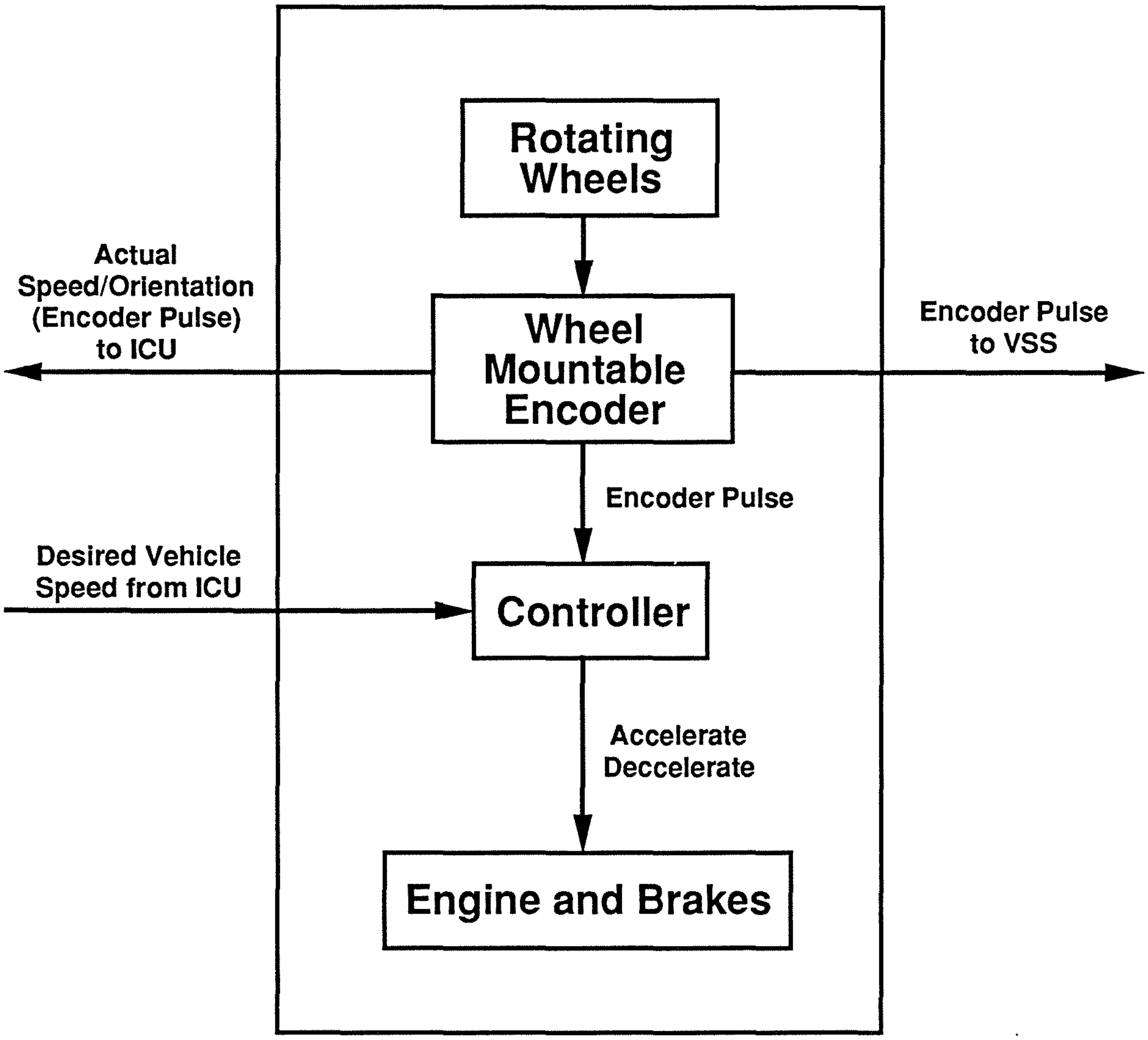
LOCAL SENSING SYSTEM
BLOCK DIAGRAM



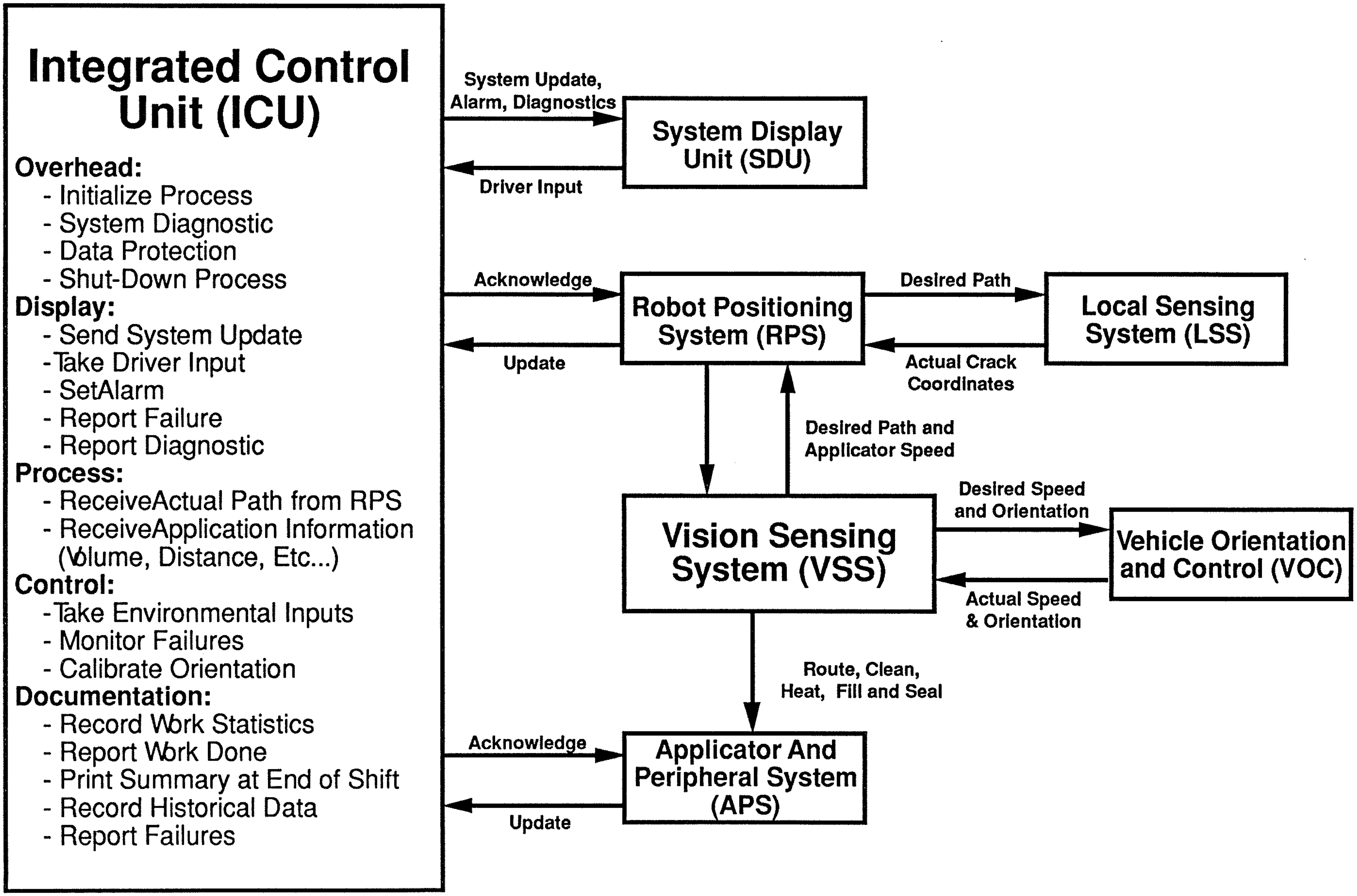
APPLICATOR AND PERIPHERAL SYSTEM
BLOCK DIAGRAM



VEHICLE ORIENTATION AND CONTROL
BLOCK DIAGRAM



ALTERNATIVE CRACK MACHINE SYSTEM ARCHITECTURE



Integrated Control Unit (ICU)

Overhead:
- Initialize Process
- System Diagnostic
- Data Protection
- Shut-Down Process

Display:
- Send System Update
- Take Driver Input
- SetAlarm
- Report Failure
- Report Diagnostic

Process:
- ReceiveActual Path from RPS
- ReceiveApplication Information (Volume, Distance, Etc...)

Control:
- Take Environmental Inputs
- Monitor Failures
- Calibrate Orientation

Documentation:
- Record Work Statistics
- Report Work Done
- Print Summary at End of Shift
- Record Historical Data
- Report Failures

MACHINE CONCEPTS

Early on in the machine development process (when the original proposal was being developed) and based on the two types of cracking that we intend to address, we have promoted the development of two independent machines, one for longitudinal cracks and joints that exist at the edge of the lane (construction joints, etc.) and the other for general (random or transverse) cracks/joints that may extend across the full lane width. However, many of the same major components would be necessary for each machine such as sealant melters, hydraulic power supply, etc. Thus, it has become quite apparent that a dual purpose machine with a portion to address longitudinal cracks and another portion to address general cracks is quite logical and would present a significant economic advantage in terms of capital investment for potential highway agency users. A schematic of this concept is included on the following page. The primary difference between the two crack sealing components is due to the positioning system as we intend to utilize as many of the same parts as possible in these two portions of the machine. Thus, this is an opportune point to discuss the differences between the two machine component positioning systems to be developed.

The development of a machine to automatically seal or fill cracks of sometimes arbitrary geometry is quite challenging. The primary challenges arise from:

- The number of degrees-of-freedom required to follow an arbitrary crack,
- The required unsteady operation of many of the components.

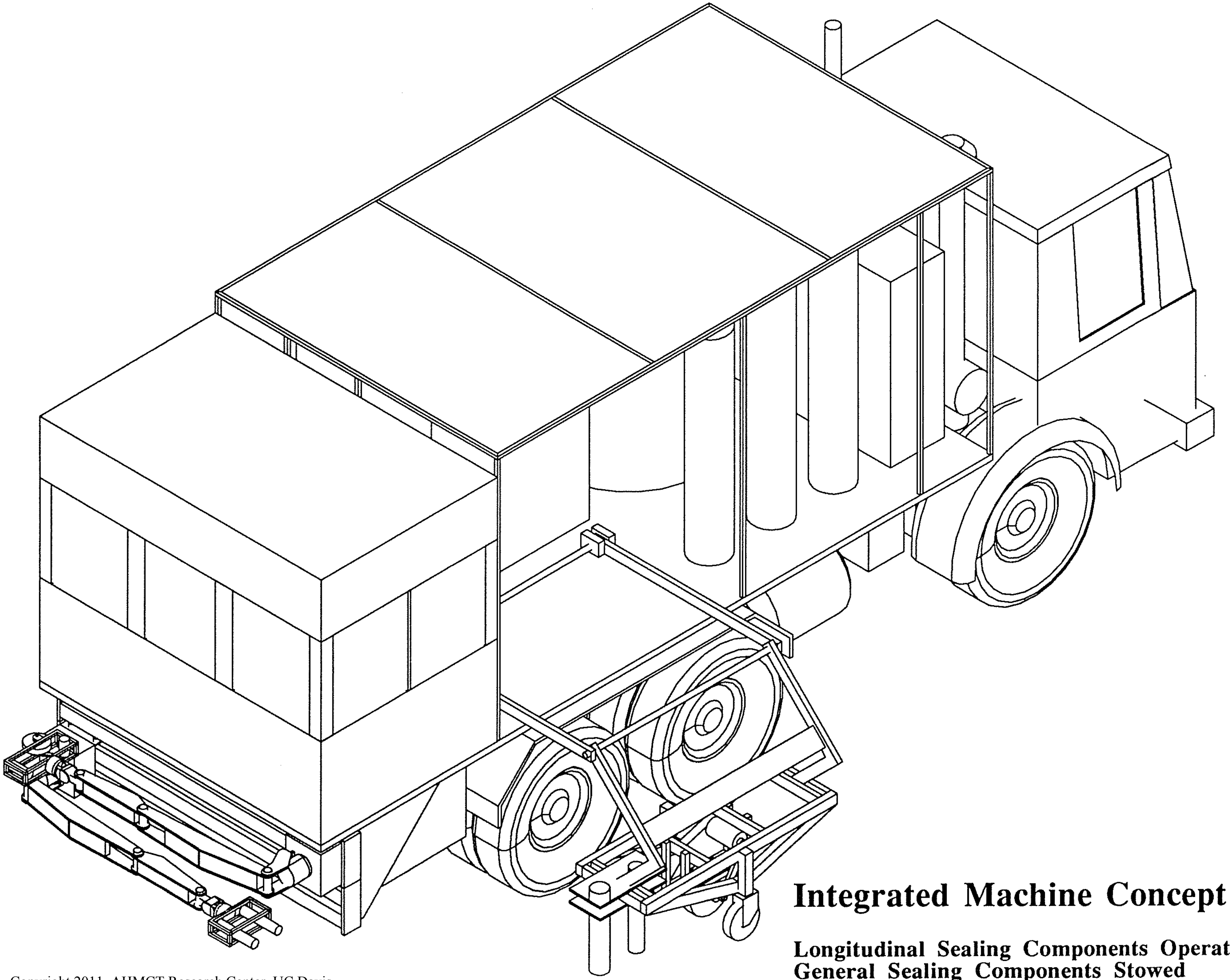
Furthermore, the use of the support vehicle to provide a continuous movement of the machine at the anticipated slow speeds (which may be desirable) may be unrealistic.

A machine to perform the longitudinal operations has several different requirements including:

- Fewer required number of degrees-of-freedom to follow longitudinal joints and cracks,
- Considerably different sensing requirements, and
- The steady-state operation of many of the components.

Furthermore, for the simpler longitudinal operations, the use of the support vehicle to provide a continuous movement of the machine will very likely be possible. As such, the positioning system concept for the longitudinal portion of the machine is significantly simpler than the general machine. Due to the straight forward nature of the longitudinal machine concept, at this juncture, we will present this system. The more detailed general machine concept will presented below when the positioning system design is discussed.

Following the generation of a number of alternative positioning concepts, we have selected a longitudinal positioning system that relies on hydraulic positioning of a simple linkage supported off the side of the support vehicle. The technical drawings below present this concept in detail. The system is designed in such manner that the weight of the end-

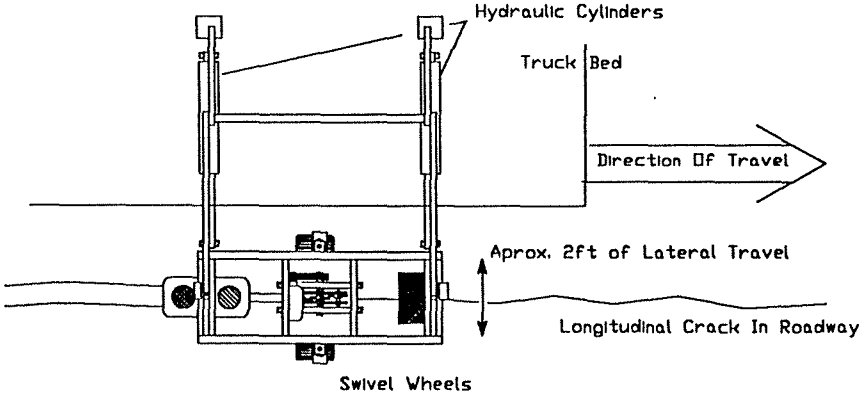


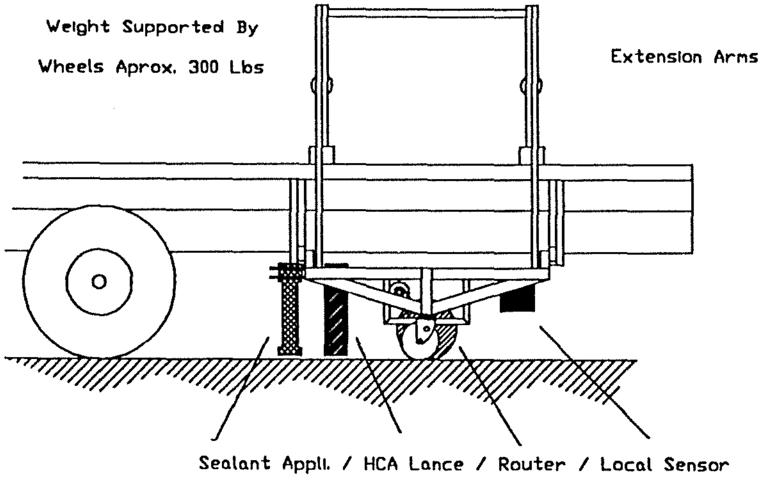
Integrated Machine Concept

Longitudinal Sealing Components Operational
General Sealing Components Stowed

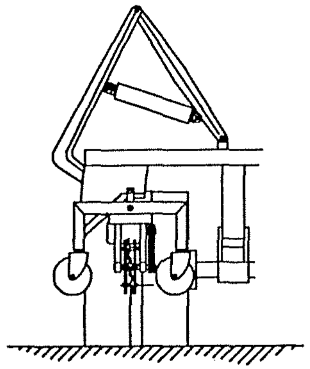
REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP

Longitudinal Crack Sealing Machine





APPLICATOR & POSITIONING SYSTEM



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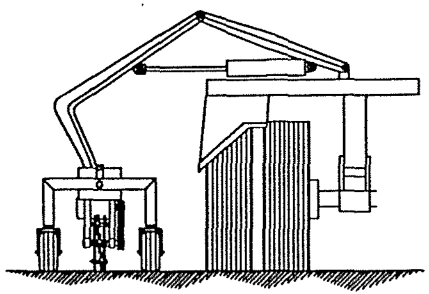

(OPERATIONAL CONFIGURATION)

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PART LIST

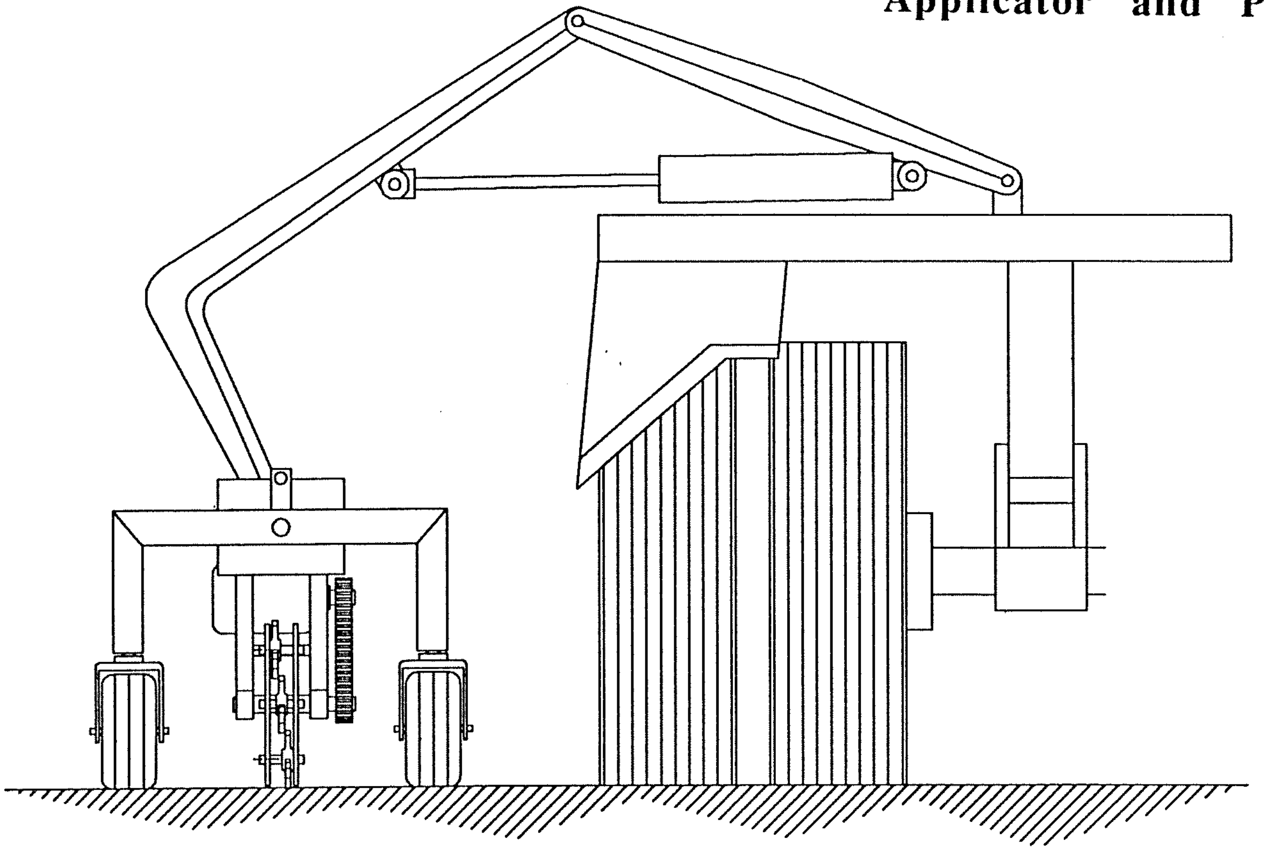
UNLESS OTHERWISE NOTED
TOLERANCES
.XX ± 0.010 ANGLES ±
.XXX ± 0.005 SUR FIN 64
DESIGN
DATE
DRAWN DAB 3/20/91
APPVD SV 4/1/91
RELEASE

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE LONGITUDINAL CRACK
SEALING MACHINE

QTY
SCALE
DRAWING NO. 322-1C-M
SHEET SH 1 PROJECT SHARP 107-A

Longitudinal Crack Sealing Applicator and Positioning System



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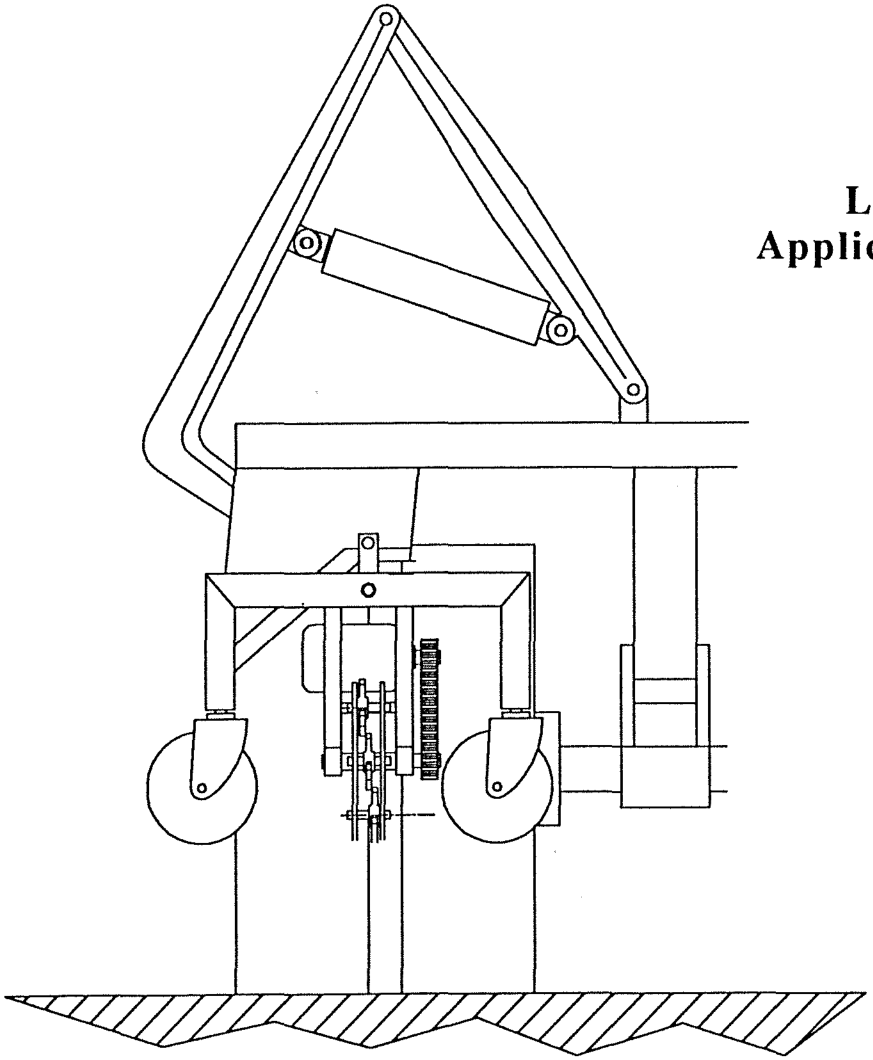
MECHANICAL ENGINEERING DEPARTMENT

APR SV 4/91
SCALE N/A
Name Longitudinal Crack Sealing Machine
Date 4/1/91 DWN TS 3/91 PROJECT SHRP 107-A

Longitudinal Crack Sealing Applicator and Positioning System



(Stowed Configuration)

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

APR SV 4/91
SCALE N/A
Name Longitudinal Crack Sealing Machine
Date 4/1/91
DWN DAB 3/91
PROJECT SHRP 107-A

effectors are supported by a support frame mounted on casters, and the casters provide positioning of the end effectors relative to the roadway. The routing, heating/blowing, and dispensing end effectors are all supported by the same frame as is the local sensing system. The positioning system provides motion of the frame normal to the direction of vehicle motion. Placement of this part of the machine would allow it to be stowed under the vehicle bed for travel to and from the job site. This design can easily be fabricated with many commercially available components.

COMPONENT DESIGNS

In earlier parts of this section, we have discussed the various functional requirements, the machine system architecture, and the technological feasibility of various components and component systems of the crack sealing machinery to be developed. We have additionally provided recommendations for the design of many of these components. This part of the report now presents detailed designs of the first generation machine components that we will fabricate and test during Phase II of this project.

Vision Sensing System Design

Earlier in this section, we have discussed details of the machine vision algorithm for identifying cracks in pavement. The algorithm has been initially developed in an off-line manner and with area scan video camera technology. Future work will implement this algorithm with both line scan camera and area scan camera technology on a 68030 based vision system so that it can operate in real-time in automated crack sealing machinery moving at speeds as high as two miles per hour. A hardware block diagram for the real-time configuration of this algorithm is shown in Fig. 1.14. The pixel rate of this system is approximately 2 MHz, and several concurrently running software processes will implement the algorithm. The image processing boards will provide histograms of the tiles and a user interface to monitor, and possibly modify, the performance of the system. The 68030 will provide the statistical moment computations, comparisons, and storage of recognized crack information. The communications board allows transmission of the crack information to other machine processors for path planning and crack repair operations; that is, the function of the VSS is to provide crack location and orientation of individually recognized crack segments to the Integration and Control Unit which will provide a path planning and real-time position update prior to preparation and sealing. A set of VSS specifications was developed (see Table 1.4) prior to the choice of this hardware configuration. To follow are additional details of the VSS design.

- The line scan camera to be used is a Fairchild CAM 1840 with 2592 pixels.
- The Encoder is a Datron Technology optical encoder used for vehicle testing.
- The A/D board is a Data Cube variable scan width data acquisition VME bus board.
- Image memory #1 and #2 are Data Cube VME bus Image Memory boards.
- The display driver is a Data Cube display board with graphics capabilities.

- The histogram generator is a Data Cube histogram generating board.
- The OS-9 Development system is a Radstone OS-9 development system with the specifications shown above.

The manufacturers specifications indicate that this configuration will satisfy our requirements for the implementation of a real-time crack detection algorithm. The first part of Phase II will be to test the performance of these VME boards on the OS-9 development system. We should note that this hardware system has been purchased with funds that have not originated from SHRP.

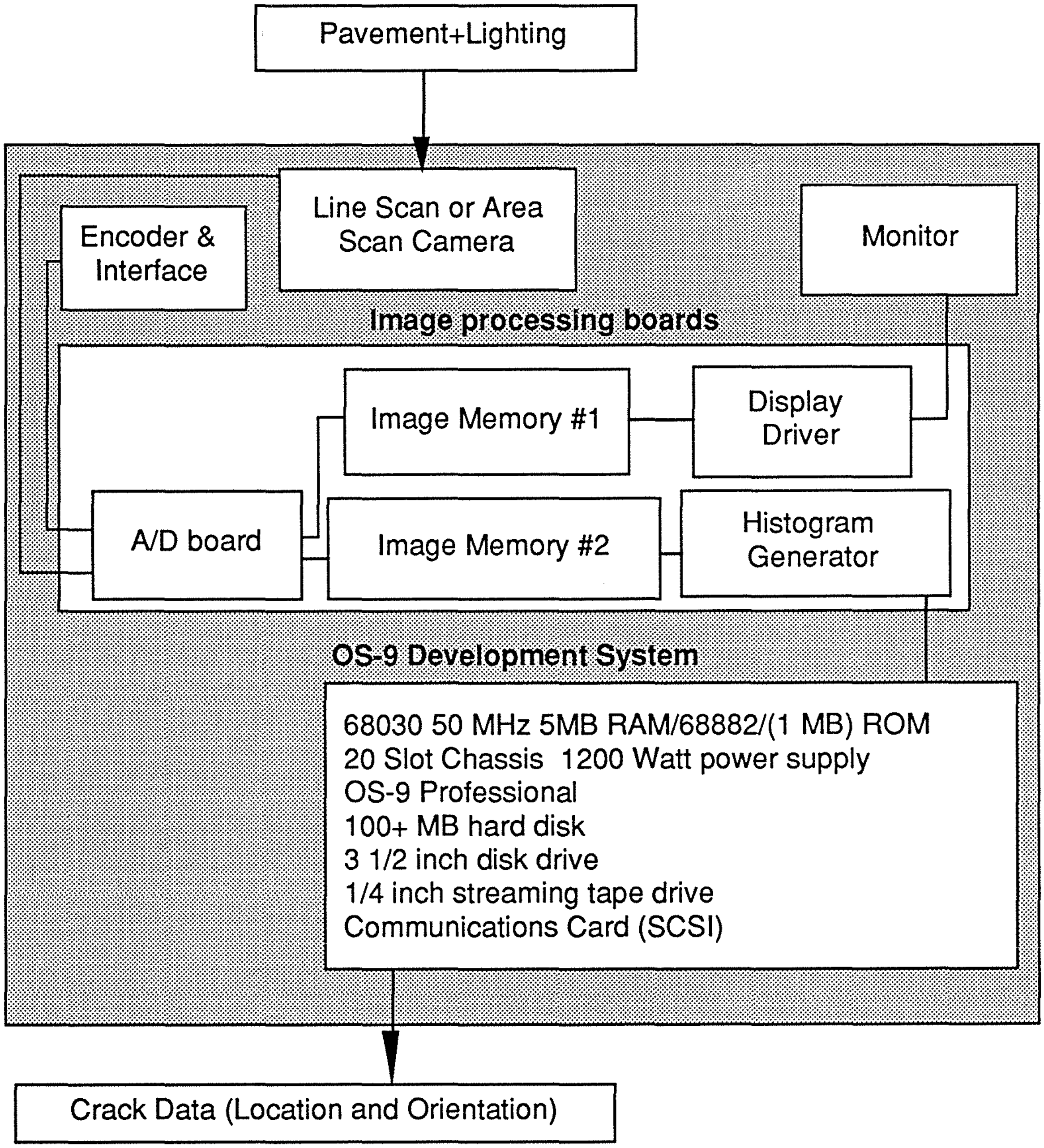


Figure 1.14 - Hardware Block Diagram

Resolution/Cycle Time

System should support processing of a minimum of a 2496 pixel line scan camera in real time. For details of the algorithm which will be recognizing the cracks, see Vision Sensing System Algorithm.

Real time is 2 miles per hour forward rate of vehicle which corresponds to a pixel rate of not more than 2 MHz. The **2496 pixels** is required to reliably support the recognition of 1/8" cracks in the image (1/16" pixel resolution).

Environmental

The line scan camera and encoder which will be external to the vehicle should be resistant to the following:

- condensating moisture
- acoustic noise
- mechanical vibration and shock
- heat
- dust and roadway debris
- temperature variations
- variations in lighting conditions
- electromagnetic interference from nearby machinery, such as a generator

Reliability and Maintainability

The field system should make use of off-the shelf-technology, should be easily accessible for component replacement or adjustment and be as modular as possible. Also, the sensor system and its expected maintenance should provide for a service life of 10 years.

Field system is the bare structure of what is included in the Vision Sensing System Hardware Block Diagram. This would not include an OS-9 Development System and would instead be a smaller OS-9, ROM based target system.

Table 1.4 - Vision Sensing System Specifications

Local Sensing System Design

As noted earlier, it is necessary for the automated machine to detect cracks as small as 1/8" in width. Therefore, according to the Nyquist sampling theorem, the local sensor must have the ability to sense a crack as small as 1/16" wide. Normal height variations in pavement are approximately ±1/16". Height deviations greater than this amount must be recognized as a potential crack. Therefore, the sensor must have the ability to resolve vertical height measurements to 1/16" accuracy.

The local sensor must operate in a dusty environment and must be able to endure typical vehicle vibration. It must accurately sense range data on a pavement surface which may vary in color from black to white and may contain reflective aggregate. Furthermore, the sensor performance should not be affected by temperature variations in its path where heat may arise from machine operations or normal pavement climatic heating. Lastly, the sensor must respond at a fast rate consistent with the machine's desired operating speed. Based on a worst case scenario, this corresponds to a scan rate of 18 scans/sec. Table 1.5 summarizes the local sensor requirements.

RESOLUTION	1/16"
ACCURACY	1/16"
RANGE	4" to 6"
FREQUENCY RESPONSE	700 Hz (-3 db @ .7 msec)
LINEARITY	1% full scale
HUMIDITY	to 85%
VIBRATION	typical vehicle vibration
SHOCK	10 G
OPERATING TEMPERATURE	-20 to 160° F
FIELD WIDTH	4"
SCAN RATE	18 Hz
SERVICE LIFE	10 yrs
SENSOR MUST ENDURE	- wind and sunlight
	- dusty environment
	- surface color variations
	- moisture on pavement
	- debris in cracks
	- road surface height variations
	- temperature variations
	- electromagnetic interference
SENSOR MUST DISTINGUISH	- previously filled cracks
	- oil spots
	- shadows
	- actual cracks

Table 1.5 - Local Sensor Requirements

To employ the use of the single point laser range finding sensor, a scanning method to acquire data points is necessary. One possible approach is to use an array of discrete sensors across the 3" area. This method was considered by Estochen, et al. (1984) as previously mentioned. In order to achieve the required resolution of 1/16", 48 sensors mounted 1/16" apart would be needed. Because of the physical size constraints of the sensors available, it is not possible to mount the sensors this close. Furthermore, the cost of using 48 sensors is high. Therefore, it was decided to use one sensor which scans the 3" of pavement, as in many of the examples found during the literature search.

Two methods were considered to create the scanning motion of the sensor. The first consideration was to move the entire sensor using a motor, as Smati, et al. (1983) did with their Optocator probe. This method is considerably less expensive than other alternatives. If the entire sensor were to scan this area, the speed of the scan would be limited by the maximum allowable shock on the sensor. The speed must also be great enough to track the worst case crack. If one sensor is used to scan the 3" area, it is not possible to meet the two requirements; a speed great enough to track the worst case crack creates too much shock on the sensor. A second alternative would be to have multiple sensors scanning sections of the 3" area. If two sensors were used, the slowest possible scan rate would be 3.5 Hz. If three sensors were used, the slowest possible scan rate would be 2.3 Hz. It is believed that this scan rate would put undo physical strain on the moving components, making this a likely failure point.

The second method to achieve the needed scan rate can be accomplished by using rotating or scanning mirrors. Figure 1.15 illustrates a method for which the rotating mirrors can be incorporated into a working design. This method is considerably more expensive than the previous scan method, although it is currently used in automated welding to scan for seam location (Appels, 1987; Nayak, et al.,1987; Edling, 1986; Baranek, et al., 1986). Based on the literature search, a scanning method employing Rioux's synchronized scanning is desired for its compactness and increased field of view and resolution. Disadvantages in this scanning method are its high cost and number of moving parts. The performance of the sensor relies heavily on the synchronization of the two rotating mirrors, which may cause misalignment and inaccuracies.

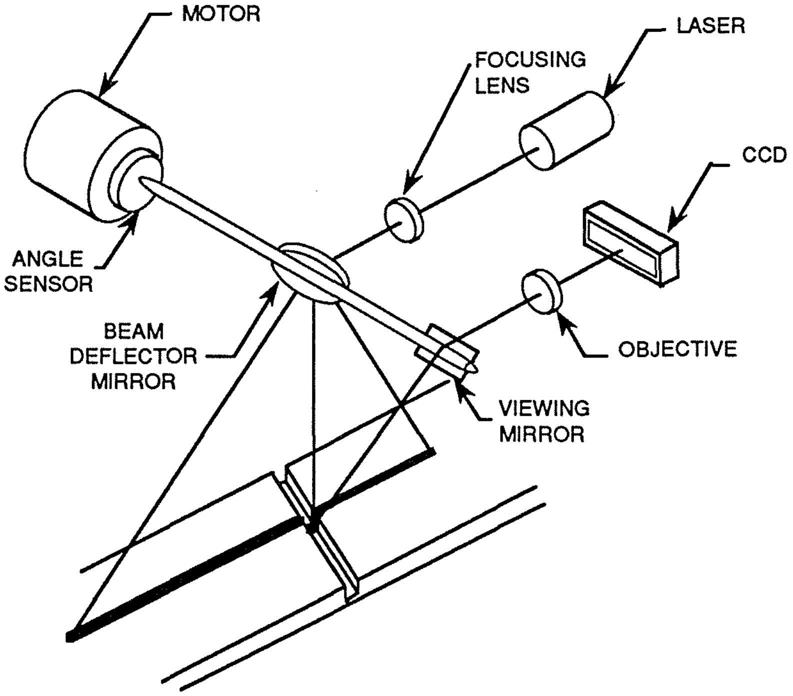


Figure 1.15 - Scanning Laser Sensor with Rotating Mirrors

One such sensor which employs the synchronization suggested by Rioux is the Saturn, developed by Servo-Robot Inc. of Quebec, Canada. This sensor has been discussed by Baranek, et al. (1986). The sensor uses a solid-state laser and a CCD sensor. Welding speeds of 5 to 20 mm/sec can be accomplished with this device. Furthermore, it can scan at speeds up to 30 scans/sec. The unit measures 100 x 100 x 100 mm and weighs 900 grams. It has a tracking accuracy near to 0.2 mm at 2 m/min. The authors also suggest the use of this sensor in other applications besides automated welding. One current application of this sensor measures railroad tracks at speeds up to 60 mph.

Figure 1.16 illustrates the use of structured light for a laser vision system. Laser vision systems employing structured lighting techniques require no moving parts; therefore, they are mechanically simpler designs and are less prone to mechanical failures. There are multiple manufacturers of such vision systems which would customize the software for the crack detecting application.

One commercially available laser vision system using structured light is produced by Modular Vision Systems Inc. (MVS). The sensor operates by projecting a laser light source in a plane approximately perpendicular to the surface being measured. The line is then observed by a CCD camera at an angle, and through triangulation the surface features are distinguished. The surface profile is extracted at a rate of 60 times per second. It has proven to be reliable in the harsh lighting conditions of arc welding. The sensing unit is small, measuring 4" x 3" x 1.6", and weighs approximately .5 lb. It is accurate to within .001". This sensor has been used to measure the gage and straightness of railroad tracks at speeds up to 60 mph.

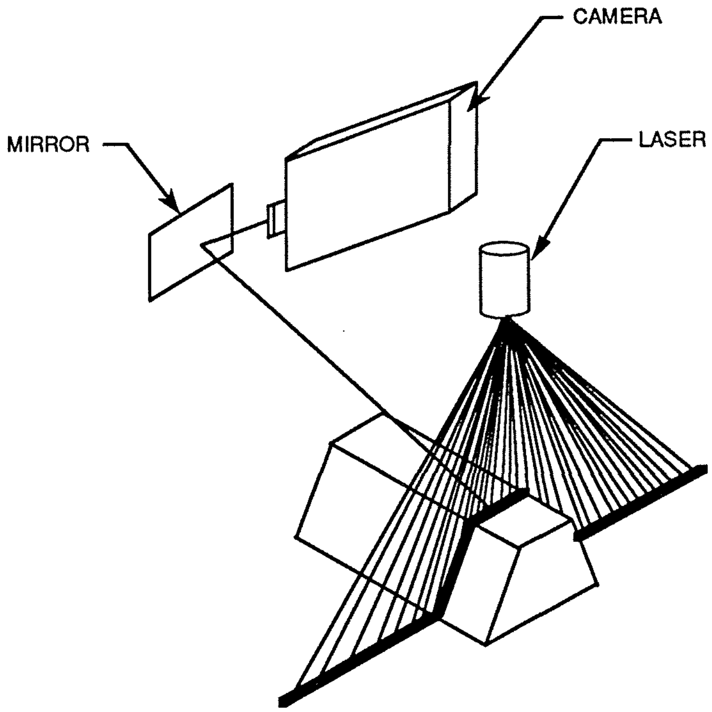


Figure 1.16 - Structured Light

Due to the sensor characteristics mentioned above and current applications of these sensors, it is believed that either a vision system using structured light or a synchronized scanning laser range finding sensor would suffice for local sensing. Both sensing methods have demonstrated ability to perform tasks similar to crack detection. Furthermore, as demonstrated by initial testing during Phase 1, the laser triangulation sensing method has proven to be reliable on pavement surfaces. To determine the optimum sensor, cost, reliability, accuracy, speed, size, weight and the number of moving parts (i.e. potential fail points) were considered.

Initial estimates of the two types of sensors have shown the synchronized scanning laser range finder to be approximately double the cost of the alternative structured light technique. This is related to the complexity of the mechanical design of the rotating mirrors. The rotating mirrors introduce more moving parts and more possible failure points.

Both systems provide more accuracy than what is required for the crack sealing application. However, the structured lighting can perform up to 60 times per second while the scanning laser performs at 20 sweeps per second. The structured light system's additional scanning capability can potentially provide for a more accurate and faster future machine and provides additional flexibility in path planning, etc. The Servo-Robot scanning laser sensor weighs approximately 2.5 pounds and measures 4.5" x 7" x 3.75", while the MVS structured light vision system weight 0.5 pounds and measures 4" x 3" x 1.6".

In conclusion, the laser vision system using structured light is more economical. It has a simpler design with less moving parts. Three times faster scan rates are achieved with the structured light. Furthermore, the structured light sensor package is both more compact and lighter. Therefore, the laser vision system using structured light is the optimum sensor for crack detection in pavement, and with vendor software development, a "turn-key" commercial system is available.

Applicator and Peripherals System Components Design

The Applicator and Peripheral System is comprised of a router, debris removal system, cleaning/heating unit, and sealant dispensing/finishing unit. For purposes of design description, each of these systems is presented separately. However, the actual machinery operates as an integrated unit. For the case of sealing meandering cracks, two modular end-effectors have been developed for attachment to the robot arms on the rear of the support vehicle. The first contains the local sensor, router, and debris removal device. The second contains the crack cleaning/heating, and sealant dispensing/finishing units. The local sensor has already been described so it will not be further discussed. For longitudinal sealing these end-effectors can be transferred to the single positioning device on the side of the support vehicle for higher speed sealing and filling.

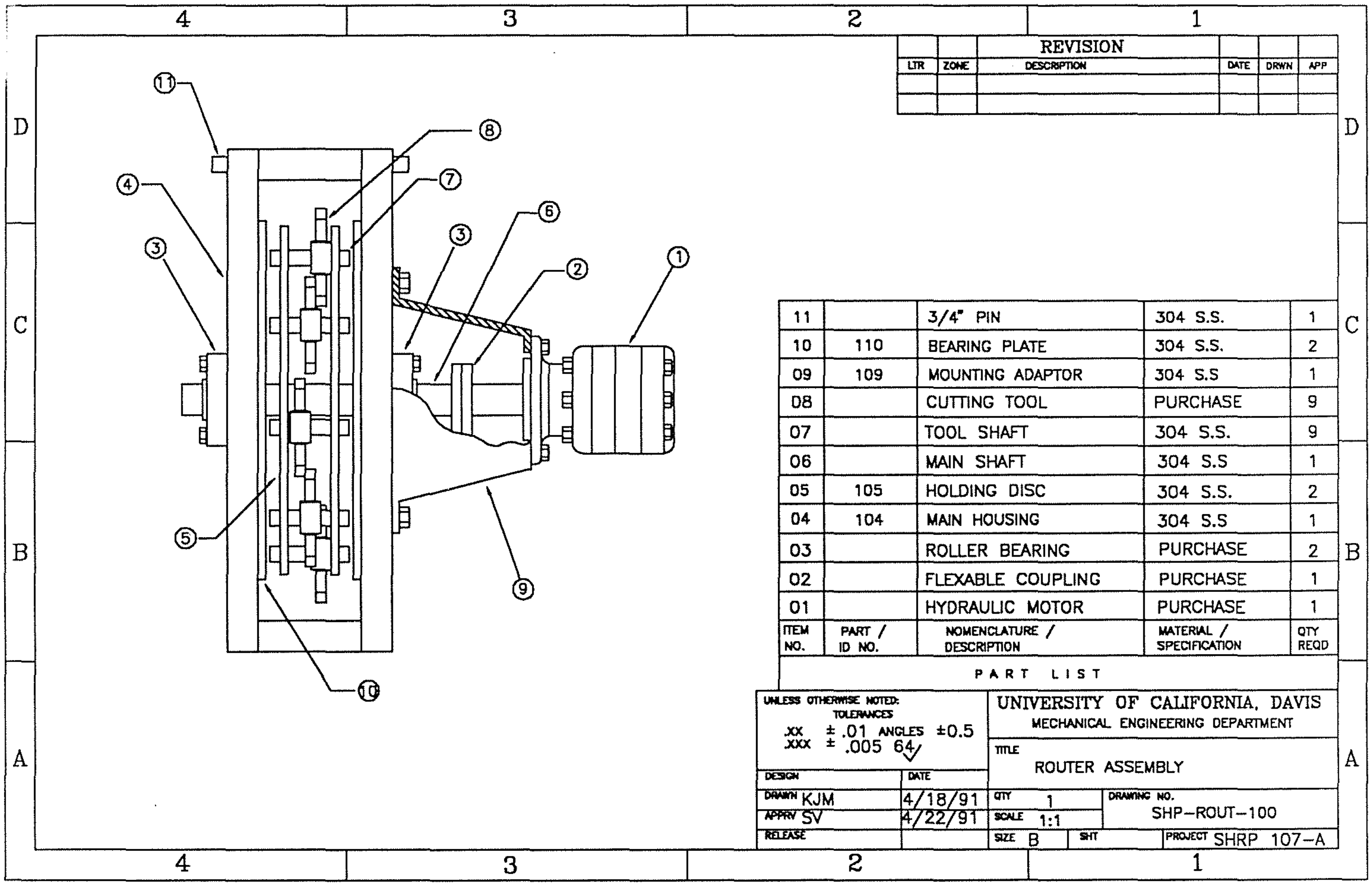
Router Component Design

The H-107A automated high surface speed impact router designed for this project is very similar to industry standard impact routers, with a few refinements. These refinements allow it to have increased production rates on AC in a smaller more maneuverable package. We have elected to employ impact router technology because of the ability of these types of units to follow random cracks. As earlier stated, the focus of this project will be on the two extremes of difficultly of roadway distress repair, the simpler longitudinal cracks and the most difficult primarily transverse, random AC cracks that occur across the entire lane width. A common impact router that was tested at the University of California, Davis proved to be capable of following pavement cracks in any orientation and it was able to negotiate a tight turning radius. Impact routers can also cut without liquid coolant. This is a considerable benefit since the use of coolant, which is a requirement for saws, introduces moisture into the prepared crack that must be removed prior to sealant application.

Cutter development for the high surface speed router was based upon the application of conventional cutting theory to current impact routing technology to attain the increased surface speed while retaining the quality of the cut. Routing cutters are designed to carry a specific material load, which is actually a shear force generated tangent to the cutter (Kronenberg, 1966). As such, an increase in the surface speed would result in an increase in the amount of material each cutting tooth would have to carry. If this load is greater than the design load, the cutter's life would be decreased dramatically and the quality of the cut would diminish. To avoid such a scenario, an increase in surface speed can be countered with either an increase in cutting speed or with the addition of extra cutters to handle the additional material. The increased surface speed would necessitate an increase in the drive motor power in order to overcome the inherent increase in material shear forces.

The H-107A router, shown in Fig. 1.17 and the set of drawings in Appendix 6.3, will use standard impact cutters shown in Appendix 6.6, with eight carbide teeth each that cut a three-quarters of an inch wide channel. To reduce vibrations, the cutters need to be staggered such that there are an equal number of cutters on either side of the cutter head center of gravity and additionally, so that the cutters contact the road in a continuously varying fashion. The number of cutters on the rotating tooling plate would depend on the width of the desired channel; e.g., for an inch and a half wide channel, the total number of cutters would be nine since cutters must be in multiples of three across (the head shown in the component drawings is based on this case).

The router is mounted inside a modular frame, or tool holder, that can be easily attached to either the longitudinal or the general crack sealing mechanism. The routing cutters need to be clear of the pavement during start-up and shut-down as well as when moving between individual cracks. Routers have the ability to raise the cutting blades clear of the pavement



REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP

ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
11		3/4" PIN	304 S.S.	1
10	110	BEARING PLATE	304 S.S.	2
09	109	MOUNTING ADAPTOR	304 S.S	1
08		CUTTING TOOL	PURCHASE	9
07		TOOL SHAFT	304 S.S.	9
06		MAIN SHAFT	304 S.S	1
05	105	HOLDING DISC	304 S.S.	2
04	104	MAIN HOUSING	304 S.S	1
03		ROLLER BEARING	PURCHASE	2
02		FLEXABLE COUPLING	PURCHASE	1
01		HYDRAULIC MOTOR	PURCHASE	1

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5
.XXX ± .005 64√

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE ROUTER ASSEMBLY

DESIGN	DATE				
DRAWN KJM	4/18/91	QTY 1	DRAWING NO. SHP–ROUT–100		
APPRV SV	4/22/91	SCALE 1:1			
RELEASE		SIZE B	SHT	PROJECT SHRP 107–A	

Figure 1.17 - Router Design

and they also have the ability to accurately adjust and maintain a desired cut depth. A cutter height travel of approximately four inches will be sufficient to clear the pavement when not routing and to rout up to one inch deep, which is the deepest of all common rout configurations. Conventional routers achieve height adjustment by separating the cutter support frame and the wheel support frame into two parts that are connected by a hinge. As the hinge is opened and closed the cutters are raised and lowered. The modular H-107A router will borrow this hinge frame height adjustment concept, but will also have the ability to disassemble from the frame at the hinge so that it can be attached to either applicator frame. The cutter height travel is produced by pivoting the frame about the hinge with a hydraulic cylinder mounted to the component frame.

The gasoline engine that typically powers conventional impact routers is replaced with a hydraulic vane motorto reduce the size of the new router and to obtain an increase in horsepower. Hydraulic motors are approximately one quarter the size of a gasoline engine for equivalent power ratings. Vane hydraulic motors are capable of speeds up to 4,000 rpm and torques up to 4,000 lb-in which easily exceeds the normal operational ranges for impact routers. Hydraulic motors are also small enough to be directly connected to the cutter drive shaft, eliminating the need for chains and sprockets. This in-line motor design eliminates the need for drive line adjustments and will result in an inherently longer service life, due to the fewer moving parts. The choice of a hydraulic system that uses separate hydraulic components is ideal for this design, because it permits the majority of weight and bulk of the hydraulic system, e.g. the reservoir, pump filter, etc., to reside on the truck platform. This reduces the components required on the preparation frame which is manipulated along the pavement crack; i.e. it is only necessary to move the drive motor and the flexible hydraulic supply lines. Thus, the weight and size requirements of the surface frame are reduced, and the dynamic and kinematic capabilities are improved.

The use of hydraulics also simplifies the router remote start-up and control scheme to a single hydraulic flow valve located on the truck platform. Since the cutting force of the H-107A router will be equivalent to conventional routers, the downward force (weight) of the router should be the same or greater. The decrease in router weight caused by the introduction of hydraulics will be countered by focusing the center of gravity of the manipulator frame's weight directly over the router cutting area which is consistent with current routing technical practices.

Debris Removal Subsystem Design

During the April 1991 SHRP Highway Operations Advisory Committee meeting, committee members showed concern for the airborne debris that arises from routing and blowing operations on pavement. We appreciate their inputs, and in response, we have included a debris removal system to the crack sealing machine. A debris removal system will eliminate the hazard of flying debris as well as leaving behind a cleaner roadway. Based on the nature of our crack preparation procedure, debris removal is possible without extensive modification of the original crack sealing machine design.

The router is the first preparation component to address the crack. The rotation of the router cutting head is such that the pavement broken loose from the cut is always ejected opposite the direction of travel. The router is followed by the heater/blower component (to be descirbed below) which is equipped with a large flow rate air blowing device to clear any remaining debris in the routed crack. The blower directs the air blast into the crack through a nozzle. The nozzle is inclined at an angle such that the debris will be propelled in the direction of vehicle travel. By careful placement of a debris catcher, debris will be propelled into a collector where suction will then pull the debris into a dust collector. Since all the debris will pass through a common area the longitudinal machine design requires only a single two sided collector. The general machine will require two single sided collectors. The design covered in this report will focus on the two sided collector design realizing the easy conversion into a single sided collector.

The Debris removal system design safely collects and disposes of the pavement debris generated by the crack preparation system. The debris enters the collector hood as shown

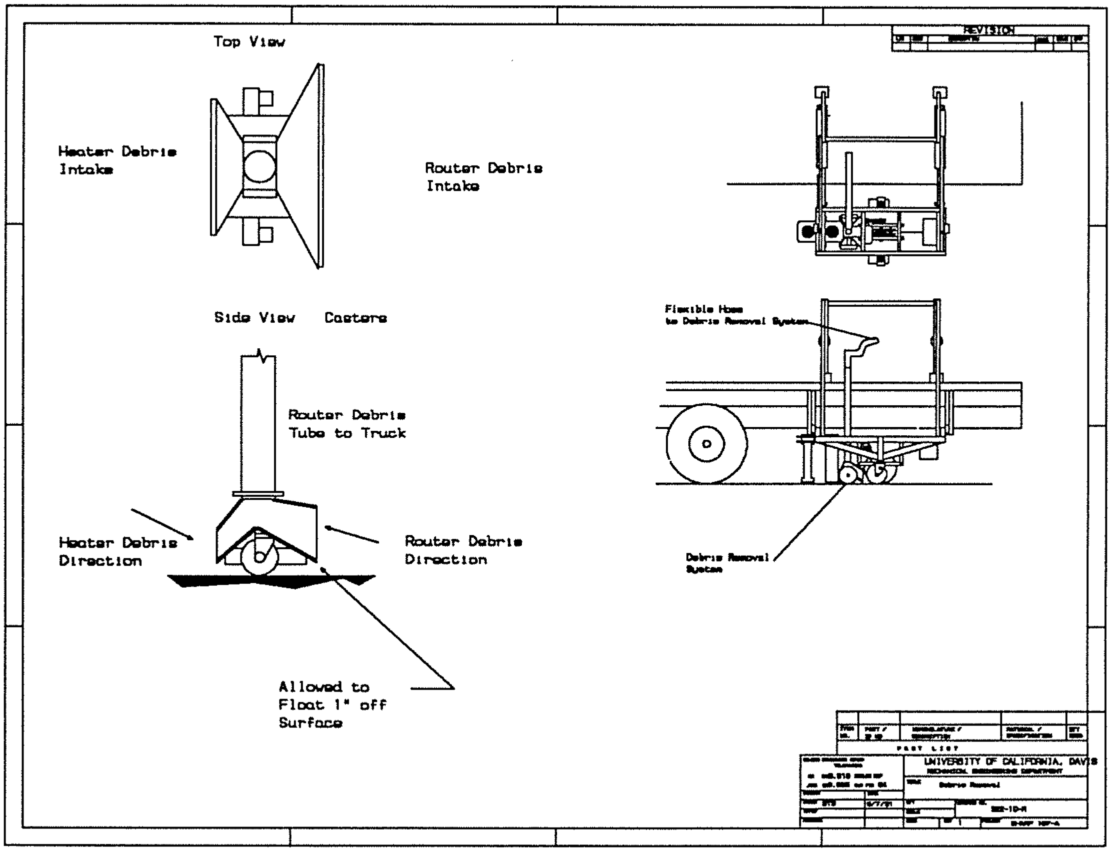


Figure 1.18 - Debris Removal Systerm

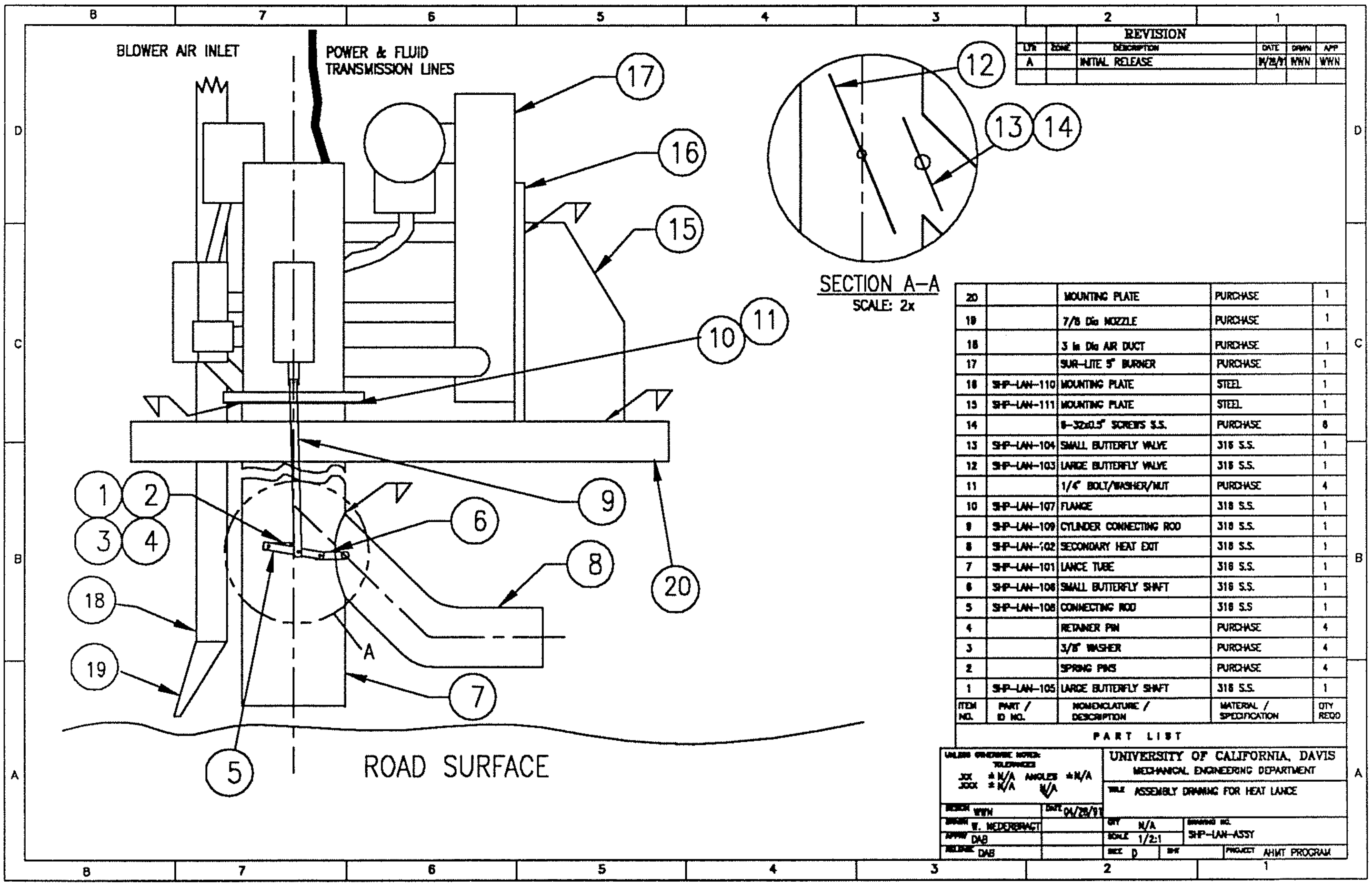
in Fig. 1.18 and is carried by vacuum through a three inch flexible duct. The duct then carries the debris to a cyclone separator dust collector were the dust and pavement chunks are removed. The air is then recirculated through the blower face and is sent down the three inch flex air duct to supply the heater/blower unit. This scheme eliminates the need for an additional component to create vacuum, since the vacuum is created at the air inlet to the 5 HP hydraulic centrifugal blower unit (see Appendix 6.6 Sonic Air Systems). This blower unit is already a requirement of the heater/blower unit located on the support vehicle platform. This system of debris removal is efficient in that it both blows the crack clean and sucks up the debris.

The possibility is also left open for pavement reclaiming or recycling. This industry has been enjoying enormous expansion in recent years and the debris collected behind a router could produce a sizable amount of recyclable pavement in a day's work. For instance, if a 1 cm x 4 cm low profile channel were cut in a road with the router travelling at 10 mph, roughly 8.4 cu. yds. of AC would be produced per hour. This future generation design issue, however, has not been fully addressed in Phase I, and it is beyond the scope of the H-107A project.

Crack Cleaning/Heating Component Design

After in depth literature study, analytical modelling and vendor contacts, a liquid propane burner package and hydraulically powered centrifugal blower has been specified for Phase II purchasing and testing. The burner unit, manufactured by Sur-Lite Burners (model no. 12145), consists of a 1.8 million BTU/hr 5" tube burner with a built in 600 cfm blower (see Appendix 6.6). It was chosen primarily for its high convective heat transfer ability and small size. Mounted to the exhaust will be a hydraulically controlled diverter valve. Crack cleaning will be accomplished via the output blower air from the 5HP Sonic Air Systems hydraulic blower previously specified in the debris removal portion of this section. Both burner and blower selection were made while keeping in mind Phase I project goals of modularity and flexibility. The design is shown in Fig. 1.19 below and detail drawings are provided in Appendix 6.4.

Sur-Lite's modular design and flexibility affords the possibility of moving much of the control system hardware and blower. These items can be remotely placed on the support vehicle platform without much difficulty should end-effector size constraints prove it necessary. The possibility also exists in future generation equipment to remove the blower



ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
20		MOUNTING PLATE	PURCHASE	1
19		7/8 Dia NOZZLE	PURCHASE	1
18		3 in Dia AIR DUCT	PURCHASE	1
17		SUR-LITE 5" BURNER	PURCHASE	1
16	SHP-LAN-110	MOUNTING PLATE	STEEL	1
15	SHP-LAN-111	MOUNTING PLATE	STEEL	1
14		8-32x0.5" SCREWS S.S.	PURCHASE	8
13	SHP-LAN-104	SMALL BUTTERFLY VALVE	316 S.S.	1
12	SHP-LAN-103	LARGE BUTTERFLY VALVE	316 S.S.	1
11		1/4" BOLT/WASHER/NUT	PURCHASE	4
10	SHP-LAN-107	FLANGE	316 S.S.	1
9	SHP-LAN-109	CYLINDER CONNECTING ROD	316 S.S.	1
8	SHP-LAN-102	SECONDARY HEAT EXIT	316 S.S.	1
7	SHP-LAN-101	LANCE TUBE	316 S.S.	1
6	SHP-LAN-106	SMALL BUTTERFLY SHAFT	316 S.S.	1
5	SHP-LAN-108	CONNECTING ROD	316 S.S	1
4		RETAINER PIN	PURCHASE	4
3		3/8" WASHER	PURCHASE	4
2		SPRING PINS	PURCHASE	4
1	SHP-LAN-105	LARGE BUTTERFLY SHAFT	316 S.S.	1

PART LIST

Figure 1.19 - Heating/Blower Unit

altogether and replace it with a larger central centrifugal blower system used for blowing, heating and removing debris. For this phase of development though, the vendor supplied 600 cfm blower will be used. 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.

The centrifugal blower air, return air from the debris removal system mentioned previously, will reach the end-effector via a 3" flex air line. This relatively large diameter is necessary in order to minimize pressure drop. The nozzle is similarly designed to gradually funnel the air to a 7/8" diameter exit providing exit air at 35,000 ft/min. Nozzle design is not crucial at this time and optimum cleaning performance will be studied in Phase II. These dimensions were provided by Sonic Air Systems engineers who are more than willing to participate in vacuum/blower system development.

The "convective force" added by the Sur-Lite system has already been shown analytically to increase AC surface temperature rise an average of 300% above that attained by using a standard HCA lance (see Fig. 1.10). However, in order to properly manage this increased heat flux, changes in the heat output of the system must occur rather instantaneously; i.e., the pavement must be heated uniformly so as to not burn the surface. Propane burners are designed primarily to be steady state devices. When quick changes in heat output are attempted, the possibility of a flame-out exists. Therefore, it is not feasible to control the burner output as a function of end-effector speed. By deflecting the flow of exhaust gases though, the same affect can be realized. This is the design strategy behind adopting a diverter valve assembly.

The diverter valve assembly utilizes a linked pair of high temperature butterfly valves to control the heat flow. Operation of the valves can be compared to that of shutters on a home window. When maximum heat is required, i.e., travelling at high speed with respect to the pavement, the shutters are open and maximum heat is sent towards the pavement. While travelling slower, the shutters are partially closed, and when stopped or during start-up, no hot exhaust flow impinges on the pavement. The valves will be controlled by a hydraulic actuator which is controlled though the ICU (see Figure 1.19, Items 1-9).

All material used in construction of the heating system will be 16 gage 316 stainless steel, as is used on an HCA lance. In the initial phase of testing the tube will be wrapped with insulation to help contain heat, with later tests planned at examining the possibility of sending centrifugal blower air though an air jacket surrounding the hot exhaust tube.

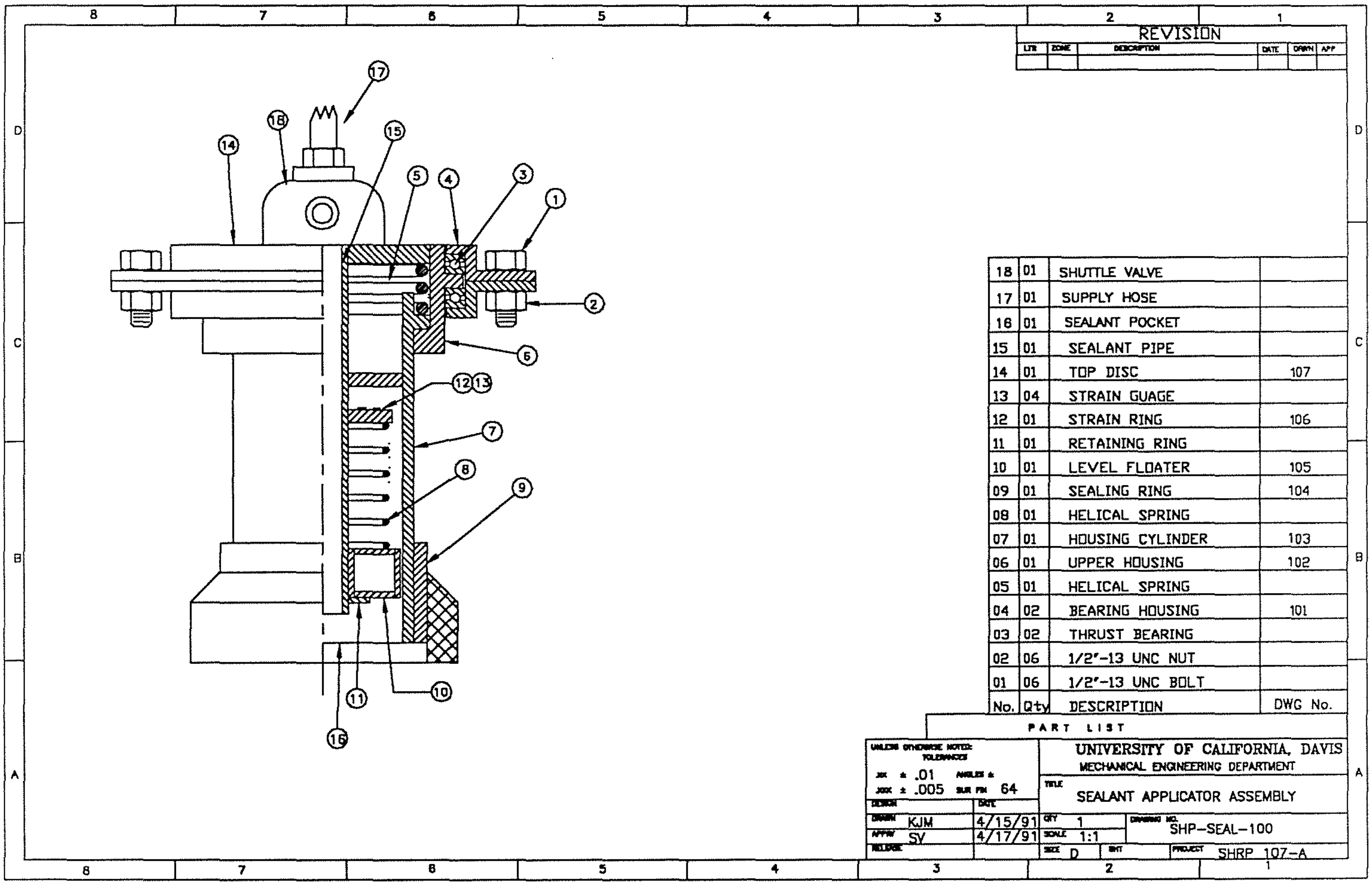
The burner on this unit, at maximum output, consumes approximately 83 lb of liquid propane (LP gas) per hour, meaning that for a normal eight hour work day, 667 lb of fuel could be consumed. By outfitting the support vehicle with 6-100 lb tanks, given a half hour of idle time, this consumption rate can be met. Tethered heater/cleaning support lines will consist of one 3" flex air line, one 1/2" flex gas line, two 1/4" hydraulic lines, and a wiring harness.

Possibilities for enhancement to the system in Phase II and III include implementing a mechatronics approach if diverter valve response is deemed to slow. By placing wheel encoders on the end-effector frame, the heater velocity with respect to the pavement can be triangulated. The digital signal could then be fed directly to a local CPU that controls the angle of diverter valve deflection. This approach is necessary only if diverter valve response quicker than that to be provided via the ICU and RPS proves necessary. Also, Caltrans has expressed interest in a mechanical linkage that ties the presence of a raised reflective road marker with diverter valve closure to avoid damaging its fragile heat sensitive surface. Furthermore, a heat exchanger may be implemented to harness the lost heat due to diverter valve closure. These three design modifications will be examined in more detail during Phases II and III as major emphasis has not been placed on them during Phase I.

Sealant Applicator Component Design

The H-107A sealant applicator component was designed with consideration of both the desired seal configuration as well as the method in which the applicator will function in the overall machine. Early in the applicator design process, it became evident that the sealant dispensing operation and the sealant configuration tooling (squeegee) would have to be combined to simplify the positioning system design. This is due to the fact that the general crack machine positioning system enlists the use of robotic manipulators to guide the preparation and sealant mechanisms along the crack. Based on cost and other logistics, it is best to minimize the number of robot manipulators. With all considerations, we have arrived at a concept that employs two robotic arms. One manipulator will position the router and it will additionally carry the local sensing unit. The other manipulator will position both the heating/blowing device and the sealant/squeegee applicator. By combining functions of the end-effectors, we will reduce the overall frame length of the longitudinal crack sealing machine which will have many positive effects.

The H-107A sealant applicator component shown in Fig. 1.20 is designed to automatically dispense and configure the correct amount of sealant in pavement cracks. The design is based upon the traditional dispensing and squeegee approach with several improvements. The combined sealant dispenser and squeegee has allowed us to develop a sealant pocket (Item 16) in the squeegee (Item 9), that has an automatic sealant level control. This is accomplished through the use of a mechanical float (Item 10) that rides on the surface on the sealant in the squeegee pocket. If the sealant level is low, sealant is introduced in the sealant pocket, below the float, through a sealant supply tube (Item 15). The sealant supply tube runs down the center of the applicator component and through the center of the float. A simple strain gauge (Item 13) is attached to a plate that is in turn connected by a spring (Item 8) to the float. This simple system allows us to sense the sealant level in the



18	01	SHUTTLE VALVE	
17	01	SUPPLY HOSE	
16	01	SEALANT POCKET	
15	01	SEALANT PIPE	
14	01	TOP DISC	107
13	04	STRAIN GUAGE	
12	01	STRAIN RING	106
11	01	RETAINING RING	
10	01	LEVEL FLOATER	105
09	01	SEALING RING	104
08	01	HELICAL SPRING	
07	01	HOUSING CYLINDER	103
06	01	UPPER HOUSING	102
05	01	HELICAL SPRING	
04	02	BEARING HOUSING	101
03	02	THRUST BEARING	
02	06	1/2"-13 UNC NUT	
01	06	1/2"-13 UNC BOLT	
No.	Qty	DESCRIPTION	DWG No.

Figure 1.20 - Sealant Dispensing/Finishing Unit

squeegee pocket; as the float displaces, a measurable deflection of the plate is indicated by the strain gage. The sealant level control eliminates crack underfilling and reduces material waste by allowing the sealant in the squeegee pocket to clear just as the applicator reaches the end of the crack.

The traditional dispensing and squeegee approach relies on gravity to drive the sealant into cracks. However, at faster surface speeds, such an approach may not allow adequate sealant dispersion resulting in a crack that is not completely filled. The H-107A applicator will maintain a sealant pressure between two and eight pounds per square inch in the squeegee pocket. The pressure results from a combination of sealant pressure from the supply hose (Item 17) and the force of the level sensing spring (Item 8) pushing down on the float. The sealant pressure developed in the squeegee pocket will force sealant down into the crack, completely filling the crack with an adequate amount of sealant. The pressure in the sealant pocket can be adjusted through the sealant supply hose to completely fill pavement cracks with sealant at any applicator surface speed. The squeegee will then wipe the sealant flush with the pavement surface creating the desired sealant configuration.

The sealant melter system that will be used circulates hot oil through the sealant hose to keep the sealant at its application temperature. Hot oil from the oil jacketed sealant hose will be circulated through the sealant supply tube and the float inside the applicator mechanism in order to maintain proper sealant application temperature. The heated internal surfaces will also assist in the initial warm-up period when the system is started and it will help to prevent the application mechanism from jamming due to the cooling of sealant on mechanical surfaces.

The incorporation of a sealant pocket in the applicator component led to the redesign of the squeegee profile. Common squeegee's have a bent "U" configuration that allows the sealant, that has been previously dispensed onto the pavement, to enter the front of the squeegee. The sealant is then troweled into the crack. The applicator sealant pocket design requires a rubber seal that encompasses the entire pocket to contain the pressurized sealant. This rubber seal additionally acts as a squeegee. The seal/squeegee was designed to be a common rubber hose that can removed and replaced on the applicator within minutes.

Standard pavement crack sealing squeegee's need a downward force of approximately ten to twenty pounds to work properly. The downward force comes from a combination of the weight of the squeegee and the operator pushing down on the squeegee handle. To duplicate the downward force on the H-107A applicator, a compression spring (Item 5) carries enough applicator body weight to duplicate the operation of the traditional squeegee. This duplicate downward force will also enable the new applicator squeegee to have a similar wear life as that of the traditional squeegee. The body spring float enables the applicator body to float, so the applicator can automatically follow the contour of the road. The three inch travel of the body spring permits the applicator to remain in contact with the pavement even when the router and the frame to which it and the applicator are attached, is raised from the roadway.

The modular design of the applicator end-effector allows the unit to be attached to either the longitudinal or the general crack sealing mechanism by a simple flange mounting (Item 2). The hot pour sealant will be supplied to the applicator from a two hundred gallon melter unit mounted on the truck platform. The sealant is pumped through a hot oil jacketed hose directly to the applicator. The flow of sealant into the squeegee pocket will be adjusted by a shuttle valve (Item 18) on top of the melter, while the sealant inside the applicator is captured by a check valve (not shown) placed inside the sealant pipe near the nozzle. When the flow is initiated, the shuttle valve is opened and the increase in sealant pressure inside applicator supply tube overcomes the check valve, and sealant flows into the squeegee pocket.

The thrust bearings (Item 3) around the mounting flange (Item 2) enable the applicator body to rotate for the option of an overband sealant configuration. Overbands are created by tilting the axis of applicator body a few degrees away from the normal direction. This allows sealant to flow out from under the squeegee at the desired sealant height. With the downward force on the squeegee focused on a small circumference of the squeegee ring, the rubber would eventually wear resulting in a flush configuration. To avoid this scenario, the applicator is rotated slowly to obtain even wear on the rubber ring and maintain the desired configuration.

Integration and Control Unit Design

Based on a thorough feasibility analysis and recommendation for component software and hardware, a system design for the Integration and Control Unit or target hardware and software has been developed, specified and purchased. The system consists of a VME bus backplane with power supply, OS-9 operating system to run on a 50 Mhz central processing unit, memory including RAM, ROM, hard drive, flexible drive and tape drive, analog and digital input and output, communication ports, and miscellaneous cabling. All recommendations were fulfilled including the rackmount card height of 6U to conform with the existing vision subsystem. The system is to be fully integrated and delivered as a "turn key operation". The total system will have a one year limited warranty on all components and system integration. The following is a list of all components specified and ordered for the integration and control system.

Qty	Description
1	HSE/17R-12V-W60-F3-S150-Ethernet Cables Includes a 17.5 inch (height) rackmount enclosure with 12-slot VME card cage, 500 Watt power supply, 60MB Embedded SCSI hard disk drive, 2MB 3.5" floppy disk drive, 150MB 1/4" Archive Streamer Tape Drive and Ethernet Cable Package which includes a Ethernet Transceiver, Transceiver Cable, 10 ft. Thin Net Cable, T-Connector (Thin Net) and 2-Terminators (Thin-Net).
1	HK68H/V3E-4MB Includes a 50 MHZ 68030 CPU with 4MB DRAM, 128 bytes non-volatile RAM, 4 RS-232 ports single parallel port, VSB compatible bus interface, SCSI interface, time of day clock and full interface to VMEbus with four level system controller functions.
1	XVME540 Analog I/O card. 12-bit A/D and D/A conversion. 16 channel, 4 channel output. Inputs configurable for bipolar or unipolar with 12-bit conversion resolution.
1	XVME201 Digital I/O Card. VMEbus interface, two 68230 Parallel Interface Timer (PI/T) chips, and TTL buffers to provide 48-bits of digital I/O. 4 bidirectional 8-bit ports and two 16-bit ports.)
1	XVME982 Software device drivers. M68000 Industrial I/O routines to control I/O module.

1	CMC ENP-10 Ethernet Communication Card. Interface between VMEbus host system and Ethernet. Processes network protocols, manages the local bus and performs DMA transfers across the bus.
1	CMC ENP-10 Software
1	OS-9 Professional Real-time, multi-user, multi-tasking operating system.
1	System State Debugger
1	Source Level Debugger

The software development platform to be used will be an Apollo 3500 workstation. The software will be developed using the UNIX operating system. The operating system choice is based upon the ICU team recommendation for a user friendly operating system that is used by many programmers. The platform selected is currently available from Caltrans and can be used for the duration of the project. The Apollo is a very capable workstation and is a Caltrans standard. The Caltrans workstation is currently being upgraded to boost its memory capacity and to install an Ethernet package which allows multiple operators concurrent access to the workstation. UNIX System V is also available for use on the workstation.

In order for the software development environment (UNIX) to download code to the target system, a cross compiler is necessary. Micro-ware Corporation manufactures a cross compiler for the UNIX operating system residing on an Apollo Workstation to the OS-9 operating system. This cross compiler is called the Unibridge. This system will be specified and purchased following the completion of the Apollo upgrade.

Figures 1.21 provides some insight into the ICU architecture and information flow from other subsystems.

Vehicle Orientation and Control Unit Design

As noted above, the Vehicle Orientation and Control Unit will serve two purposes. It will control the motion of the support vehicle based on instructions from the ICU and additionally, it will provide vehicle motion measurements necessary for accurate crack sensing and end-effector positioning. During Phase I initial considerations have been given to the design of this system and a method for monitoring vehicle velocity has been devised. Table 1.6 presents specifications for this system.

The platform vehicle velocity will be monitored using a wheel encoder system. Two wheel encoders are attached to the rear drive wheels of the platform vehicle and monitored with an IBM-PC based data acquisition system. Each wheel encoder can resolve 0.1° of rotational motion. The output of a wheel encoder is in the standard Transistor Transistor Logic (TTL) form which is a widely used integrated circuit logic. The output normally produces a"low" signal (0 - 0.8 V) and pulses to a "high" level output (2.0 - 5.0 V) 3600 times

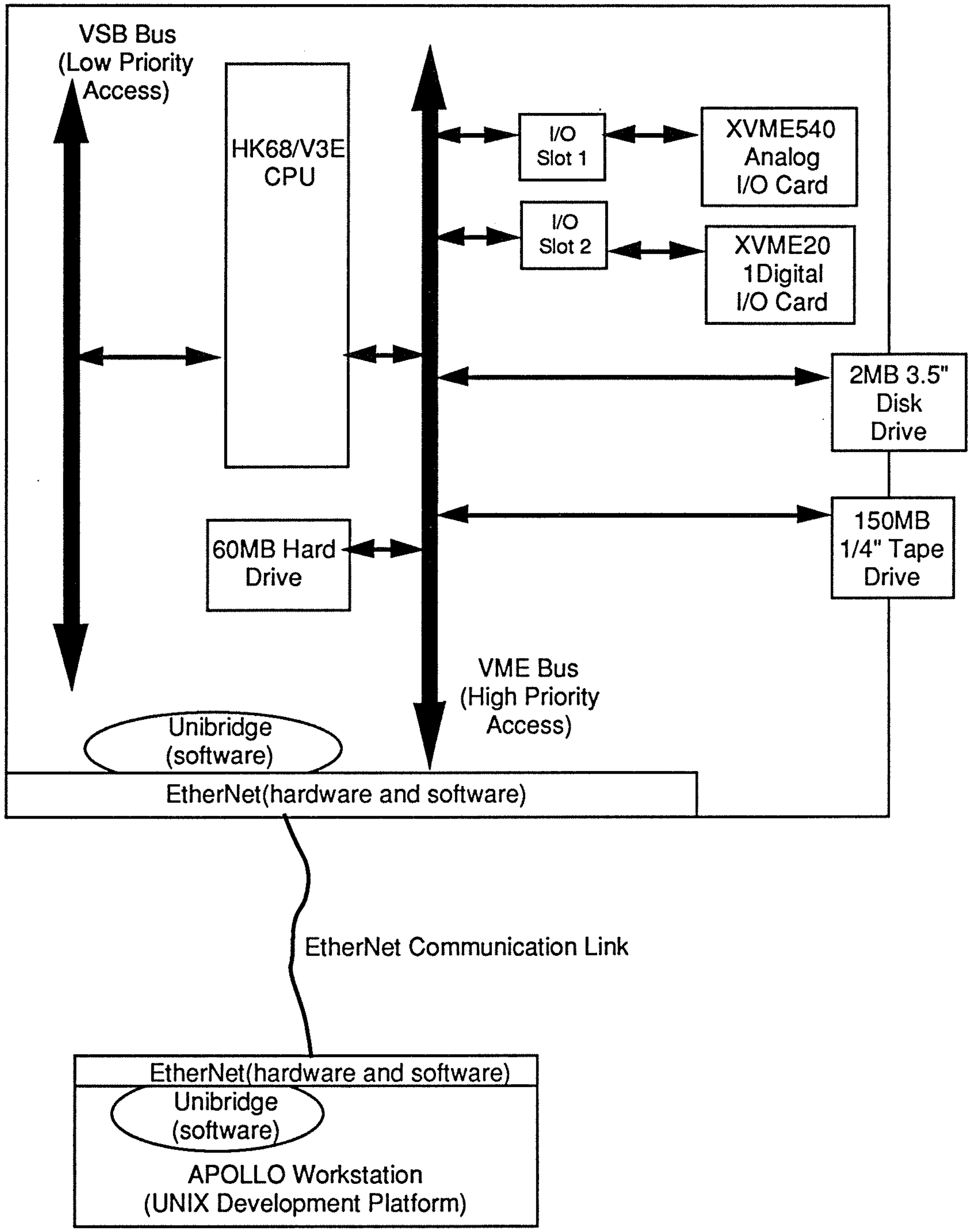


Figure 1.21 - VME Target Hardware and Software Development Plan

per revolution. The frequency of the output pulses vary with the platform vehicle speed. The frequency is measured with a Metrabyte DAS-16G data acquisition card.

The DAS-16G is a multi-function high speed I/O board designed for use in Microchannel based IBM PS/2 computers. The board contains an Intel 8254 programmable interval timer, which consists of three independent down counters. Two of the channel counters are used as a frequency divider from an internal 10 MHz xtal clock. The third channel provides a gated counter that can be used in conjunction with the other channels for frequency measurement.

The frequency of the input pulses from the wheel encoder is measured over 0.1 s intervals thus providing an updated and accurate velocity 10 times per second. The velocity update interval can be adjusted for various application requirements and expected vehicle speeds.

Resolution/Cycle Time

System should support sensing of a minimum of 1/16" of vehicle forward travel with the capability of sensing rotation of the vehicle.

The rolling radius of a standard heavy truck tire is approximately 20 inches. A 2010 pulse encoder (32*π*r(in)) would give 1/16" accuracy for this rolling radius. So the encoder must have at least 2010 pulses per revolution.

Environmental

The encoders should be resistant to the following:

- •condensating moisture
- •acoustic noise
- •mechanical vibration and shock
- •heat
- •dust and roadway debris
- •temperature variations
- •variations in lighting conditions
- •electromagnetic interference from nearby machinery, such as a generator

Reliability and Maintainability

The field system should make use of off-the shelf-technology, should be easily accessible for component replacement or adjustment and be as modular as possible. Also, the sensor system and its expected maintenance should provide for a service life of 10 years.

Field system would be more compactly mounted encoders than the fender mounted units which will be used for development

Table 1.6 - Vehicle Orientation and Control Specifications

Robot Positioning System Design

The function of the positioning system is to guide the process equipment used to prepare and seal the crack along the identified crack profiles. The system should have the capability to seal one lane width (approximately 13 feet) of road surface at an overall average speed of 2 mph. The process equipment usually consist of a heat lance, a router and the sealant applicator. This applicator has to track behind the the router and the heat lance. The positioning system is guided by a global and a local sensing system. The global sensing is used to identify cracks and it is used to move the positioning system in location for the sealing operation. The local sensing unit then guides the system along the crack profile.

The basic concept for the positioning system is developed such that it takes advantage of proven off-the-shelf component technologies and has the simplicity and the modularity necessary for ease of maintainability and system integration. The overall conceptual design of the system is shown in Figure 1.22. It consists of a pair of robot manipulators mounted on linear tracks along the rear bumper of a maintenance truck. These two manipulators can latch onto two "process carts" used for crack preparation and sealing. In this manner, the robot manipulators work as tool guides, moving the tools (the process carts) along a crack for the preparation and sealing operations. At the end of operation over a section of the roadway, the carts are moved (by the manipulators) to a home position on a ramp that lifts the carts into a stowed position on the truck. Sealant and other materials are transferred to the carts during the operation via interfaces on the robot end-effectors. The use of the process carts decouples the payload from the robots allowing utilization of commercially available manipulator technology. The linear tracks and the articulated robot configurations allow accessibility over the entire 13 feet lane width of the roadway.

The robot configurations are selected after a careful evaluation of the workspace requirements for the system. First of all, since the system should not add to the overall width

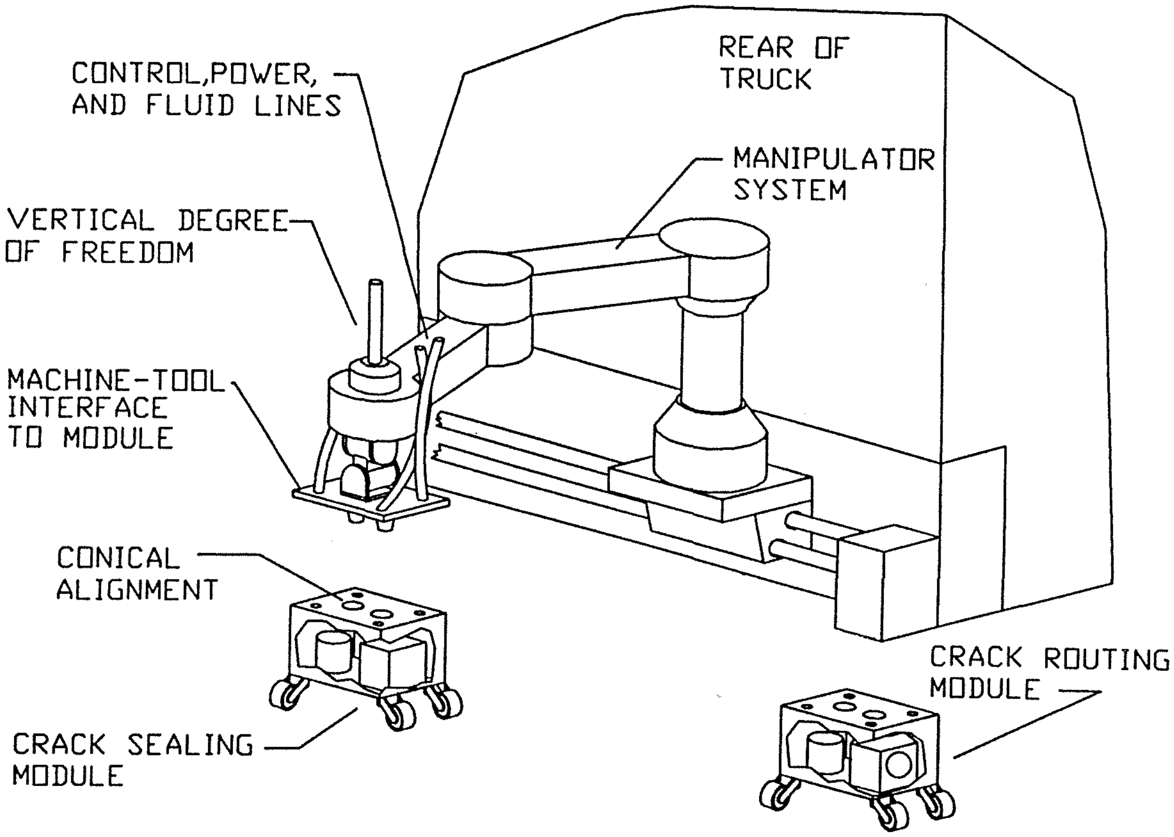


Figure 1.22 - Conceptual Design

of the maintenance truck but should be able to reach the entire 13 feet width of the roadway, gantry type robot configurations cannot be easily incorporated for the positioning system. The gantry configurations have the advantage of singularity free workspace but require a 13 feet axis of motion extending their mounting frame beyond the width of the maintenance truck. Other mounting configurations that would stow the manipulator vertically and then bring it into the horizontal position during operations were considered but it was found that it would degrade the system stability and rigidity while adding to the system complexity. The gantry type configurations were therefore eliminated from consideration.

The robot manipulators have to bring the process carts to the beginning of a crack on the top surface of the roadway and then follow the crack along its profile. This means that the robot manipulators can have decoupled motions in the horizontal (parallel to the top surface of the roadway) and the vertical planes. The motion in the horizontal plane is used for positioning and following the crack profile while the motion in the vertical plane is to adjust the clearance of the applicators as a function of local variations in the roadway geometry and heights. There is no dexterity requirements in the vertical plane while the motion in the horizontal plane require some level of dexterity to ensure that at any point within the workspace the robot can move parallel to the crack profile. Among all commercially available robot configurations, the SCARA configuration satisfies all the above mentioned motion requirements. The SCARA robot turns out to also be one of the simplest and most advanced commercially available robotic systems. The only limitation is that most commercial offerings of such a manipulator configuration do not have enough dexterity in the horizontal plane to provide the redundancy needed for avoiding singularities in following the crack profile. For this reason, our basic concept has the manipulator installed on a linear track (see Figure 1.23). This adds the redundant degree of freedom in the horizontal plane necessary for avoiding singularities and also adds to the reachable workspace of the

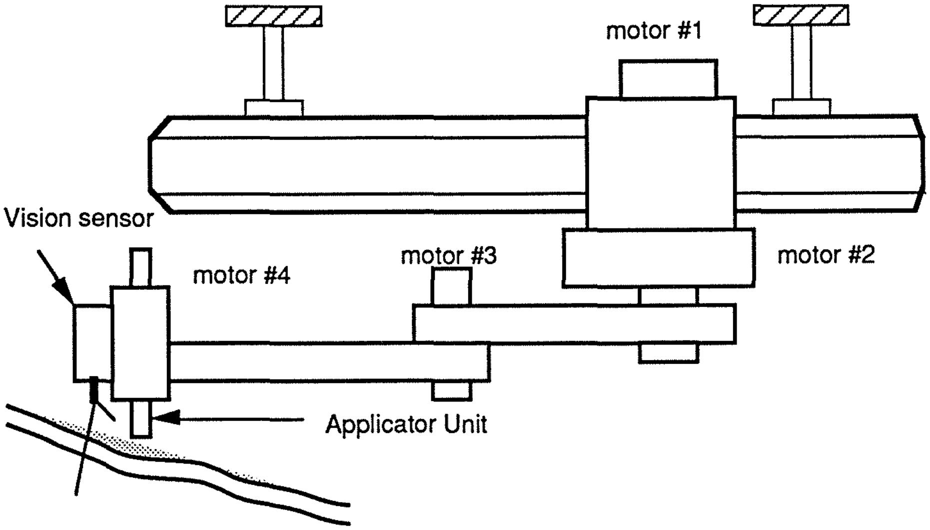


Figure 1.23 - Overview of Crack Sealing Robot

manipulator allowing it to reach beyond the truck width to cover the entire 13 feet width of the roadway.

The robot end-effectors consist of interface plates with all the hoses for the sealant an other process material attached to them. They can latch to the top surface of the process cart using a conical latching system similar to the conical tool change interface used in commercially available machine tools. The conical sections provide for large area of contact between the end-effector and the process cart increasing the stability of the attachment. In addition, the tapered nature of the conical sections, provide enough chamfer reducing the positioning accuracy requirement for the robot in latching to the process cart. The process cart for the sealant dispenser is shown in Figure 1.24. These process carts are designed to decouple the payload from the robot manipulators. The entire weight of the applicators are then carried by the wheels of the process carts and not the robots. The wheels have caster giving them the dexterity necessary to move them along the crack profiles. This innovative design of the applicator handling system, substantially reduces the payloads that need to be carried by the manipulators. The process carts can be eliminated, if during the detailed design of the system (during phase 2 of the project), the weight of the entire

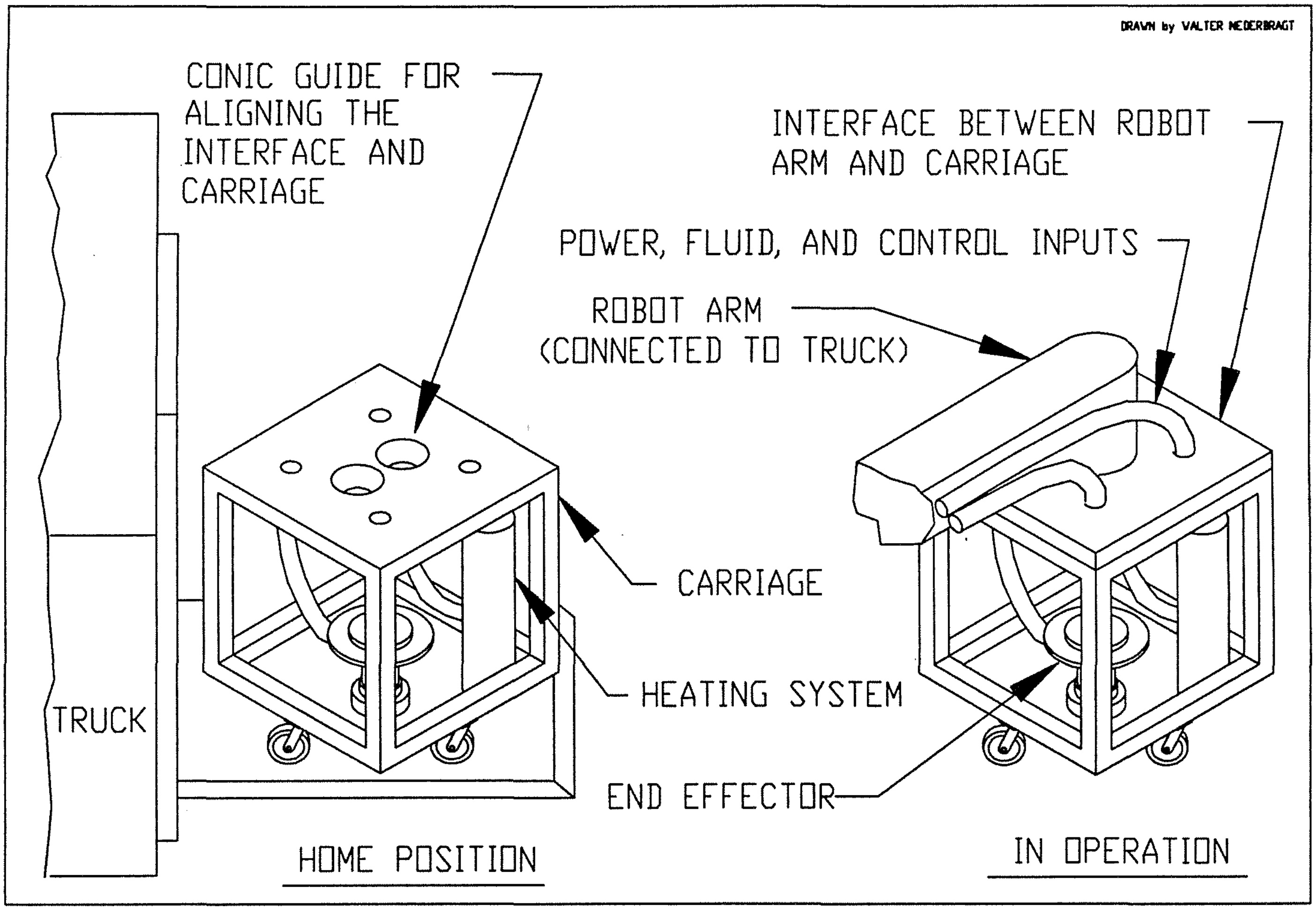


Figure 1.24 - Tool Guide for Crack Sealing

applicator assembly can be made within the dynamic load envelope of the manipulator. It should be mentioned that since the cracks have to be followed at speeds of approximately 2 mph, the payload is carried dynamically by the manipulator and will therefore be less than the manufacturer specification of the static payload of the robot. The decoupled design proposed here would eliminate any risks in terms of satisfying the robots load carrying capacities. In the research work plan, experiments are designed to determine the dynamic load carrying capacity of the manipulators in following a crack at 2 mph.

MACHINE PERFORMANCE SPECIFICATIONS

The development of machine performance specifications is quite difficult since these will be highly dependent on the necessary methods of operation which will be dictated by the H-106 study. Furthermore, there is no standard crack density and configuration with which performance can be gaged. Each state (and sometimes each region within a state) has its own guidelines related to the appropriate time to seal pavement cracks. Guidelines are related to such aspects as crack density and traffic volume.

In an effort to develop these specifications, we have queried maintenance districts within California to understand rates of sealant delivery, etc. While there is a reasonable amount of scatter in the lane miles covered in a given day of sealing, the average amount of sealant dispensed per mile is fairly consistent, that being on the order of 100 gallons per lane mile. We should note that this delivery rate is for unrouted cracks and an overband sealant configuration. In the event that a machine can operate at an average speed of 2 mph, it will require 200 gallons per hour of sealant which is at the upper limit of the standard commercially available melters.

Another means of determining sealant amounts is by considering the volume of standard rout configurations and the required sealant to just fill those channels. For a 1" x 1" channel, 273 gallons of sealant is required for each linear mile of crack. Again, this is pushing the limit for available melter equipment for an average speed of approximately 1 mph in this case (the slower speed corresponds to the additional time required for the routing process). However, both of these sealant delivery rates is feasible provided adequate melter tanks are available, or a support vehicle is used to provide additional melted material. Furthermore, lower profile rout configurations and/or slightly recessed seals can alleviate some of these requirements.

Another approach towards the estimate of machine sealing rates considers the required time to operate on each section of road. Earlier, we have noted that the crack sealing machinery would receive general sealing location information from a previous pavement distress survey. With such information, the sealing machinery can travel at a significantly higher travelling speed over sections of highway that will not require sealing. We now consider a worst case scenario in which the machinery will operate in a stop and go manner, it will be able to operate on a section at a time and each section will require sealing. Furthermore, let us assume that the workspace of the machine when stopped for a given section is 13 feet by 13 feet. If it takes 1 minute to operate on an individual section and reposition the machine from one section to the next, then the machine will seal 1 lane mile in 6.7 hours. This corresponds very closely to current manual sealing rates. Any increase in average speed, by reducing the time to operate on an individual section to under 1 minute or by avoiding the necessity to stop at each section, will have a pronounced effect on increasing the performance rate of the automated machinery over the current manual operations.

Although there are uncertainties in estimating machine performance, we expect to design each of the individual components of the integrated machine to perform at a rate consistent with a continuously moving general crack sealing machine moving at 2 mph. For the longitudinal machine components, we will design for speeds of two to five times the general machine.

As the project progresses, we will continue to monitor the estimated machine performance based on component testing. Additionally, the use of the Bechtel WALKTHRU simulation system will allow a further assessment of machine motion capabilities which will be quite valuable for the selection and design of positioning components, etc. during Phase II. In the following subsection, we will provide a cost benefit analysis of the integrated machine. Results will be based on automated sealing speeds both equal to, and twice that of, current manual sealing rates. Based on the data developed above, these rates seem quite reasonable for the automated machine and the next section will show its benefits.

COST BENEFIT ANALYSIS

An automated crack sealing system is a major investment that can offer substantial cost savings in labor and materials required to perform its tasks for up to ten years. In addition, many intangible benefits such as work crew safety, reduced traffic disruptions and higher quality maintenance of pavement can be realized.

In analyzing the system's cost and benefits, one may be concerned with two important questions: how long will it take the system to pay for itself, and how much benefits can one realize from this investment? The following analysis seeks to answer these questions in terms of the investment recovery period and net present value.

To ensure a high level of accuracy and reliability, all data and scenario used in this analysis are conservative and worst-case. Some data are based on California Department of Transportation's records. However, the analysis is generic in nature and should be applicable in any given situation. Reasonable assumptions are also made to facilitate the analysis. These assumptions will be clearly identified.

The major cost to implement the automated crack sealing system is the cost of the equipment. The platform for the new system may cost up to $250,000 based on the price of a similar platform used in current operation plus supporting equipment such as an air compressor, a heater, and an on-board computer system. Additionally, special devices are required to perform specific functions such as preparing the pavement, heating and applying bitumin. These may cost an average of $200,000, bringing the total system cost to $450,000.

The annual operational and material costs per system are estimated at $45,000, and $90,000 respectively. The operational costs include fuel, supplies, and maintenance of the system. The material costs include surface cleaning materials and bitumin. The estimated costs for the above are based on the average cost incurred by Caltrans. These costs are assumed to be a constant since the new system does not offer a significant advantage in operational and material costs.

The system cost savings analysis is performed based on three scenarios. In all cases, the rate of return for the investment (i) and the inflation rate (e) are assumed to be 10% and 5% respectively. The system service life is expected to be 10 years. The detailed cost savings analysis, including all relevant data, assumptions and a ten-year summary, is provided in Appendix 6.7.

In the first scenario, the analysis takes into account the reduction in the crew size alone. Currently, an average Caltrans crack sealing crew consists of 8 persons. Supporting tasks, such as lane closure and signing, are provided by a separate crew which will not be affected by the new system. An automated system will require a crew of 4 persons, one to operate the platform vehicle, one to monitor the system performance and two to operate a supply vehicle. If necessary, the supply vehicle team may also perform touch-up tasks and other duties as required. Assuming an average cost of $50,000 per person-year, the annual labor cost savings as a result of the crew size reduction alone would amount to $200,000. At this rate, the cost of investing in the new system may be recovered within 2.25 years and the system's net present value is over $500,000 (see summary case 1).

In the second scenario, the analysis takes into account the speed improvement over the existing system. Assuming that the new system may operate at up to 4 miles per day, the reduction in labor cost, allowing for overhead, may be reduced by an additional 30%. The annual labor cost savings would amount to an additional $60,000. Coupled with the savings from case 1, the recovery period is less than 2 years and the system's net present value is over $800,000 (see summary case 2). This is a rather conservative estimate given that the system will be designed to operate at an average speed of 2 miles per hour. Nonetheless, this estimate should be accurate early in the implementation stage due to the learning curve and logistical problems.

In the last scenario, the analysis assumes that a better sealing process performed by the new system will prolong the maintenance cycle from an average of once every two years to once every three years. This assumption is based on Caltrans data. This cycle change will not significantly affect the labor and operational costs but will decrease the annual cost of materials by 16.67%, an additional savings of $15,000. The annual savings resulting from the crew size reduction, the speed advantage, and the prolonged maintenance cycle now totals $275,000. The recovery period is reduced to just over 1.5 year whereas the net present value increases to over $900,000 (see summary case 3).

Note that the ten-year summary provides estimated actual cost savings for the system's entire service life. This may be helpful in the budgeting process.

The cost savings analysis clearly shows that the automated crack sealing system is an excellent investment for it offers a recovery period of less than 2.5 years and a net present value of up to $900,000. This is quite an attractive proposition even without considering the monetary value of the intangible benefits, which may be quite substantial. For instance, according to Caltrans' records, each accident involving personnel on the job costs the State on the order of hundreds of thousands of dollars in medical expenses and other compensation. The cost of litigations and liabilities may exceed one million dollars per incident. The automated crack sealing system will reduce or eliminate hazardous elements on the job as well as improving the crew's working environment, thereby allowing them to focus on the quality of work. The indirect savings from increased safety to the work crew alone may exceed the cost of the system.

CLOSURE

The purpose of the SHRP H-107A project is to develop automated pavement repair equipment. This section has presented the findings of Phase I of this project. The work presented has included a detailed feasibility study of the individual components that will comprise automated pavement repair machinery. This was followed by the development of both a global machine system architecture and the conceptual design of the prototype machinery to be developed during this project. The design of first generation machine components was then presented. These first generation components will be fabricated and qualification tested during Phase II of this project. The results of Phase I clearly indicate the feasibility for developing integrated machinery to repair pavement in an automated fashion, and a detailed cost benefit analysis has clearly indicated the potential value of this machinery.

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SECTION 2

WORK PLAN

SECTION 2 WORK PLAN

INTRODUCTION

This section details the work to be performed during Phase II of the H-107A project. Specifically, this phase includes two specific tasks; 1) the fabrication of first generation component prototypes, and 2) the testing of these components and the development of component modifications based on this testing. More globally, the goal of this phase is to make satisfactory progress concerning machine components such that the development of the integrated machinery in the last phase can be accomplished.

Due to contractual delays, the H-107A project started two months later than initially expected, and additionally subcontracts to ERES and Bechtel were further delayed. However, the nature of the SHRP program precludes the ability to merely push the entire project back; it is essential that the H-107A be completed by the initially proposed completion date. That is, the H-107A research team must produce the desired prototype machinery including its field testing and documentation in 25 months as opposed to the originally planned 27 months. As such, it will be necessary to accelerate the project during Phase II. The successful completion of the two noted tasks during the nine month Phase II period will have to be supplemented by additional work that will lead toward the integrated machinery.

The H-107A research group proposes to accelerate the project in several ways. We have found that the procurement of equipment and materials is sometimes a lengthy process. As such, we propose to purchase the vehicle platform, upon which the automated crack sealing machine will be based, during Phase II. This will require a redistribution of funds from Phase III into Phase II. Upon its procurement, we will immediately initiate the necessary vehicle modifications, and additionally, we anticipate the incorporation of select components as soon as possible. Secondly, we have made every effort to incorporate commercially available equipment in our component designs. Such equipment will therefore require a reduced amount of qualification testing and presumably this will result in less modifications for the final component designs. Next, we have incorporated computer simulation in our development process and we will continue to develop a detailed computer simulation model of the integrated machine during Phase II. Such computer models are extremely valuable for determining the physical configuration of the machinery as well as its limitations. These simulation models are not merely cartoons, but include the actual physical dimensions of the equipment and accurately simulate the machinery and its components' kinematics. They are therefore invaluable for ascertaining interference between components, etc. prior to fabrication. We also plan to refine the cost benefit analysis and machine performance specifications as progress is made in Phase II, and additionally, we expect to project the commercial cost of this equipment.

The proposed acceleration comes at no additional expense to SHRP. The personnel costs are virtually identical to that originally proposed for Phase II, and the only difference arises from the redistribution of Phase III monies into Phase II primarily for equipment. We will discuss more details of this modification in the budget section of this report. However to help put this redistribution in perspective, Phases I and Phase II constitute 60% of the total project duration, and we are requesting that the phases be supported by 64% of the total SHRP provided funds. It should also be noted that the last couple of months of the project will be heavily weighted by preparation of the project documentation and final reports, requiring little or no funds for equipment. As such, we feel that the requested redistribution of funds is both necessary and reasonable, and we appreciate your consideration on this critical matter.

FABRICATION AND TESTING OF FIRST GENERATION PROTOTYPES

At this point, we will first present an overview of the two tasks of Phase II, and then discuss details of the work plan for each individual component system and the integrated machine.

TASK 3: Fabricate First-generation Prototype of Equipment Components

Based on the plans, specifications and shop drawings to be approved by SHRP based on this report, the Purchase orders and subcontracts will be awarded and component fabrication/software development will begin. The component fabrication and software development work will be closely monitored and controlled. Detailed schedules for each operation will be agreed upon and serve as the basis for this control. During the fabrication of the Prototype Equipment Components, suggestions will be evaluated to improve the components and their functionality. These suggestions will be evaluated in accordance with an informal procedure which will consider the impact of the change on the fabrication process and determine the optimum time to implement an approved change. Often the project weekly meetings will be used to view progress first hand and discuss issues which could affect the component, system or project. In most cases some preliminary testing will be conducted prior to Task 4 - Conduct Component Test Program. These tests may also be observed as part of the project weekly meetings. Although not presently planned, the resources of the Bechtel Worldwide Procurement Network could be requested to provide assistance in inspecting the work or expediting delivery of a critical or key component.

At the same time that the fabrication of the equipment prototype components begins, the test sites chosen by the H-106 contractor will be investigated and local test sites will be established which are similar to the SHRP H-106 test sites. Since ERES is the H-106 contractor, they will coordiante this activity. All components will be modified according to SHRP recommendations and any subsequent debugging will be performed. Also components will be ruggedized and/or mounted in ruggedized enclosures and put in a form where they can be mounted to the applicator assembly.

Most component fabrication will take place at UC-Davis and Caltrans facilities. The detailed drawings of the equipment will continue to be produced in the UC-Davis Computer Integrated Design and Manufacturing Laboratory. ERES will be responsible for the development of component specification modifications since they will closely monitor the latest developments of commercial equipment for pavement maintenance.

TASK 4: Conduct a Laboratory Test Program Using Prototype Components & Prepare an Interim Report of Phase II

A laboratory testing plan will be developed to guide the actual testing of all components to ascertain that they comply with the conceptual design and meet all the operational requirements. ERES will be responsible for developing the plan with major input and comments from Caltrans and UC-Davis. Although this is a test plan for components, every possible effort will be made to verify compatibility and integration capability of all components. This will insure matching of system protocols and performance characteristics for team members and applicability to the actual crack and joint sealing and filling configurations that the H-106 contractor will be recommending.

The plan will address testing of all components under normal operating conditions to verify crucial parameters, as well as under adverse environments to assure the ruggedness of all components. Many electronic testing and data-collecting devices will be used. The actual tests will be performed at Caltrans Laboratory and UC-Davis with assistance from Caltrans pavement specialists and the Caltrans Divisions of Maintenance and Equipment. Certain tests requiring actual roadways may be performed at Caltrans facilities around Sacramento or at appropriate sites within the UC-Davis campus. Additionally, some of the vision and laser based sensor testing will be conducted with the use of the Odetics' Mobile Sensor Laboratory.

Environmental tests will be performed at Caltrans Laboratory using some of its specialized facilities and equipment such as:

- Temperature and humidity controlled chambers to simulate operations under extreme temperatures and a wide range of humidity levels.
- The Whirly Bird to verify results at various operating speeds.
- The Light Tunnel to test the vision system under various lighting levels and conditions.
- The Vibration Station to measure the ruggedness of each component under shock and vibrations.
- The Rain Tower to verify proper design and tolerance to rain and other liquids.

The detailed plan will be developed to incorporate the above items at the minimum. If necessary, additional testing will be designed and facilities identified. The component testing will be coincident with the field installation of repair material of the H-106 contract, and it should provide some early performance results for the H-106 contractor to include in their short term field evaluation reports. Modifications will be proposed based on test results, and following SHRP approval, they will be incorporated as revisions to the prototype specifications and drawings developed in Phase I.

Following the successful completion of Phase II testing, a report will be prepared which describes the testing program in detail. It will include information on what tests were performed, how the tests were conducted, what the results were, and an evaluation of the results. UC-Davis will assume the primary responsibility for preparing and submitting this report, but will receive extensive input from the rest of the project team. It is expected that this report will form the basis for the decision-making process regarding continuation toward the third phase of the project. This report will define the suggested modifications, which will allow for the initiation of the detailed drawings and specifications of the second generation prototype.

DETAILED WORK PLAN FOR COMPONENTS AND MACHINERY

Vision Sensing System

The end result of the component fabrication phase will be a machine vision system which recognizes cracks in real time for vehicle speeds as high as two miles per hour. This machine vision system will operate with both area scan and line scan camera technologies. During task 3 the implementation of the real-time application will begin with the testing of the image processing hardware and the interface of the line scan camera. Following the testing and interfacing of the image processing hardware, the necessary real-time software will be developed. The computer software will be developed in the C programming language under an OS-9 operating system environment. A portion of this work will involve programming the image processing boards using Data Cube's proprietary Imageflow software. We will additionally be involved in the computational aspects of the algorithm which are independent of the image processing boards.

Concurrent to the real-time implementation, efforts will be directed at further development of the detailed algorithm; e.g., other tile sizes and comparison criteria are being considered. Additionally, path planning algorithm development will be initiated. Appropriate path planning algorithms will have the potential to enhance the accuracy of the crack recognition.

The testing of the global machine vision system will involve the installation of the OS-9 development system and an optical encoder on a test vehicle. The test vehicle is the Odetics' Mobile Sensor Laboratory, a 7.5 x 12 foot enclosed air conditioned van which is used regularly as part of their own sensor development work. This vehicle contains the power, processing, displays, software, and sensor mounting and motion platforms which allow a wide variety of sensor technologies to be examined and tests to be performed. Odetics is a well respected company with one area of specialty in robotics and associated machine vision. Odetics has additional expertise in integrating vision systems, and this will be valuable. Six two day trips are anticipated for integrating the machine vision system with the test vehicle and one trip is anticipated for a Phase II demonstration of the machine vision system working on the test vehicle.

In parallel with the Phase II fabrication and testing, Phase III integration aspects will be considered in detail to ensure that communication with the integration and control unit will not hinder the performance of the global machine vision system nor the integration and control unit. The interaction of the local sensing system will also be considered which will also lead to an assessment of the alternative machine systems architecture.

Local Sensing Unit

During Phase II, a laser vision system using structured light will be purchased and the crack detecting algorithm will be implemented on the laser vision system dedicated computer. Additions to the current algorithm will address the possibility of multiple cracks in the scan width. Also, images of cracks filled with vegetation, dirt, and gravel will be categorized and a decision tree in software will be implemented to recognize these types of cracks. The algorithm will be refined for optimal performance on both AC and PCC. This software development will take place in a laboratory environment and outside on actual pavement surfaces under various conditions.

Procedures to test the integrity of the system software and hardware under worst case conditions will be developed. These tests will insure that the sensor requirements per Table 3 of the previous section are not degraded under various environmental conditions. To insure optimal performance, environmental testing will be performed at Caltrans Laboratory. The sensor must perform per specified sensor requirements at operating temperatures from -20° to 160° F and humidities to 85%. This will be verified in control chambers. The sensor performance will also be tested under various lighting conditions in the Caltrans Light Tunnel. Next, the Vibration Station will verify the vision system ruggedness under shock. Last, the sensor performance will be tested for its intolerance to rain in the Rain Tower.

Final tests will be developed to insure optimal sensor performance on the actual crack sealing vehicle. Sensor performance will be tested at varying operating speeds, weather conditions and lighting conditions. The local sensor will be tested along with the vision sensing system on the Odetics' Mobile Sensor Laboratory. As noted above, this vehicle provides an outstanding facility for simulation of the actual crack sealing machine environment. Work will include validation testing of the sensor and algorithms under the expected crack sealing conditions including a variety of types of pavements, types of cracks, and speeds.

During Phase II, the local sensing system will be integrated with a robotic arm manipulator system in order to demonstrate the feasibility of incorporating local sensing system feedback in the robot control algorithm. This will allow the initial development of control algorithms which will lead to the alternative machine system architecture discussed earlier.

Applicator and Peripherals System

Router Subsystem

The first step in the development of the high surface speed router will the initiation of procurement for all purchasable items, including an impact router, similar to that in Appendix #(Aeroil), extra impact cutters, hydraulic vane motor and miscellaneous hardware items. Fabrication will be initiated early in Phase II on the modular frame, as shown in the in the previous section. As the procured items arrive, fabrication will be extended to the cutting head and the drive train. When the purchased common impact router is received, it will be disassembled and its parts modified and assembled on the H-107A router.

The final assembly of the H-107A router will take place in a stepwise fashion where each step is collaborated with specific tests. This approach provides a means for isolating the cause of problems should they occur during development. The stepwise approach will also provide a method of evaluating the performance of each improvement made to the router, including the hydraulic system, larger cutting head, etc. As such, the new router's capabilities can be quantified on an elemental basis comparing each modification to the performance of the stock router.

The overall performance of the H-107A router will be determined by mounting the router to a generic frame attached to a modified test truck platform, which is capable of providing the controllable surface speeds required for testing over actual AC road test sites located on the UCD campus. The test frame of a generic nature such that other components can be mounted to it and tested. The completed router component will be systematically used and abused in an attempt to expose the strengths and weaknesses of the new design. The actual test procedures will be developed with ERES and will reflect the desired routed channel characteristics in light of the H-106 study. When testing is complete the entire group will review and discuss its performance and its capabilities to meet expected production rates. Finally, the group will discuss and develop recommendations for the next generation of high surface speed router.

Cleaning/Blowing/Heating Subsystem

During Phase II, testing of the heating unit and crack cleaning/debris removal system will be performed in order to optimize their performance. Testing on the Sur-Lite burner will be geared towards the development of a control algorithm for the diverter valve assembly and burner controller necessary to be implemented by the ICU. This will be accomplished through utilizing a test apparatus that was already constructed in Phase I for initial evaluation of HCA lance feasibility. The device uses quick response thermocouples placed at various depths connected to a PC based data acquisition system in order to capture a picture of temperature distribution in the pavement as the heater is passed over. The pavement surface temperature will be examined as a function of speed, LP gas pressure, fly height, and air supply. The results should indicate the best configuration for heater operation.

The blower/vacuum system will be tested primarily through trial and error in order to find the best cleaning configuration. As mentioned previously, a vacuum "catcher" will reside just behind the router. The entrance to this catcher must be optimized so as to retain maximum suction while capturing the maximum amount of debris. The cleaning nozzle exit profile must be optimized so as to clear a low profile routed path while travelling at high speed, yet enough force must still be behind the air to remove dirt film and crack debris. Pressure drop in both 2" flex air lines will be minimized through minimization of hose length, number of elbows, turns, and obstructions by optimal placement of the centrifugal blowing unit.

Sealant Applicator

Phase II will begin with the fabrication of the applicator component as shown in the design drawings. Fabrication will be distributed between the University of California, Davis and Caltrans fabrication shop facilities to expedite the building process. The procurement process will begin early in the second phase to compensate for unforeseen delay's in receiving these components, so the fabrication or assembly process will not be delayed. With the purchasing under way, ERES will spearhead the effort with the group to develop and design a test plan and the associated testing fixtures to evaluate the applicator component design. The applicator testing plan will have several goals including the evaluation of the maximum surface speed of the component, quality of the seal configuration and its expected service life.

The testing apparatus is expected to be a generic frame attached to a modified test truck platform, which will provide controllable surface speeds on actual AC road test sites located on the UCD campus. The test frame will be generic enough that other components can be mounted to it and tested. The modification of the test truck platform and the fabrication of the test frame will be the responsibility of UCD personnel. The group has already purchased a sealant melter that was specifically designed and built for this project to have a large sealant flow rate up to twenty gallons a minute. The melter will be towed behind the test truck supplying the applicator component during testing.

As the parts are received and fabricated the applicator component will be assembled in the SHRP/AHMT lab located on the UCD campus. First static testing will occur to adjust and verify the performance of the applicator component including the automatic sealant level system, squeegee downward force and road contour following system. Upon successful completion of this task, the applicator will be mounted on the mobile test frame and tested on the UCD test site. The component will be subjected to rigorous operating conditions to determine its limits and weaknesses. The group will then review and discuss the test results, to formulate recommendations on the next generation applicator components.

Robot Positioning System

Longitudinal Machine Positioning System

The development of the longitudinal positioning system involves detailed analysis and design of the numerous structural and positioning components. A detailed kinematic and dynamic analysis of the positioning linkage will be performed using the DADS software program. This will be followed by finite element analysis of the structural components and the selection of appropriate actuators and sensors. Bechtel will provide computer simulation of this system in order to assess integration problems such as interference. Subsequently, the system will be fabricated at a combination of UC-Davis and Caltrans facilities,and it will then be integrated onto the vehicle platform. Initial validation testing of this component will be performed with ballast weights as opposed to actual end-effector hardware and in a telerobotic mode to assess actual motion capabilities. The integration of actual end-effector components will take place early in Phase III.

General Machine Positioning System

The development of the general positioning system would involve both integration of commercially available components such as the SCARA manipulators and in-house detailed design, fabrication and developments that is necessary for the process carts, the linear slide, the end-effectors and the overall control unit integrating the local sensor and the linear slides with the robot controllers.

Two commercially available SCARA robot systems will be purchased and incorporated into a linear slide system. At present Direct Drive SCARA robots manufactured by Adept technologies are being considered for the project. The Adept controller is one of the most advanced commercially available robot controllers and allows integration of other controlled axes. The controller allows continuous path, Cartesian level programming with speed control along the path. This is specially suitable for following the crack profiles. The same controller can also coordinate the control of the extra degree of freedom due to the linear slide. This facilitates control of the redundant degree of freedom due to the linear slide allowing the avoidance of singularities in path following.

Once these robots are purchased, testing is necessary in two areas. One involves determination of the best mounting configuration that would maximize the dexterous workspace of the manipulators in accessing the road surface. The other involves determination of the dynamic load carrying capacity of the manipulator in following a crack profile at speeds as high as 2 mph. The first area would involve some level of simulation and testing, and this is an opportune part of the work to employ the capabilities of the Bechtel WALKTHRU simulation system. The result will be the determination of the sub-space of the robot workspace that would allow the end-effector to move parallel to the crack profile from any point within its reachable workspace.

The second test would determine the size, weight and inertia of the maximum payload that the manipulators can carry at speeds up to 2 mph. Our staff have extensive experience in determination of the dynamic load carrying capacity of robot manipulators. This experience base will be used and the load envelope of the robots will be used to develop the detailed specifications of the applicator heads. The result of this test would determine whether or not the applicator heads can be directly mounted to the robot end-effectors or if process carts have to be used as discussed in the section on the conceptual design. In this case, the detailed design of these carts will be developed and they will be fabricated. Non-holonomic path planning algorithms then need to be developed for proper guidance of the process carts along the crack profiles.

The testing and the development of the positioning system will be performed at the AHMT laboratory at UC-Davis with involvement from Caltrans and Bechtel personnel. The empirical determination of the best mounting configurations for the manipulators for maximum dexterity using the WALKTHRU simulation system will be performed by Bechtel corporation. The mounting of the manipulators on the linear slide and the coordinated control of this extra degree of freedom will be performed within the same laboratory. The integration of the end point local sensing system into the path following control system will be performed using the expertise within the Mechatronics laboratory at UC-Davis. The end-effectors and the process carts will be designed in-house but may be fabricated with collaboration with Caltrans machine shop facilities or Bechtel's vendor collaborations.

The entire integrated positioning system will then be tested and debugged, in a laboratory environment, at the end of the Phase II.

Integration and Control Unit

Phase II requires the demonstration of a working integration unit. The overall control need not be in place, but input and output protocols with all subsystems should be demonstrated, while the controlling procedures should be well-specified and possibly implemented.

TASKS

As the Integration and Control Unit (ICU) is the heart of the Automated Crack Sealing Machine(ACSM), a great deal of up front work is needed to make sure that all subsystem components are compatible with the ICU and therefore other subsystem components. For this reason, following a complete feasibility analysis and specification, a purchase order for the ICU was submitted at the end of Phase I. As delivery of the ICU is anticipated at the beginning of Phase II, work in this phase will be confined to the following tasks: Software development system and target system integration, target system acceptance and durability testing, standardization of communication protocol and parameters, system flow and test plans, and ICU/subsystem integration capability demonstration.

Meeting the objectives of Phase II begins with finalizing the workstation upgrade and testing and installing the target system. As was indicated in the Phase I feasibility report, the Apollo workstation to be supplied by Caltrans will undergo a major memory and communication upgrade that is anticipated to be complete within the first days of Phase II. Following the upgrade, effort will focus on setting up the workstation, installing software, and setting up user accounts. During this time frame, acceptance testing of the vendor delivered target system operation will be conducted with special attention given to testing board integration and communication.

Following operational acceptance testing of the target system, durability testing will begin. Laboratory tests will be conducted to be assured that all target system components comply with manufacturer's specification for ruggedness. These tests will include shock and vibration, temperature and humidity testing of the vehicle mounted target system. The durability tests will only ascertain the components capability to live up to the manufacturer's specifications. These tests are not designed to specify critical breakdown points by exceeding the manufacture's recommended limits. Additional ruggedization of components will be considered if actual vehicle vibration and shock exceed the manufacturer's specifications.

Subsequent to all acceptance and endurance testing, the software development platform will be interfaced to the target hardware. The communication link (Unibridge cross compiler) between both systems will be installed and tested, and communication between the two systems will be attempted. Because the target operating system is multi-tasking and the workstation will have a windowing capability, both operating systems can be run simultaneously and viewed on the workstation monitor.

In a parallel effort to previously mentioned tasks, the ICU group will partition specific subsystem software tasks and specify in more detail the general responsibilities of the ICU. The ICU group will then meet with each subsystem group to establish a formal division of tasks over the entire automated crack sealing machine. Interface protocol, software porting parameters, and communication timing between the subsystems and the ICU will be specified. Following these discussions, priority of subsystem tasks and specific program procedure flow can be completed. In order to perfect program effectiveness and efficiency, test plans and software tasks will be developed in parallel. The critical points in each program, including questionable input, should be foreseen in order to develop a quality system.

The next task will involve the demonstration of a limited version of the ICU target hardware and software. The demonstration will include limited communication and control of one or more subsystems. As an example, the ICU may pass coordinates to the robot position subsystem to produce basic robot movement, or the ICU might receive coordinates from the vision subsystem and display on the system display unit subsystem. These tests will demonstrate that all ICU input and output work effectively, and that communication protocol between ICU and subsystems are acceptable. This task will involve software development on the workstation and testing and debugging on the target system.

The final task is the preparation of results for the interim report of Phase II. Documentation of all acceptance and endurance testing results, conclusions and suggestions will be presented in addition to all established protocols and parameters. The specific procedure flow of the automated crack sealing machine and the results of the limited integration of one or more subsystems will also be documented in the interim report.

The following is a list of specific ICU tasks for Phase II:

- Complete upgrade and set-up of development platform, set-up target hardware, and install cross-compiler software.
- Interface software development platform to target hardware.
- Specify task requirements and communication protocol with subsystems.
- Specify procedures and develop test plan.
- Develop software on the development platform.
- Test & Debug software on target hardware.
- Demonstrate the limited version of ICU target hardware/software based on work to date.
- Compile documentation and progress report on Phase II.

Integrated Machine Development

Although the integrated machinery is to be developed during Phase III of this project, we anticipate initial work in this area during Phase II in order to accelerate the program. First, as noted earlier, the support vehicle platform will be selected and purchased. Based on the lead time to acquire such large equipment, this will be necessary during Phase II. Once procured, modifications to the platform will be initiated as will the incorporation of some of the equipment.

During Phase II, work will progress on the development of a detailed simulation model of the integrated machine using Bechtel's WALKTHRU simulation package. This will allow detailed analysis of the integrated machine prior to fabrication and will be extremely valuable in assessing such aspects as interference. Also during this phase, we will initiate the integration of component systems such as the integration of the local sensor system on an existing robot. Each of these activities will help lead toward the successful development of the integrated machine in Phase III.

ANTICIPATED RESEARCH RESULTS

Here, the research results are merely summarized as the deliverables from each task. It should be noted that additional work will be performed, as discussed above, in order to accelerate the project and meet the final machine development deadline.

Task 3:

PRODUCT: The first generation prototype equipment for each component identified above along with a report detailing its schematic configuration and principles of operation.

Task 4:

PRODUCT: A report detailing a comprehensive test program for the prototype equipment components fabricated in Task 3.

PRODUCT: A report detailing the results of the comprehensive test program for the prototype components. The document will discuss the quality of work accomplished by each component and provide associated data to support the quality achieved. Additionally, it will discuss and recommend modifications for the second generation components. Finally, the report will discuss the projected commercial cost of the equipment.

CLOSURE

This section has discussed the proposed work plan for Phase II of the SHRP H-107A project. In addition to completing the two tasks originally proposed, the project team has discussed an approach towards accelerating the progress of this project in order to meet the original project completion date based on SHRP deadlines.

SECTION 3

MANAGEMENT PLAN

SECTION 3 MANAGEMENT PLAN

INTRODUCTION

The research team for this project is comprised of individuals from the University of California at Davis (UC-Davis), California Department of Transportation (Caltrans), Bechtel Corporation, and ERES Consultants, Inc. The University of California is taking the leading management role with the Principal Investigator being Prof. Steven A. Velinsky and the Co-Principal Investigator is Prof. Bahram Ravani. The University of California is the prime contractor and assumes full responsibility for all technical, financial, and performance requirements of the work. The management structure described below has been employed successfully during Phase I of this project, and its use will continue through Phase II.

PROJECT MANAGEMENT

Management Philosophy

The participants from UC-Davis and Caltrans had a close working relationship based on the UC-Davis Advanced Highway Maintenance Technology (AHMT) Program prior to the start of H-107A. Through AHMT, a highly successful management structure has been developed to effectively coordinate the efforts of various working groups, and this structure has carried through to SHRP H-107A. The management structure that has been used successfully thus far for H-107A is shown in Fig. 3-1. It is designed with a streamlined, high flexibility concept and is a fairly standard management philosophy for this type of project. The Principal Investigator is the focal point of all decision making and activities. He is responsible for the coordination with the Co-Investigators, and the Project Managers from Caltrans, Bechtel, and ERES. Each Project Manager is in turn responsible for work assigned to each working group, and he is to stay in close contact with the Principal Investigator. The Project Manager ensures that advancements are continually being made on the project; that time constraints and budget limitations are carefully observed in the conduct of the work; that staffing requirements are available to correspond to the fluctuating needs of the project; and that problem areas and conflicts are quickly and effectively addressed. At least one alternate project manager is assigned by each party to ensure continuity and unobstructed work flow during absences, etc.

Overall technical direction for a project is provided by senior personnel who possess a strong technical background in the subject area. The work is continually reviewed within the working groups themselves. Additionally, work is reviewed on a regular basis by the entire research team to provide additional insights and to ensure the overall compatibility and quality of the work.

Management Team

The managerial organization as depicted in Fig. 3.1 has allowed maximum control and flexibility of the project team. The Principal Investigators and Project Managers have been selected based on their technical expertise and their management abilities. Professor Steven Velinsky of UC-Davis is the Principal Investigator, the Co-Principal Investigator is Prof. Bahram Ravani, and Prof. Kazou Yamazaki is Co-Investigator for Phase II. Prof. Ravani and Prof. Yamazaki offer direct assistance to the Principal Investigator in the day-to-day operations of the project. For Phase II, Prof. Velinsky will commit 33% of his time during the academic year and 100% of his time for three summer months. Additionally, Prof. Ravani will commit 10% of his time during the academic year and 66% of his time for the three summer months, and Prof. Yamazaki will commit 10% of his time during the academic year and 33% of his time for the three summer months. This significant commitment of time will provide the necessary direction for a successful phase. Additionally, Mr. Duane Bennett, UC-Davis Project Engineer, will spend 100% of his time on this project. . Mr. Bennett has over fourteen years experience as a machinist in addition to his B.S. in engineering. He will report directly to the Principal and Co-Principal Investigator and he will serve as a liaison between the team of graduate students, undergraduate hourly students, visiting scholars and other support personnel. Additionally, the Project Engineer will coordinate work with the machine shops and other university support facilities.

Each other organization in the research team has designated a project manager an alternate project manager, and a Project Engineer, each committing a significant portion of their time to the project, such that there is a direct line of communication and direction. The project managers from Caltrans and the industrial participants report directly to the Principal Investigator. Mr. Sompol Chatusripitak is Caltrans' Project Manager, with Mr. Tom West serving as his alternate. Mr. Ken Kirschke will serve as Caltrans' Project Engineer. He has spent, and will continue to spend, 100% of his time on this project. In addition to leading the machine vision development portion of this work, he has been liaison with Caltrans' pavement experts and maintenance personnel.

Mr. John Robinson is designated the Project Manager from Bechtel, Mr. Bob Graham is Bechtel's Alternate Project Manager, and Mr. Kim Auclair is Bechtel's designated Project Engineer. This group has experience in areas as diverse as systems integration, vendor management, special remote/robotic system development, construction, and operational requirements.

Mr. David Peshkin is designated as ERES' Project Manager. Mr. Peshkin is acutely aware of the demands of this type of project and he will work with other team members to ensure that the project requirements are met. Mr. Kurt Johnson will be Mr. Peshkin's alternate and he has also been assigned as Senior Project Engineer. Mr. Kurt D. Smith, P.E. has also been assigned as Senior Project Engineer within ERES.

Division of Labor

UC-Davis together with Caltrans will take the primary responsibility for Phase II activities. Most component fabrication and testing will take place at UC-Davis and Caltrans facilities. UC-Davis will also be responsible for monitoring the progress of subcontractors. The detailed drawings of the equipment will continue to be produced in the UC-Davis Computer Integrated Design and Manufacturing Laboratory. Bechtel's experience with robotics and vendors that produce automation equipment will be relied upon all through this Phase, as will ERES extensive experience in the pavement field. Bechtel will play a major role in further development of the machine concept through such aspects as computer simulation and animation. They will participate in the final choices for robotic and automation components. They will also initiate an ergonomic evaluation of the machinery including such aspects as the required information to relay to the operator through the System Display Unit, for purposes of optimizing the operational efficiency of the crack sealing process. ERES will be responsible for the development of component and test specifications. They will additionally keep a close watch on the latest material developments through their H-106 involvement, and they will closely monitor the latest developments of commercial equipment for pavement maintenance. ERES will initiate the development of local test sites (in California) to correspond to the types of test sites of H-106 which will lead to their development of test specifications for the final field testing and demonstrations of Phase III.

Project Coordination

A project meeting will be held weekly to assess the progress and to provide direction for continuing efforts. All team members from UC-Davis and Caltrans will participate in these weekly sessions. At least one Bechtel participant will attend each weekly meeting. When appropriate, specialists and experts from various fields such as pavement technology, sealant materials, highway maintenance, heavy equipment, chemical analysis, safety procedures, etc., from Caltrans as well as other organizations will be invited to participate at these meetings..

The weekly meetings will serve several purposes. Each week, each project manager will make a short presentation on the progress of his working group. The Principal Investigator will communicate bi-weekly with the ERES Project Manager by telephone and fax, and he will present ERES' progress. Each week a specific working group will be selected for a more in-depth presentation. Such meetings will allow for considerable interaction by all team members and will be extremely valuable at critical times in the design process. Additionally, there will be many individuals with deep knowledge of the project.

In addition to the weekly meetings, there will be a quarterly meeting involving all UC-Davis, Caltrans, and Bechtel participants in addition to at least one ERES participant. At the time of the quarterly meeting, the ERES representative will spend additional time interacting individually with each organization.

Integration of Outside Organizations

In addition to communication among the project team members, frequent interaction with SHRP is essential. The guidance and direction provided by the SHRP staff is considered critical to the successful completion of the project. The team assembled for this project desires active participation from SHRP. In addition to quarterly progress reports, we will maintain frequent communication with SHRP throughout the length of the project. Furthermore, we encourage SHRP staff to make frequent visits to the various team facilities to discuss the progress of the project, to conduct on-site inspections, and to participate in the testing and evaluation of the equipment. Since ERES is the H-106 contractor, we have close coordination with that research group. Additionally, we anticipate a meeting approximately every six months to transfer technology with the H-107B group.

Project Administration

Strict adherence to the project schedule is needed to ensure that the project goals are met. To achieve this, all work efforts will be constantly monitored by the Project Managers and overseen by the Principal Investigator. If it is discovered that work is falling behind schedule, additional resources will be mobilized. This can be accomplished by increasing individual time commitments or adding personnel to the project. All participant organizations of this proposal have committed their resources to ensure the successful completion of the project.

The project managers will maintain tight control over project expenditures. Labor and direct costs will be reported on a monthly, task-by-task basis. In addition to financial information, monthly progress reports will briefly summarize technical progress. Quarterly progress reports will provide much additional detail including:

- Technical achievements over the reporting period.
- Status of work.
- Proposed modifications to the work plan (if any).
- Time/budget review.
- Work schedule for the following quarter.

These quarterly reports will include as much graphical information as possible to clearly illustrate the rate of expenditure, time schedule of the project, and estimations of completion dates and future expenditures. Additionally, video will be used regularly to show such aspects as prototype components in operation, etc. The format of the quarterly reports will be in strict accordance with the format and guidelines prescribed by SHRP.

Conflict Prevention

Every effort will be made by the project team to avoid the development of conflicts. First and foremost in this effort is the establishment of strong interactive communication. Clear and open lines of communication must be established and maintained between all team members, managers and SHRP. With the close working relationship of UC-Davis and Caltrans, the extensive experience of Bechtel personnel in Caltrans and their regular coordination with universities, government agencies and other companies, and the experience of ERES interacting with a variety of organizations (including SHRP), we anticipate a smooth working relationship with the potential for conflicts being minimal. However, in the event that conflicts do arise, the respective Project Mangers will work with the SHRP Contract Manager to explore every avenue to resolve the issue.

CONTINUATION CRITERIA

The team of UC-Davis, Caltrans, Bechtel and ERES are committed to the development and delivery of high quality work and products. This is quite evident from the past accomplishments of each organization. The extensive cost sharing aspects of this proposal illustrate the firm commitment of the research team to produce the most effective machines possible.

As this research project is designated in funding phases, funding for each phase must be authorized by SHRP and an authorization for continuation into Phase III will occur at the end of Phase II. It is recognized that the continuation of work is not automatic and that it will be based on several factors, as outlined in the original Request for Proposal including:

1. Quality, thoroughness and timeliness of the work.

2. Demonstrated ability of the project team to achieve technical progress, to identify problems, to overcome problems, and to maintain focus on a practical, cost-effective end product.
3. Demonstrated ability of the contractor to cooperate productively with SHRP staff and other SHRP contractors in pursuit of the overall objectives of SHRP's research program.
4. Adherence to project budget and schedules.
5. Quarterly progress reports during the evaluation period.

The detailed work plan presented in Section 2 has been structured such that checkpoints or products are provided at the conclusion of Phase II. These products match the milestones and deliverables over the nine month Phase II period summarized in the Request for Proposal, those being:

1. Construct a first-generation prototype of all equipment components, accompanied by a report describing the schematic configuration and the principles of operation.
2. Develop a plan for the laboratory testing of all components.
3. Produce a report describing the conduct, results, and evaluation of the laboratory test program with respect to performance targets.

These criteria provide reasonable milestones with which to gage the progress of the work.

FLEXIBILITY OF THE RESEARCH TEAM

By their very nature, research projects require a certain amount of flexibility in order to meet the changing needs of the project. This project is certainly no exception, as the goals and objectives of the SHRP-sponsored research are apt to change due to interim developments, technology changes, and findings of both this and other research activities. The project team recognizes the need to be able to respond to changing research needs and direction and will remain flexible so that the overall objectives and goals of SHRP are fulfilled.

In addition, the project team is well aware that SHRP sometimes has needs that are not explicitly included in the work plan. These include the need for presentation materials, attendance at meetings, presentation or preparation of reports, etc. The project team is fully aware of these needs, recognizes their importance, and is committed to assisting SHRP staff to meet their needs in anyway.

SUMMARY

This section has outlined the management plan for Phase II of this project. UC-Davis and Caltrans have developed a strong working relationship over the past few years on a variety of projects, and in particular, they have been involved on the development of automated highway maintenance machinery for two years. The management plan for this project, which was derived directly from their joint experience, has performed quite well during Phase I. Bechtel and ERES personnel have become acclimated to the group during Phase I, and their continued involvement will be quite valuable. The principal participants' technical expertise, management experience, ability to work together, and accomplishments through Phase I of this project clearly indicate the likelihood of a highly successful Phase II.

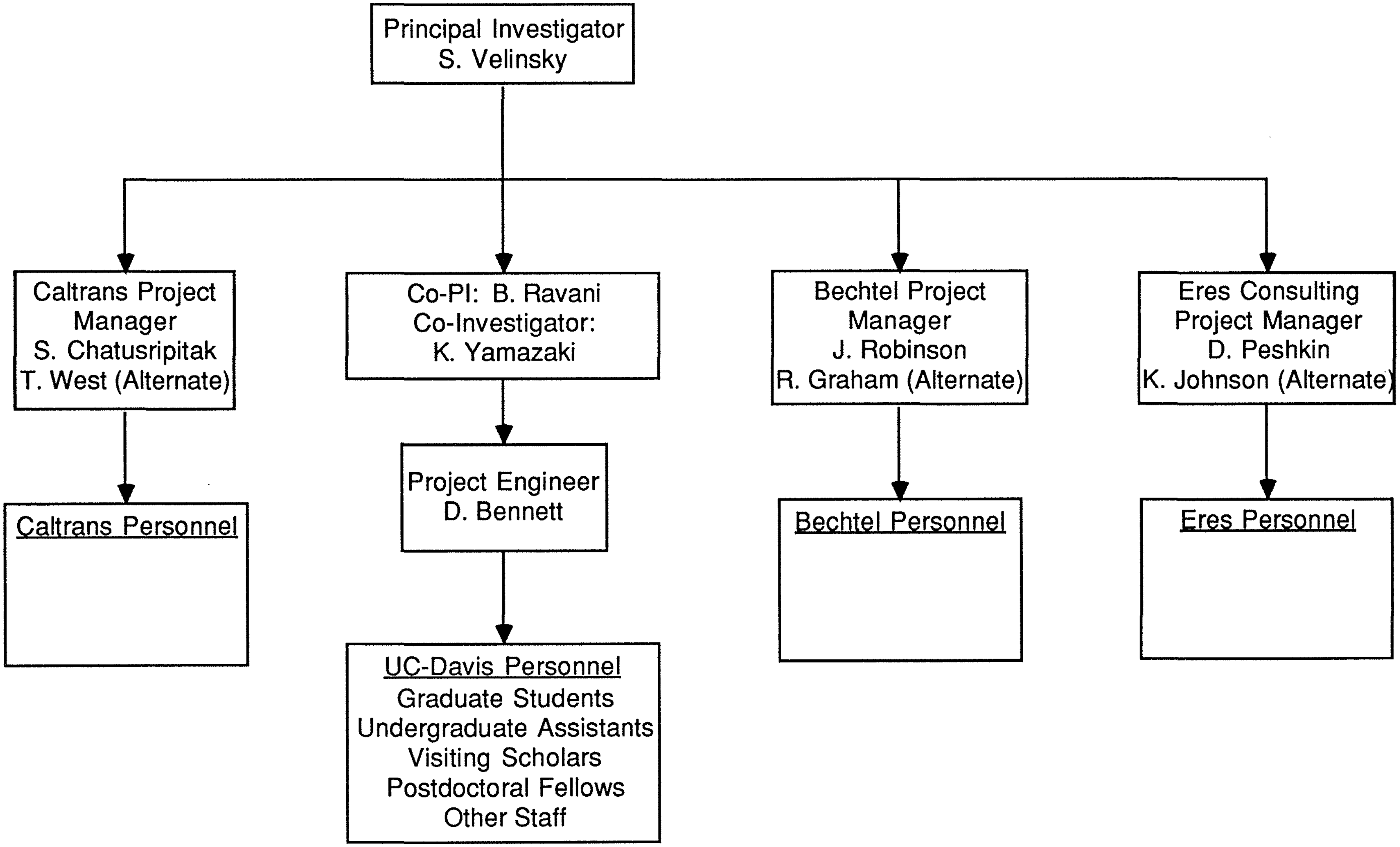


Fig. 3-1 Management Structure

SECTION 4

TIME REQUIREMENTS

SECTION 4 TIME REQUIREMENTS

A PERT Chart is included at the end of this section showing the flow of tasks through Phase II. Phase II has a nine month duration and it includes two specific tasks. Task 3, the fabrication of the first-generation prototype components, begins at the start of Phase II. Task 4, the design of experimental procedures and the experimental laboratory testing of the components also begins at the start of Phase II, as Tasks 3 and 4 run concurrently. That is, testing procedures and fixturing will be designed and built as early as possible in Phase II so that components can be tested as soon as they are fabricated. Since there are numerous components, it will be essential to initiate testing on some while others are being fabricated. We envision Task 3 continuing into Phase III so that the final component designs can incorporate all of SHRP's suggestions and a smooth transition can made into the next phase. We intend to provide materials for review to SHRP throughout the task periods so that SHRP will have had significant input prior to the final submittal. In doing so, we will expedite the final review at the end of Phase II and smoothly progress to Phase III.

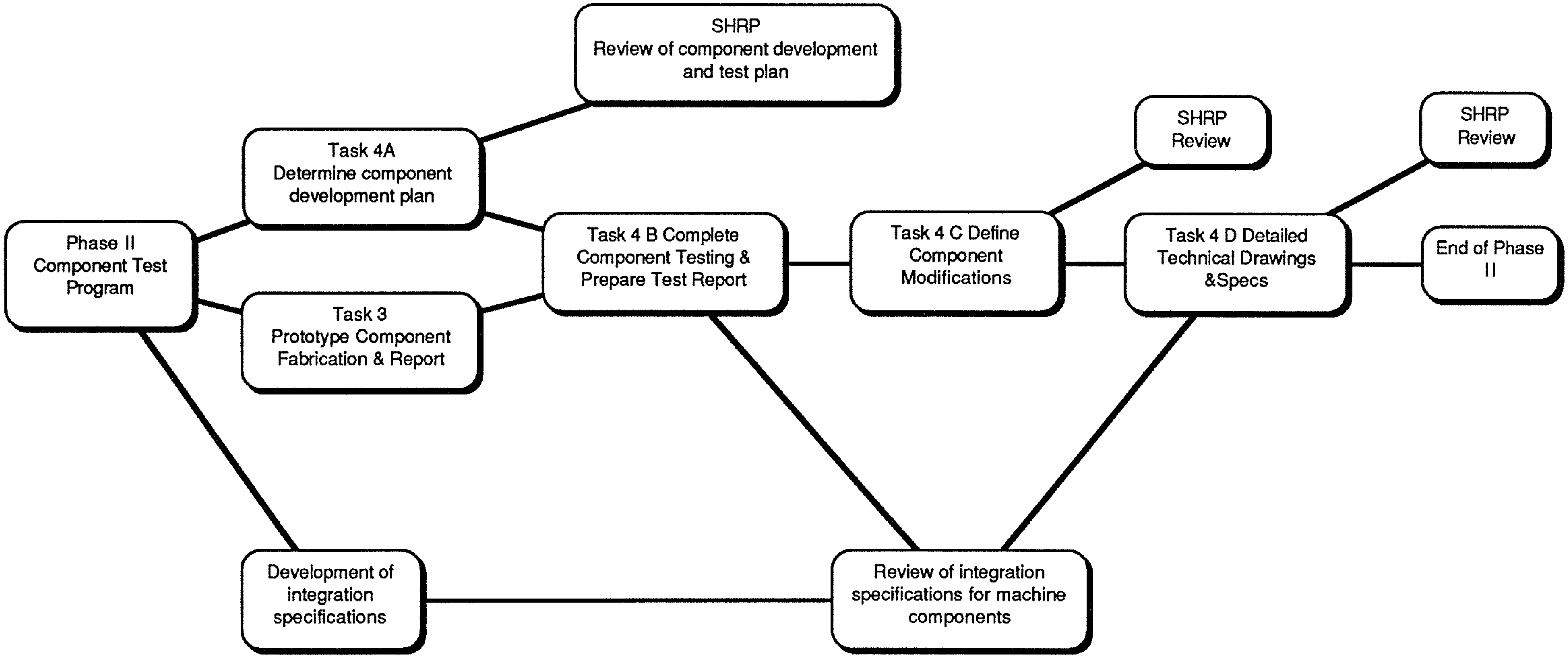
Since research goals and objectives are apt to change according to on-going findings of this and other studies, the actual duration of each task will be a function of the refinement of SHRP goals. The project team assembled to perform this study will remain very flexible in scheduling to address the needs of their research study.

In addition to tasks 3 and 4, our hope is to accelerate progress of this project by initiating some of the Phase III tasks. In particular, Tasks 5 and 6 are logical tasks to begin addressing during Phase II. Task 5 concerns the design and fabrication of the second generation component prototypes, and task 6 concerns the fabrication and assembly of the integrated prototype machine. As component testing in Phase II progresses, we hope to refine the initial designs of some of the components perhaps avoiding the necessity to redesign and fabricate these during task 5. Secondly, we have proposed to purchase and begin modifications on the vehicle platform during Phase II. In light of the procurement time necessary, we feel that this is essential. Furthermore, initial component integration can take place after the platform is available. Finally, we will develop integration specifications during Phase II that will help lead to a smooth system integration in Phase III.

Phase II activities last for nine months, and authorization to continue into Phase III will given at the end of Phase II without competition. This authorization to proceed will be based on the demonstrated ability of the project team to achieve technical progress, to overcome problems, and to maintain a focus on a practical, cost-effective end product; on adherence to project budget and schedule; and on quarterly progress reports during the evaluation period. Specific continuation criteria for the third phase are the quality, thoroughness, and timeliness of the work completed on the first-generation prototype components and their reports associated with the Phase II effort.

SHRP H-107A Phase II Project Plan

FABRICATION & TESTING OF COMPONENTS



Phase II
Component Test
Program

Task 4A
Determine component
development plan

SHRP
Review of component development
and test plan

Task 3
Prototype Component
Fabrication & Report

Task 4 B Complete
Component Testing &
Prepare Test Report

Task 4 C Define
Component
Modifications

SHRP
Review

Task 4 D Detailed
Technical Drawings
&Specs

SHRP
Review

End of Phase
II

Development of
integration
specifications

Review of integration
specifications for machine
components

SECTION 5

ITEMIZED BUDGET

SECTION 5 PHASE II ITEMIZED BUDGET

The Itemized Budget for the Phase II work is included at the end of this section in three tables. Table 5-1 provides a breakdown of the effort of the participants by task. Table 5-2 provides a summary of Project Costs for Phase II. Table 5-3 provides a summary of costs associated with capital equipment and subcontracts that will be purchased as part of the proposed work.

There are several aspects that are important to note. The H-107A project was initiated two months later than initially anticipated due to contractual delays. As a result, it is necessary to accelerate the progress of this project in order to successfully deliver prototype machinery according to SHRP deadlines. In order to do so, we are requesting a transfer of funds from the Phase III budget into the Phase II budget. We are not requesting additional project monies, merely a redistribution. The projected personnel costs for Phase II are approximately the same as proposed in the original budget. The modification of Phase II expenditures comes almost entirely from the purchase of additional capital equipment during this phase, as opposed to the originally proposed purchase of this same equipment during Phase III. Due to the tight schedule and the lead time necessary to acquire large items, we feel that this redistribution of funds is a necessity. Furthermore, the acquisition of these items, primarily the vehicle platform, will allow some initial progress on what was originally denoted as Phase III work; i.e., initial modifications to the platform, etc.

To help put this redistribution in perspective, the SHRP contribution to the total project will be $1,674,573, and with the proposed modifications, the Phase I and Phase II SHRP contributions amount to $1,067,291. That is, we are requesting approximately 64% of the total SHRP provided funds in Phases I and II. The total project duration is 25 months (shortened from the originally anticipated 27 months as noted above) and Phases I and II amount to 15 months; i.e., Phases I and II constitute 60% of the total project duration. Additionally, the last couple of months of the project will be heavily weighted by preparation of the project documentation and final reports. As such, we feel that the requested redistribution of funds is both necessary and reasonable, and we appreciate your consideration on this critical matter.

To follow are abbreviated explanations of each of the budget items presented in the included tables.

A) <u>Wage Costs</u> - Includes the Base (Bare) costs of Salaries and Wages for each Team Member/Employee. The breakdown of wage costs by name, group, role and task are included in Table 5-1 pages 1 and 2. Bechtel and ERES base their time on a 174 hour work-month. Caltrans bases their wages on a 152 hour work-month. UC-Davis bases their wages on a 174 hour work-month for staff and students. Faculty wages are based on a 152 hour work-month.

The estimate of Bechtel Wage costs are based on the actual average salary for each Salary Grade, for Bechtel Personnel as of April 30, 1990. Caltrans, and ERES wage costs are based on salary rates as of July 1, 1990. UC-Davis wage costs are based on current rates.

B) Payroll Benefits and Taxes - Includes the cost of Employee Benefit Plans, San Francisco Payroll Taxes (for Bechtel), and Payroll Additives. Payroll additives apply to regular straight time salaries, and include Employer's portion of FICA, SUI, FUI, payroll insurances, paid absences, and retirement benefits. ERES includes their Payroll Benefits within their Overhead. The rates are as follows:

UC-Davis	Faculty (academic year)	17.0%
	Faculty (summer)	9.85%
	Students	4.70%
	Staff	24.0%
Caltrans		22.0%
Bechtel		39.8%

C) Borrowed Personnel - No Borrowed Personnel are anticipated for this project.

D) Consultants - No Consultants are anticipated for this project.

E) Subcontracts and Suppliers - The breakdown of Subcontractor costs are included as Table 5-3. The Subcontracts for Phase II relate to testing of the sensing systems and modifications to the vehicle platform to be purchased. In addition, this sheet includes capital equipment expenditures. The total cost in this table is derived as follows: $375,000 through UC-Davis Capital Equipment Budget Item F, and $30,000 through UC-Davis Subcontracts Item E. This amounts to $480,000.

F) Capital Equipment Costs - The Capital Equipment Costs are listed in Table 5-2 , and are detailed in Table 5-3 as noted in the previous paragraph. Bechtel's Capital Equipment costs as listed in the original proposal have been moved to the UC-Davis budget.

G) Materials and Services - This item includes $50,000 of materials to be purchased by UC-Davis for the fabrication of the components. UC-Davis has an additional cost for machining which amounts to $15,000; UC-Davis' total Material and Services Costs = $65,000.

Bechtel includes their costs associated with preparing and reproducing reports as well which are determined as:

Bechtel	$1.54/Jobhour plus escalation

Caltrans' Material and Services Costs include: Transportation Laboratory modeling and machining services, Transportation Laboratory consulting and support services, Equipment shop machining services, Maintenance consulting and review services, Management services, Maintenance equipment and services for lane closures, use of testing facilities and specialized equipment for environmental tests, high speed analysis, and material testing.

H) Communications and Shipping - Includes Long Distance Telephone calls, Telegrams, TWX, Postage, Express Mail Services & Freight. Additionally, this includes the costs associated with preparing and transporting the reports associated with the project by UC-Davis. The rates for communications and shipping are as follows:

UC-Davis	$4,000
Caltrans	0
ERES ($240/task)	$480
Bechtel	$0.60/Jobhour plus escalation

I) Travel - Includes Transportation Costs plus reasonable actual subsistence costs in accordance with FAR 31.205-46. The destinations, number of trips, duration of each trip, and itinerary will be developed by the Principal Investigator and key project personnel. Travel expenses include travel to SHRP meetings. By proper planning, we feel that travel costs can be minimized and our estimated costs are $1000/trip per man. Additionally, travel expenses include transportation to weekly meetings for Bechtel.

J) Workshops - N/A.

K) Other Direct Costs - The Bechtel estimate includes a Standard Automation Rate of $1.55 per jobhour which allows for the recovery of cost related to Bechtel standardized computer services.

L) Labor Escalation - The Bechtel rate which is applied to labor escalation is 5% (Five Percent) per annum for 1990 and subsequent years calculated to the midpoint of each phase. Caltrans bases their labor escalation on 10% per year. UC-Davis bases their labor escalation on 5% per year for all faculty, staff, and students, and also allows for one 5% merit increase for faculty over the contract period. ERES labor escalation is based on one 5% increase between Phases II and III.

M) FCCM - Facilities Capital Cost of Money The FCCM is only applicable to Bechtel whose rates are shown below:

Transportation Group overhead	2.27%
Transportation Group G&A	0.19%
R&D Overhead	1.76%
R&D G&A	0.10%

FCCM for overhead is not applied to Bechtel procurement, corporate services and to the other Team Members.

N) G&A - (General and Administrative Expense) The G&A rates are only applicable to Bechtel and are as follows:

Transportation Group 1991-1193	14.9%
R&D 1991-1993	15.2%

These rates are applied to all Bechtel direct labor, overhead and other direct costs excluding engineering supplies, outside services, subcontracts, consultants, and Facilities Capital Cost of Money (FCCM).

O) Overhead/Burden - The rates for the Team Members are as follows:

UC-Davis	42.7%
Caltrans	30.0%
ERES (applied to direct labor costs)	150.0%
Bechtel	
Transportation 1991-1993	57.27%
R&D 1991-1993	84.45%
Procurement 1991-1993	20.60%

Bechtel Corporate Services such as Legal and Insurance and Controller attract no labor overhead. Note the Bechtel Overhead/Burden and other Bechtel rates are on file with the local DCAA office. These rates are presently approved for estimating, however are subject to adjustment during the Project. ERES overhead is applied to their direct labor costs and include benefits and taxes.

P) Fee - ERES Fixed Fee is 7% of their labor costs, travel, and communications and shipping expenses. Bechtel is cost sharing their fee for this project. Caltrans and UC-Davis have no fee.

Q) Cost Sharing Contribution - This contribution by the Team Members will assist in leveraging the funds of SHRP to produce more efficient repair vehicles at less cost to SHRP. Caltrans intends to share in the development costs of the automated crack sealing machine at a level of approximately $346,000 during the 9 month Phase II duration. Approximately one-fifth of that amount, or $75,000, will be provided in actual dollars made available to fund capital equipment during Phase II. The remaining $271,000 will be provided in terms of labor, materials, and services from Caltrans. It is important to note that in addition to the $346,000 in real expenditures to be cost shared by Caltrans, some costs that will occur are very hard to quantify and are therefore not included. An example of this is the cost associated with the use of Caltrans extensive highway facilities for prototype testing. Bechtel also is cost-sharing in this project; they are omitting their usual fee which is $16,619 for Phase II. Thus, total cost sharing for this phase is $360,000.

R) Additional Caltrans Cost Sharing to UC-Davis for Crack Sealing Project - These funds are discussed in the previous paragraph.

Q) Caltrans Travel in UC-Davis Budget - Based on state mandates, it is difficult for Caltrans personnel to travel, particularly out of the state of California. Due to the team effort and corresponding critical involvement of Caltrans personnel, it is essential that they participate at key meetings, etc. It is necessary for Caltrans personnel to travel through funds administered by UC-Davis and originating from SHRP. It should be noted that these funds are the only ones incurred to SHRP by Caltrans; Caltrans covers the transportation expenses of their personnel to weekly team meetings, etc..

Compensation

Based on the budget detailed in the enclosed tables, the requested Phase II project costs to be provided by SHRP amount to **$892,291**.

Level of Effort by Tasks (Man Hours and Wage Costs) **Table 5-1**

Phase II

Page 1 of 2

			(Manhours)			(Dollars)	
			Phase II				
Name	Position	Time (%)	Task 3	Task 4	Total (Mhs)	Hourly Rate (Bare)	Wage Costs
U.C. Davis Staff							
S. Velinsky	Principal Investigator	56	380	380	760	43.27	32,890
B. Ravani	Co-Principal Inv.	29	198	197	395	45.47	17,969
K. Yamazaki	Co-Investigator	18	121	122	243	46.35	11,271
D. Bennett	Project Engineer	100	783	783	1566	19.16	30,000
Grad Student #1	Technical Asst.	67	1044	0	1044	11.91	12,432
Grad Student #2	Technical Asst.	67	1044	0	1044	11.91	12,432
Grad Student #3	Technical Asst.	67	1044	0	1044	11.91	12,432
Grad Student #4	Technical Asst.	67	0	1044	1044	11.91	12,432
Grad Student #5	Technical Asst.	67	1044	0	1044	11.91	12,432
Grad Student #6	Technical Asst.	67	0	1044	1044	11.91	12,432
Student Hourlies	Support	232	1818	1818	3636	5.50	20,000
Secretary	Support	103	798	798	1596	11.59	18,501
Subtotal U. C. Davis			8274	6186	14,460		205,223
Caltrans Staff							
S. Chatusripitak	Project Manager	20	80	200	280	27.31	7,647
T. West	Alternate Proj. Mgr.	20	115	125	240	17.51	4,202
K. Kirschke	Project Engineer	100	801	523	1,324	16.75	22,177
Subtotal Caltrans			996	848	1,844		34,026

Level of Effort by Tasks (Man Hours and Wage Costs)

Table 5-1

Phase II

Page 2 of 2

Name	Position	Time (%)	Phase II Task 3 (Manhours)	Phase II Task 4 (Manhours)	Total (Mhs) (Manhours)	Hourly Rate (Bare) (Dollars)	Wage Costs (Dollars)
ERES Staff							
D. Peshkin	Project Manager	14	90	78	168	24.68	4,146
K. Johnson	Project Engineer	23	200	200	400	20.25	8,100
K. Smith	Project Engineer	11		120	120	20.25	2,430
Subtotal ERES			290	398	688		14,676
Bechtel Staff							
J. Robinson	Project Manager	9	64	48	112	34.00	3,808
R. Graham	Alternate Proj. Mgr.	4	29	29	58	36.87	2,138
K. Auclair	Project Engineer	8	49	59	108	26.47	2,859
Procurement Staff	Procurement	N/A	64	16	80	26.47	2,118
Other Bechtel	Support	N/A	115	30	145	20.17	2,925
Subtotal Bechtel			321	182	503		13,767

Project Cost Summary Phase II

Table 5-2
Sheet 1 of 1

Item	U. C. Davis ($)	Caltrans ($)	Eres ($)	Bechtel ($)	Total Costs($)
A) Wages (From Table 5-1)	205,223	34,026	14,676	13,767	267,692
B) Payroll Benefits and Taxes	23,745	7,486	Inc.	6,093	37,324
C) Borrowed Personnel	N/A	N/A	N/A	N/A	N/A
D) Consultants	N/A	N/A	N/A	N/A	N/A
E) Subcontracts (From Table 5-3)	30,000	N/A	N/A	N/A	30,000
F) Capital Equipment (Table 5-3)	375,000	0	N/A	Inc.	375,000
G) Materials and Services	65,000	159,000	N/A	830	224,830
H) Communications & Shipping	4,000	0	480	325	4,805
I) Travel	15,000	0	3000	5,074	23,074
J) Workshops	N/A	N/A	N/A	N/A	N/A
K) Other Direct Costs	0	0	0	839	839
L) Labor Escalation	0	7,034	0	1,020	8,054
M) FCCM	N/A	N/A	N/A	318	318
N) G&A	N/A	N/A	N/A	6,077	6,077
O) Overhead/Burden	156,373	63,763	22,014	12,166	254,316
P) Fee	0	0	1,271	16,619	17,890
Q) Cost Sharing Contribution	0	(271,309)	0	(16,619)	(287,928)
R) Additional Caltrans Cost Sharing to UCD for Crack Sealing Project	N/A	(75,000)	N/A	N/A	(75,000)
S) Caltrans Travel in UC-D Budget	5,000	N/A	N/A	N/A	5,000
Total Project Costs	879,341	(75,000)	41,441	46,509	**892,291**

Phase II Subcontracts and Equipment

Table 5-3
Sheet 1 of 1

Subcontract/Equipment Scope	Cost (Dollars)
Furnish Vehicles (1 vehicle platform)	85,000
Vehicle Modifications (Drivetrain modifications, Integration of select components)	55,000
Test Crack Sensing Systems (Use of Odetics mobile laboratory and all associated costs)	30,000
Furnish Robots for Positioning System (2 multi-manipulator commercial robots including controllers)	120,000
Furnish Motion Unit to Position Robot (Linear machine slide including drive motors and controllers)	50,000
Furnish Local Sensing Unit (Laser based sensor, processing hardware and software, etc.)	30,000
Furnish Other Miscellaneous Equipment (APS components: burner, blower, router, etc.)	35,000
Total Subcontract/Equipment Costs	405,000

SECTION 6

APPENDICES

6.1 TRADE-OFFS OF CLEANING METHODS

VEGETATION REMOVAL METHODS

ADVANTAGES	*DISADVANTAGES*
VERY HIGH PRESSURE/LOW FLOW WATER JET	
EFFECTIVENESS - Cleanly cuts vegetation. Experiments to confirm this claim have not been conducted. However, high pressure water jets have been used widely in industry to cut a wide range of materials including plastics and composites, steels and other metals, foam rubber, etc. with a high degree of success. It is assumed from these experiences that high pressure water jets could be used quite successfully to cut vegetation.	EFFECTIVENESS - This type of very high pressure water jet system would not efficiently prepare area surrounding crack surface. Because of the jet diameter (approximately 0.5 mm), wide coverage of the surrounding crack surface would be difficult.
SIZE & MANEUVERABILITY - The water jet head would have a very reasonable mass and physical size. The head could probably be designed such that it would be adequately flexible and maneuverable. However, it may be difficult to obtain or design flexible very high pressure hoses and tubing necessary for the system.	SAFETY - While not dangerous to the environment, this type of very high pressure water jet system can be hazardous to people who come in contact with the water jet. The water jet can inflict physical injury on the person. Because of this hazard, it would be necessary to properly shield (or otherwise safeguard the system) so that human contact with the water jet is not possible.
ROAD SURFACE CONTACT - No parts of the water jet assembly are in contact with the road surface and the water jet system has few moving parts (excluding pumps), that routine maintenance would be minimal.	POSITIONING - It is presumed that the design of the water jet head could be such that very precise positioning of the head would not be required. Experimentation with different concept designs has not been conducted.
RELIABILITY - This type of system employs few moving parts (excluding pumps) relative to other cleaning methods.	COST - high cost - Due to the sophistication of the equipment and the high water pressures involved, research indicates that an adequate water jet system would be very costly (as compared to other methods).
MOISTURE REMOVAL - This system would employ a very low water flow rate (as compared to medium pressure water jet).	POWER REQUIREMENTS - The exact power requirements of such a system have not been investigated thoroughly. However, it is presumed that substantial power would be required to create the very high water pressures.
LOGISTICS - Research indicates that the logistics of supplying water to the work site would not in itself be prohibitive since a relatively low flow rate of water would be required (as compared to a medium pressure/ higher flow rate water jet). The amount of water required daily (per water jet nozzle) would be on the order of 500 - 1000 gallons.	SERVICEABILITY - The sophisticated equipment would be difficult to repair in the field.
	MOISTURE REMOVAL - A small amount of moisture removal could probably be required prior to crack sealing.
	LOGISTICS - The physical size of the support equipment for the very high pressure water jet system would be logistically prohibitive.
BURNING + BLOWING/BRUSHING	
SAFETY - This method does not appear to be an unacceptable risk to machine operators, motorists, or the environment. Burners, power brushes, and air jets can pose significant dangers (i.e. fire, burns, flying debris etc.). However, it is believed that adequate safety precautions (i.e. fire shields, debris shields, emergency shut-off switches, etc.) can be employed to reduce the risk to an acceptable levels.	EFFECTIVENESS - Experiments confirm that high pressure (approximately 100 psi) air jets are largely ineffective for removing vegetation from road cracks. Power brushing is somewhat more effective than air jets. However, results of experiments indicate that power brushing is still far from adequate. Applying engineering judgement, it does not seem likely that additional expenditures of time and effort on power brushing technology for removing vegetation from cracks would be well spent. An additional experiment observation is that vegetation roots must be dead and/or degraded significantly to assist the blowing/brushing operation.

Table #1 (page 1 of 3)

VEGETATION REMOVAL METHODS
continued

ADVANTAGES	DISADVANTAGES
BURNING + BLOWING/BRUSHING (cont.)	
SIZE & MANEUVERABILITY - From a review of commercially available equipment, it is believed that the Burning/ brushing/air jet head would have a reasonable mass and physical size. The head could be designed such that it would be adequately flexible and maneuverable. The power brush would probably be hydraulically powered so that maneuverability could be maximized and a good power to weight ratio could be achieved.	EFFECTIVENESS - Research has shown that vegetation roots must be dead and/or degraded significantly prior to the brushing/blowing operation. From the experiments conducted, it seems doubtful that the burning operation could be accomplished fast enough to be feasible.
AREA COVERAGE - A wide brush could prepare a broad area surrounding crack surface	POSITIONING - Research has shown that the rotation and position of the brush would have to be aligned with the general crack direction at all times. The rotational inertia of the power brush may create positioning problems.
EQUIPMENT AVAILABILITY - This type of equipment is readily available from commercial sources.	BRUSH WEAR - Periodic replacement of the rotary brushes would be required although machine downtime for brush replacement would be minimal (approximately 15 minutes). Cost of brushes may not be insignificant (as compared to the overall operating cost) since the brushes may cost on the order of $100 - $200 each.
BURNING+ABRASIVE BLASTING WITH VACUUM	
EFFECTIVENESS - Research has demonstrated that it is probably not necessary to burn the vegetation prior to abrasive blasting since abrasive blasting is quite effective as a sole method of vegetation removal.	
ABRASIVE BLASTING WITH VACUUM	
EFFECTIVENESS - Research has shown that this method can do an exceptional job of removing dirt film from the road surface. The abrasive blaster provides a high mass flow rate (as compared with an air jet), thus providing more efficient cleaning of the road surface.	POWER REQUIREMENTS - This process requires large power inputs (possibly on the order of hundreds of horse power per blast head).
SAFETY - The type of blast media could be selected such that it would not pose a significant hazard to the machine operators or the environment.	ROAD SURFACE CONTACT - This method requires that a brush "skirt" (or seal) attached to the blast/vacuum head be in contact with the road surface. Periodic replacement of the brush would be required. Cost of this brush is not presumed to be significant as compared to the overall operating cost of the machine.
SAFETY - The blasting operation is completely contained thus reducing risk to operators, motorists, and property from flying debris.	RECYCLING - Reclaiming of the blast media is required.
SIZE & MANEUVERABILITY - Blast/vacuum head would have a reasonable mass and physical size. Head could be designed such that it would be adequately flexible and maneuverable.	DAMAGE TO ROAD SURFACE - Abrasive blasting will severely damage road reflectors/dots.
AREA COVERAGE - This method could provide broad coverage of the surrounding crack area. therefore, this method would not necessarily require precise positioning of the blast head (either laterally or rotationally).	EFFECTIVENESS - For vegetation with exceptionally tough stems, abrasive blasting may tend to only strip leaves from the vegetation, leaving the stems rooted in the crack.
RELIABILITY - This type of system would have few moving parts (excluding the air compressor).	
RECYCLING - Blast media is reusable.	

Table #1 (page 2 of 3)

VEGETATION REMOVAL METHODS *continued*	
ADVANTAGES	***DISADVANTAGES***
SPRAYING (HERBICIDE) + AIR JET	
EFFECTIVENESS - This method would kill the vegetation roots, thus making it easier to remove vegetation with air jet (or other means).	LOGISTICS - It is necessary to spray approximately 2 weeks prior to crack sealing to allow the vegetation to allow time for the vegetation to die. This would create unacceptable scheduling difficulties. Therefore, this method will not be pursued further.

Table #1 (page 3 of 3)

"LOOSE" DEBRIS REMOVAL METHODS	
ADVANTAGES	DISADVANTAGES
COMPRESSED AIR JET	
EFFECTIVENESS - Research has shown that air jets can be used to remove some of the loose debris from the crack. Although this method would not be very effective as the sole method for removing loose debris, it could be very useful as a supplementary method.	EFFECTIVENESS - Air jet alone may have great difficulty removing all loose debris from cracks (especially large gravel or similar debris). Air jets cannot remove dirt film.
SIZE & MANEUVERABILITY - The air jet head would have a small mass and size (as compared to the other methods). The head could quite easily be designed such that it would be adequately flexible and maneuverable.	EFFECTIVENESS - Low air density requires that air flow rate and air pressure be relatively high in order to move significant amounts of debris.
ROAD SURFACE CONTACT - No parts of the air jet assembly are in contact with the road surface and the air jet system has few moving parts (excluding an air compressor unit). Routine maintenance should be minimal.	SAFETY - Use of high pressure air jets on road surfaces can result in flying debris which could injure people or damage property. Several safety precautions could be employed to reduce this hazard significantly.
RELIABILITY - This type of system employs few moving parts (excluding an air compressor unit). It should be very reliable.	POSITIONING - Fairly precise positioning of the air jet head would be required. This method is very ineffective if the air jet is positioned more than 1/2" (laterally) away from the crack.
SERVICEABILITY - The unit would be relatively easy to maintain.	COST - The main costs of this system would be for an air compressor/engine unit (approximately 185 cfm - 95 hp). This cost would be relatively low (as compared to the other methods).
	POWER REQUIREMENTS - Estimated power requirements for this system would be approximately 30-50 hp per nozzle (depending on type of usage).
MEDIUM PRESSURE / HIGH FLOW WATER JET	
EFFECTIVENESS - All research, commercial literature, and video tape supports the claim that this type of water jet can be used to remove loose debris from cracks and road surfaces with a very high degree of success.	SAFETY - While not dangerous to the environment, this type of very high pressure water jet system can be hazardous to people who come in contact with the water jet. The water jet can inflict physical injury on the person. Because of this hazard, it would be necessary to properly shield (or otherwise safeguard the system) so that human contact with the water jet is not possible.
SIZE & MANEUVERABILITY - The water jet head would have a reasonable mass and physical size. The head could probably be designed such that it would be adequately flexible and maneuverable. Obtaining adequate, medium pressure, flexible hoses and tubes is not expected to be a major problem.	POSITIONING - It is presumed that the design of the water jet head could be such that very precise positioning of the head would not be required. Experimentation with different concept designs has not been conducted.
ROAD SURFACE CONTACT - No parts of the water jet assembly are in contact with the road surface and the water jet system has few moving parts (excluding pumps), that routine maintenance would be minimal.	COST - Exact costs of this type of system have not been investigated. However, it is estimated that the cost for such a system would be relatively high (as compared with other methods).
RELIABILITY - This type of system employs few moving parts (excluding pumps) relative to other cleaning methods.	POWER REQUIREMENTS - The exact power requirements of such a system have not been investigated thoroughly. However, it is presumed that substantial power would be required to create adequate water pressures and to move the necessary volume of water.
AREA COVERAGE - Sufficient area coverage could be obtained by employing a fan-type nozzle or some type of reciprocating water jet.	SERVICEABILITY - The sophisticated equipment would be difficult to repair in the field.

Table #2 (page 1 of 3)

"LOOSE" DEBRIS REMOVAL METHODS
continued

ADVANTAGES	*DISADVANTAGES*
MEDIUM PRESSURE / HIGH FLOW WATER JET (cont.)	
	MOISTURE REMOVAL - Moisture removal would be a very large problem since it is estimated that the water flow rate from one jet would be approximately 5-15 gpm. All of this moisture must be removed from the local crack area prior to sealing.
	LOGISTICS - The physical size of the support equipment for the very high pressure water jet system would be logistically prohibitive.
	LOGISTICS - The logistics of supplying water to the work site and removing water from the work site would be very prohibitive - (estimates of water usage rate are approximately 5 - 15 gpm).
ABRASIVE BLASTING WITH VACUUMING	
EFFECTIVENESS - Research has shown that this method can do an exceptional job of removing dirt film from the road surface. The abrasive blaster provides a high mass flow rate (as compared with an air jet), thus providing more efficient cleaning of the road surface.	POWER REQUIREMENTS - This process requires large power inputs (possibly on the order of hundreds of horse power per blast head).
SAFETY - The type of blast media could be selected such that it would not pose a significant hazard to the machine operators or the environment.	ROAD SURFACE CONTACT - This method requires that a brush "skirt" (or seal) attached to the blast/vacuum head be in contact with the road surface. Periodic replacement of the brush would be required. Cost of this brush is not presumed to be significant as compared to the overall operating cost of the machine.
SAFETY - The blasting operation is completely contained thus reducing risk to operators, motorists, and property from flying debris.	RECYCLING - Reclaiming of the blast media is required.
SIZE & MANEUVERABILITY - Blast/vacuum head would have a reasonable mass and physical size. Head could be designed such that it would be adequately flexible and maneuverable.	
AREA COVERAGE - This method could provide broad coverage of the surrounding crack area. therefore, this method would not necessarily require precise positioning of the blast head (either laterally or rotationally).	
RELIABILITY - This type of system would have few moving parts (excluding the air compressor).	
RECYCLING - Blast media is reusable.	
BRUSHING	
SAFETY - This method does not appear to pose significant risks to machine operators, motorists, or the environment. Power brushes can create flying debris. However, it is believed that adequate safety shields can be employed to reduce the risk of flying debris.	EFFECTIVENESS - Initial research has shown that it is very difficult for the rotary brush to clean cracks adequately. Brushes of various stiffness and composition have not been researched in detail.

Table #2 (page 2 of 3)

"LOOSE" DEBRIS REMOVAL METHODS
continued

ADVANTAGES	*DISADVANTAGES*
BRUSHING (cont.)	
SIZE & MANEUVERABILITY - From a review of commercially available equipment, it is believed that the brushing head would have a reasonable mass and physical size. The head could be designed such that it would be adequately flexible and maneuverable. The power brush would probably be hydraulically powered so that maneuverability could be maximized and a good power to weight ratio could be achieved.	POSITIONING - Research has shown that the rotation and position of the brush would have to be aligned with the general crack direction at all times so that the bristles could get into the crack. The rotational inertia of the power brush may create positioning problems.
AREA COVERAGE - A wide brush could prepare a broad area surrounding crack surface	BRUSH WEAR - Periodic replacement of the rotary brushes would be required although machine downtime for brush replacement would be minimal (approximately 15 minutes). Cost of brushes may not be insignificant (as compared to the overall operating cost) since the brushes may cost on the order of $100 - $200 each.
EQUIPMENT AVAILABILITY - This type of equipment is readily available from commercial sources.	
LOW PRESSURE/HIGH VOLUME AIR JET (BLOWER)	
EFFECTIVENESS - This method should perform as well or better than a compressed air jet. The air does not expand as much or as rapidly after leaving the nozzle (as compared to a compressed air jet) This method is more efficient than the compressed air method and a higher air flow rate can be achieved more easily.	EFFECTIVENESS - The air jet alone may have great difficulty removing all loose debris from cracks (especially large gravel or similar debris). Air jets cannot remove dirt film.
SIZE & MANEUVERABILITY - This method would require approximately 2 cubic feet of space (for the blower and motor) as opposed to the compressed air system which would require approximately 72 cubic feet of space (for the compressor and motor.	SAFETY - Use of air jets on road surfaces can result in flying debris which could injure people or damage property. Several safety precautions could be employed to reduce this hazard significantly.
ROAD SURFACE CONTACT - No parts of the air jet assembly are in contact with the road surface. Routine maintenance should be minimal.	SIZE & MANEUVERABILITY - The air jet hose would be larger than for a compressed air system. This may result in some maneuverability problems. However, this is not expected to be a major problem.
COST - Cost is relatively low since system is fairly simple and the main components are commercially available blowers, motors, and filtration systems.	
RELIABILITY - This type of system employs few moving parts (excluding an air compressor unit). It should be very reliable.	
POSITIONING - Precise positioning of the air jet head is not as important as with a compressed air jet.	
POWER REQUIREMENTS - Estimated power requirements for this system would be approximately 5 hp per nozzle (depending on type of usage).	
SERVICEABILITY - The unit would be relatively easy to maintain.	

Table #2 (page 3 of 3)

DIRT FILM REMOVAL METHODS

ADVANTAGES	DISADVANTAGES
ABRASIVE BLASTING WITH VACUUM	
EFFECTIVENESS - Research has shown that this method can do an exceptional job of removing dirt film from the road surface. The abrasive blaster provides a high mass flow rate (as compared with an air jet), thus providing more efficient cleaning of the road surface.	POWER REQUIREMENTS - This process requires large power inputs (possibly on the order of hundreds of horse power per blast head).
SAFETY - The type of blast media could be selected such that it would not pose a significant hazard to the machine operators or the environment.	ROAD SURFACE CONTACT - This method requires that a brush "skirt" (or seal) attached to the blast/vacuum head be in contact with the road surface. Periodic replacement of the brush would be required. Cost of this brush is not presumed to be significant as compared to the overall operating cost of the machine.
SAFETY - The blasting operation is completely contained thus reducing risk to operators, motorists, and property from flying debris.	RECYCLING - Reclaiming of the blast media is required.
SIZE & MANEUVERABILITY - Blast/vacuum head would have a reasonable mass and physical size. Head could be designed such that it would be adequately flexible and maneuverable.	
AREA COVERAGE - This method could provide broad coverage of the surrounding crack area. therefore, this method would not necessarily require precise positioning of the blast head (either laterally or rotationally).	
RELIABILITY - This type of system would have few moving parts (excluding the air compressor).	
RECYCLING - Blast media is reusable.	
STEAM CLEANING (This method has not yet been investigated. All comments presented below are based on general engineering judgment of the method.)	
EFFECTIVENESS - It is assumed that this method would be quite effective for removing dirt film. The relatively high mass of the steam (as compared to hot air) could be expected to loosen and remove dirt film quite easily.	SAFETY - This method could pose a hazard to machine operators and motorists. Since the steam (and hot water) cannot be easily contained, it could cause physical injury to machine operators. Breaks in steam or hot water lines could cause great physical injury. Steam clouds could conceivably obstruct a motorists' view of the roadway. These hazards could be reduced through the use of shields, fluid and steam line covers, and other safety devices. However, it is believed that significant hazards would still remain.
SAFETY - This method would not be harmful to the environment.	POSITIONING - It is presumed that the design of the steam jet head could be such that very precise positioning of the head would not be required.
SIZE & MANEUVERABILITY - The steam jet head would probably have a reasonable mass and physical size. The head could probably be designed such that it would be adequately flexible and maneuverable.	COST - Cost of this type of system is not known at this time.
ROAD SURFACE CONTACT - No parts of the steam jet assembly are in contact with the road surface.	POWER REQUIREMENTS - The power requirements of this type of system are not known. However, it is believed that significant power would be required to heat the water into steam.
RELIABILITY - This type of system employs few moving parts (excluding pumps) relative to other cleaning methods.	SERVICEABILITY - The sophisticated equipment would be difficult to repair in the field.

Table #3 (page 1 of 3)

DIRT FILM REMOVAL METHODS
continued

ADVANTAGES	*DISADVANTAGES*
STEAM CLEANING (cont.)	
AREA COVERAGE - Sufficient area coverage could be obtained by employing a fan-type nozzle or some type of reciprocating steam jet.	
MOISTURE REMOVAL - It is unknown how much moisture would have to be removed from the road surface. However, it is assumed that only a small amount of moisture would remain in the local crack area since much of it would evaporate quickly.	
LOGISTICS - The logistics of supplying water to the work site would probably not be prohibitive since high flow rates are not required (as with some water jet systems).	
BRUSHING	
SAFETY - This method does not appear to pose significant risks to machine operators, motorists, or the environment. Power brushes can create flying debris. However, it is believed that adequate safety shields can be employed to reduce the risk of flying debris.	EFFECTIVENESS - Initial research has shown that the rotary brush does not adequately remove dirt film from the bottoms and sides of cracks. Applying engineering judgment, it does not seem likely that this situation can be improved significantly by additional experimentation.
SIZE & MANEUVERABILITY - From a review of commercially available equipment, it is believed that the brushing head would have a reasonable mass and physical size. The head could be designed such that it would be adequately flexible and maneuverable. The power brush would probably be hydraulically powered so that maneuverability could be maximized and a good power to weight ratio could be achieved.	POSITIONING - Research has shown that the rotation and position of the brush would have to be aligned with the general crack direction at all times so that the bristles could get into the crack. The rotational inertia of the power brush may create positioning problems.
AREA COVERAGE - A wide brush could prepare a broad area surrounding crack surface.	BRUSH WEAR - Periodic replacement of the rotary brushes would be required although machine downtime for brush replacement would be minimal (approximately 15 minutes). Cost of brushes may not be insignificant (as compared to the overall operating cost) since the brushes may cost on the order of $100 - $200 each.
EQUIPMENT AVAILABILITY - This type of equipment is readily available from commercial sources.	
MEDIUM PRESSURE / HIGH FLOW WATER JET	
EFFECTIVENESS - All research, commercial literature, and video tape supports the claim that this type of water jet can be used to remove dirt film from cracks and road surfaces with a very high degree of success.	SAFETY - While not dangerous to the environment, this type of water jet system can be hazardous to people who come in contact with the water jet. The water jet can inflict physical injury on the person. Flying debris, propelled by the water jet can also be hazardous to people and property. Because of these hazards, it would be necessary to properly shield (or otherwise safeguard the system) so that human contact with the water jet is not possible.
SIZE & MANEUVERABILITY - The water jet head would have a reasonable mass and physical size. The head could probably be designed such that it would be adequately flexible and maneuverable. Obtaining adequate, medium pressure, flexible hoses and tubes is not expected to be a major problem.	POSITIONING - It is presumed that the design of the water jet head could be such that very precise positioning of the head would not be required. Experimentation with different concept designs has not been conducted.

Table #3 (page 2 of 3)

DIRT FILM REMOVAL METHODS
continued

ADVANTAGES	*DISADVANTAGES*
MEDIUM PRESSURE / HIGH FLOW WATER JET (cont.)	
ROAD SURFACE CONTACT - No parts of the water jet assembly are in contact with the road surface and the water jet system has few moving parts (excluding pumps), that routine maintenance would be minimal.	COST - Exact costs of this type of system have not been investigated. However, it is estimated that the cost for such a system would be relatively high (as compared with other systems).
RELIABILITY - This type of system employs few moving parts (excluding pumps) relative to other cleaning methods.	POWER REQUIREMENTS - The exact power requirements of such a system have not been investigated thoroughly. However, it is presumed that substantial power would be required to create adequate water pressures and to move the necessary volume of water.
AREA COVERAGE - Sufficient area coverage could be obtained by employing a fan-type nozzle or some type of reciprocating water jet.	SERVICEABILITY - The sophisticated equipment would be difficult to repair in the field.
	MOISTURE REMOVAL - Moisture removal would be a very large problem since it is estimated that the water flow rate from one jet would be approximately 5-15 gpm. All of this moisture must be removed from the local crack area prior to sealing.
	LOGISTICS - The physical size of the support equipment for the very high pressure water jet system would be logistically prohibitive.
	LOGISTICS - The logistics of supplying water to the work site and removing water from the work site would be very prohibitive - (estimates of water usage rate are approximately 5 - 15 gpm).

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6.2 MANUFACTURER'S LITERATURE REVIEWED

MANUFACTURER'S LITERATURE REVIEWED AND ON FILE

ABRASIVE BLAST EQUIPMENT

Abrasive Blast Systems Inc.
Boride Products Inc.
Clemco Industries Corp.
Empire Abrasive Blast Equipment Corp.
Equipment Development Co. Inc. (EDCO)
Goff Corp.
LTC International, Inc.
Nelco Mfg. Corp.
Poly & Griffin Co.
Schmidt Mfg. Corp.

AIR NOZZLES & RELATED EQUIPMENT

ACB Technology Corp.
Nortel Machinery, Inc.

ALLOYS (HIGH TEMPERATURE)

A&F Alloys, Inc.
General Aerospace Corp.

BLOWERS (AIR) AND VACUUM SYSTEMS

Maxon Corp.
Paxton Centrifugal Blowers
Sonic Air Systems

BURNERS AND BURNER CONTROL SYSTEMS

Burners Inc.
Control Technology Specialists
Davis Instrumentation
Flynn Burner Corp.
Honeywell
Maxon Corp.
Sur-Lite
T Thermal, Inc.
TransFlow Energy, Inc.

CABLE/HOSE CARRIERS, FLEXIBLE HOSE, CONDUIT

Gleason Reel Corp.
Gortite - A & A Mfg. Co.
Kabelschlepp America
OBAC Quick Connect Couplings

Wampfler Inc.

COMPRESSORS (AIR)
Ingersoll-Rand
Sullair Corp.

COMPUTER HARDWARE AND SOFTWARE
Creative Engineering
GCC Technologies
JMI Sortware Consultants, Inc.
Kadak Products Ltd.
MacAvenue (Compuadd Corp.)
Microtec Research, Inc.
Microware Systems Corp.
Softsunc, Inc.
Software Components Group
Tektronix

COMPUTER PRODUCTS (REAL-TIME SYSTEMS)
Advin Systems, Inc.
A.T. Barrett & Associates
Buscon
Ciprico, Inc.
ComputerBoards, Inc.
Computer Products
Concurrent Computer Corp.
Dawn VME Products
Eyring
FPS Computing
Idec Corp.
Industrial Computer Source
KMS Advanced Products
Kontron Electronik
Magnetic Shield Corp.
Micro/Sys
Motorola, Inc.
Rapid Systems
RealTime Control, Inc.
SGS-Thomson Microelectronics, Inc.
Texas Instruments
Validyne Engineering Group
VenturCom
Vigra
VMetro
VMIC
Western Technology Marketing

Zendex Corporation

DATA ACQUISITION AND CONTROL SYSTEMS
ADAC Corp.
Autotech Corp.
Burr-Brown
Campbell Scientific, Inc.
Data Translation
Daytronic
Dynapar Corp.
Galil Motion Control Inc.
Hi-Techniques, Inc.
Industrial Devices Corp.
Keithley Metrabyte/Asyst/DAC
Love Controls Corp.
Mallory Controls
Mallory Timers Co.
Micro Specialty Systems, Inc.
MTS Systems Corp.
Neff
New England Affiliated Technologies
Omega
Onsite Instruments
Penny + Giles
RDP Electrosense Inc.
Saber Enterprises Inc.
Schlumberger Industries
SMC Pneumatics, Inc.

DATA COMMUNICATIONS
BT&D (British Telecom & Dupont) Technologies
Kalpana
Matec Fiberoptics
MicroLink/Sea-Ilan, Inc.
SBE, Inc.

DIVERTER VALVES
RotoLok Valves, Inc.
Bush & wilton Valves, Inc.

HAND TOOLS (MISC. POWERED TOOLS)
Kango USA Inc.
Oztec Industries Inc.

HEATERS (HEAT LANCES, RADIENT HEATERS, MISC. HEATERS)
Aeroil Products Co. Inc.
Cimline Corp.

Gencorp
LA Mfg. Inc.
Love Controls Corp.
Maxon Corp.
Process Heating Co.
Rama Corp.
Seal All Marketing, Inc.
Solarflo Corp.
Solaranics

HYDRAULIC COMPONENTS
Helac Corp.
Rexroth Worldwide Hydraulics
Snap-Tite
Sonic Air Systems
Miller Fluid Power

INSTRUMENTS
Acculex
BK Precision
Conax Buffalo Corp.
DH Instruments, Inc.
Extech Instruments
Vaisala Sensor Systems
Viatran

LASERS
MWK Industries

MECHANICAL COMPONENTS (MISC.)
Vlier
Berg
Dodge
Stock Drive
Nordex
Accurate Screw Machine Co.
RAF
Martin
Morse
Boston Gear
Southco Fasteners
R. C. Dudek & Co., Inc. (PEM Fasteners)
Dynacorp, Inc.

MELTERS
Aeroil Products Co. Inc.
BearCat Mfg.

Berry Corp.
Cimline Inc.
Crafco Inc.
Dispensing Technology Corp. (DTC)
Redland Prismo Corp.
Savalco (Sweden)
Stepp Mfg. Co., Inc.
Western Industries, Inc.

MISC.

B & B Electromatic
Kano Laboratories Inc.
Sigmund Cohn Corp.
Sinco Products Inc.

MOTORS / GENERATORS (ELECTRIC)

Baldor / Boehm
LIMA
No Brush
Universal Float Lure Inc.

OPTICS

Matec Fiberoptics
Olympus
Technical Mfg. Corp. (TMC)

PAVING EQUIPMENT (SPREADERS, PATCHERS, ETC.)

Equipment Development Co. Inc.
Guntert & Zimmerman Const. Div., Inc.
Savalco (Sweden)

POSITIONING EQUIPMENT AND ROBOTICS (ACTUATORS, BRAKES, CLUTCHES, DRIVE BELTS, ENCODERS, GEAR TRAINS, MOTORS, POSITIONERS, ROBOTICS, SERVOS, SLIDES, SOLENOIDS)

Ability Technologies Corp.
AMI
Anorad Corp.
Anorad Corp.
Baldor Motion Products Group
BEI Motion Systems Co.
Brecoflex Corp.
Daedal Inc.
Design Components Inc.) DCI
Dynapar Corp.
Electroid Co.
Encoder Products Co.
Futaba Corp. of America

G & L Electronics
Helac Corp.
IKO Intl., Inc.
Industrial Devices Corp.
Industrial Indexing Systems
Jasta
Klinger Scientific
Lexagon Inc.
Lucas Ledex Inc.
Lucas Ledex Inc.
Miller Fluid Power
Morse Electrical Products
New England Affiliated Technologies Inc.
Nippon Pulse Motor Co. LTD.
Nippon Thompson co., LTD.
Nord Gear Corp.
Origa Corp.
Pacific Scientific
Precision Ball Screws
RACA Intl. (Hauser)
Rexroth Worldwide Hydraulics
Robbins and Myers / Electrocraft
Robotic Accessories Co.
Samtak (Div. of Daido Corp.)
Schilling Development
Schneeberger Inc.
SMC Pneumatics, Inc.
Suco
Thomson Saginaw
Tol-O-Matic, Inc.
UNISlide
Universal Thread Grinding Co.

POWER BRUSHES
Crafco Inc.
Equipment Development Development Co. Inc.

PUMPS (SEALANT, FLUID, TRASH)
Pyles (Graco)
Rexroth Worldwide Hydraulics
Wacker Construction Equipment

ROLLERS (ROCK AND ASPHALT)
Wacker Construction Equipment

ROUTERS, SAWS, PLANERS, DRILLS, AND BLADES
Aeroil Products Co. Inc.

Alitec - Systems and Allied Products
Cimline Inc.
Crafco Inc.
Equipment Development Co. Inc. (EDCO)
Gehl (IC Group)
Magnum Diamond and Machinery, Inc.
Parsons
Partner Industrial Products
Pearl Abrasive Co.
Seal-All
Soff-Cut Intl.
Stow Saws
Vermeer Mfg. Co.
Wacker Construction Equipment

SEALANTS

Crafco Inc.
Hodson Chemical Construction Corp.
NAPA (Natl. Asphalt Pavement Assn.)
Percol - Polymerics Inc.
Smith Chemical Corp.
Spraymation Inc.
Tapecoat Co.
Textile Rubber and Chemical Co. Inc.
U.S. Pro-Tec Inc. (QPR 2000)
Wespro Co.

SENSORS

Agastat (proximity)
Agastat Ultrasonics
Aromat (optical displacement)
Baumer Electric
Centronic (photodetectors)
Cleveland Machine Controls (ultrasonic)
Columbia Research Labs., Inc. (inertial products)
Cosense (ultrasonic)
Data Instruments (pressure)
Data Recal (laser scanners)
Degussa Corp.
E G & G (flow)
EOTec Corp. (3M)
Fastar (linear displacement)
Foxboro / ICT, Inc.
General Scanning Systems (optical scanning)
Hamamatsu (optical displacement sensors)
Hoffer Flow Controls Inc. (flow)

Humphrey Inc. (inertial products)
Ircon (temperature)
Kaman (position)
Kavlico Corp. (pressure)
Keyance (optical displacement)
Kistler (vibration)
Laser Data Corporation (laser scanners)
Lucas Sensing Systems
MagneTek
Magnetrol
Max (flow)
Micro Switch
Micro Switch
Motorola
MTS Systems Corp. (linear displacement)
MVS Modular Vision Systems Inc. (laser vision sensors)
Namco (photoelectric)
Pulse Radar Inc.
RCA Inc., Electro Optics
RdF Corporation (temperature)
Saber Enterprises Inc.
Sensor Engineering Co. (motion, speed, position)
Sensotec (pressure, load, acceleration, displacement)
SMC Pneumatics, Inc.
Spectron (tilt)
Spectron Systems Technology Inc. (inclinometers and angle control units)
Sunstrand Data Control (accelerometers)
Sunx (displacement)
Symbol Technologies (laser scanners)
Trans-tek Incorporated (linear velocity, linear and angular displacement)
Turbo Instruments Inc. (flow)
United Detector Technology
YSI Inc.

SPRINGS
Century Spring Co.

STREET SWEEPERS
Tymco Regenerative Air Systems

TRANSDUCERS
Schlumberger Industries

TRENCHING EQUIPMENT
Vermeer Mfg. Co.

TRUCKS, PLATFORMS, TRACKS, AND AUTONOMOUS VEHICLES

Cybermotion
Taylor-Dunn Co.
Tufpads (Track Pads)

VIBRATORY PLATES AND RAMMERS

Wacker Construction Equipment

VISION SYSTEMS

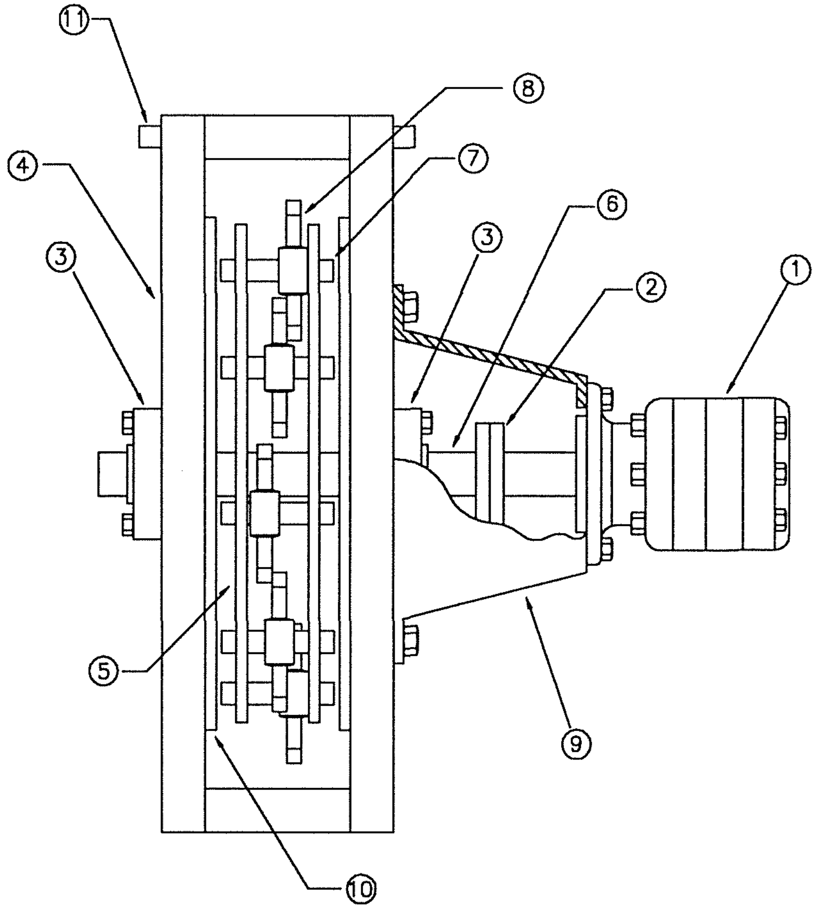
Amerinex Artificial Intelligence, Inc. (AAI)
Dalsa Inc.
Data Cube Inc.
Pavedex, Inc.
Tau Corp.

WATER JET EQUIPMENT (CUTTING AND CLEANING)

Harben - (High Pressure Water Jet Technology)
Jet Edge, Inc.
NLB (National Liquid Blasting) Corp.
Propave Co.
RGF Environmental Systems
Sealant Finishing Tooling

6.3 ROUTER TECHNICAL DRAWINGS

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP



ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
11		3/4" PIN	304 S.S.	1
10	110	BEARING PLATE	304 S.S.	2
09	109	MOUNTING ADAPTOR	304 S.S	1
08		CUTTING TOOL	PURCHASE	9
07		TOOL SHAFT	304 S.S.	9
06		MAIN SHAFT	304 S.S	1
05	105	HOLDING DISC	304 S.S.	2
04	104	MAIN HOUSING	304 S.S	1
03		ROLLER BEARING	PURCHASE	2
02		FLEXABLE COUPLING	PURCHASE	1
01		HYDRAULIC MOTOR	PURCHASE	1

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5
.XXX ± .005 64√

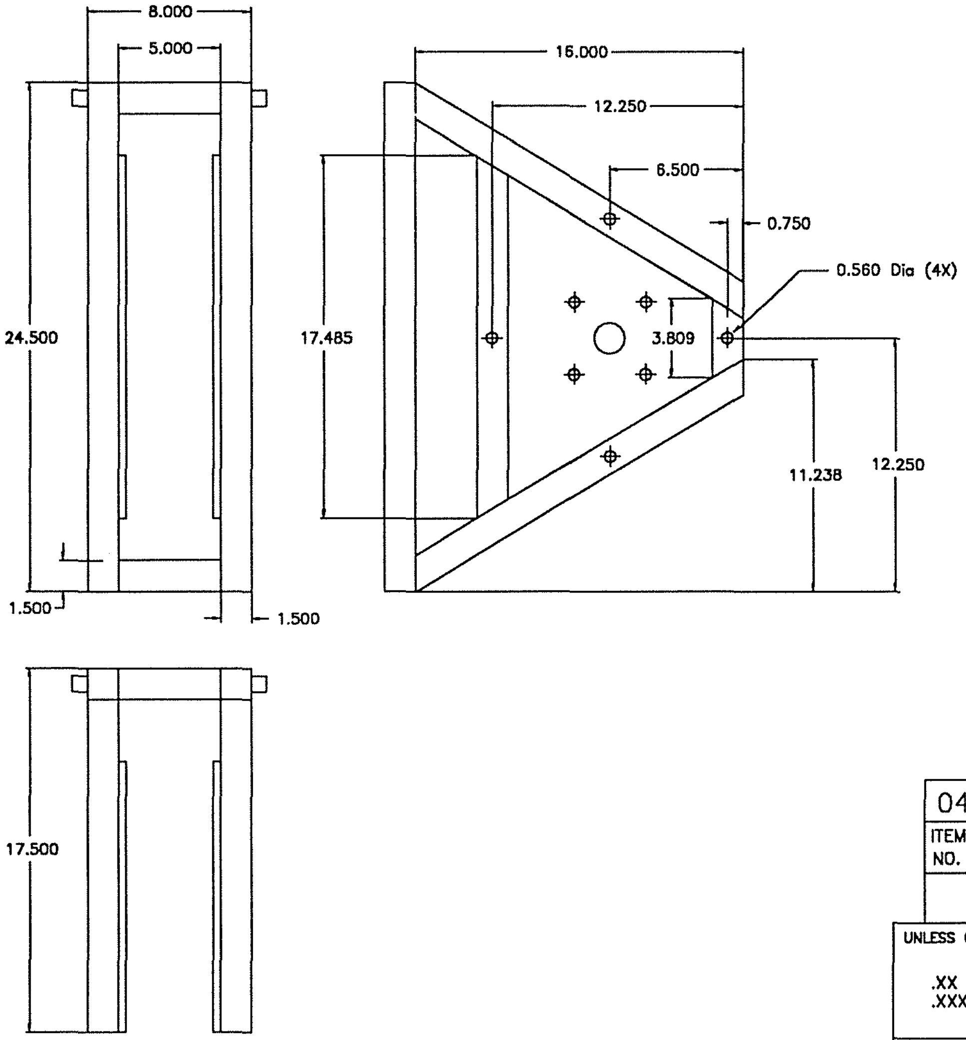
DESIGN	DATE	
DRAWN KJM	4/18/91	
APPRV SV	4/22/91	
RELEASE		

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE
ROUTER ASSEMBLY

QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHP-ROUT-100
PROJECT SHRP 107-A

		REVISION			
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP



04			304 S.S.	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5
.XXX ± .005 64√

DESIGN	DATE
DRAWN KJM	4/18/91
APPRV SV	4/22/91
RELEASE	

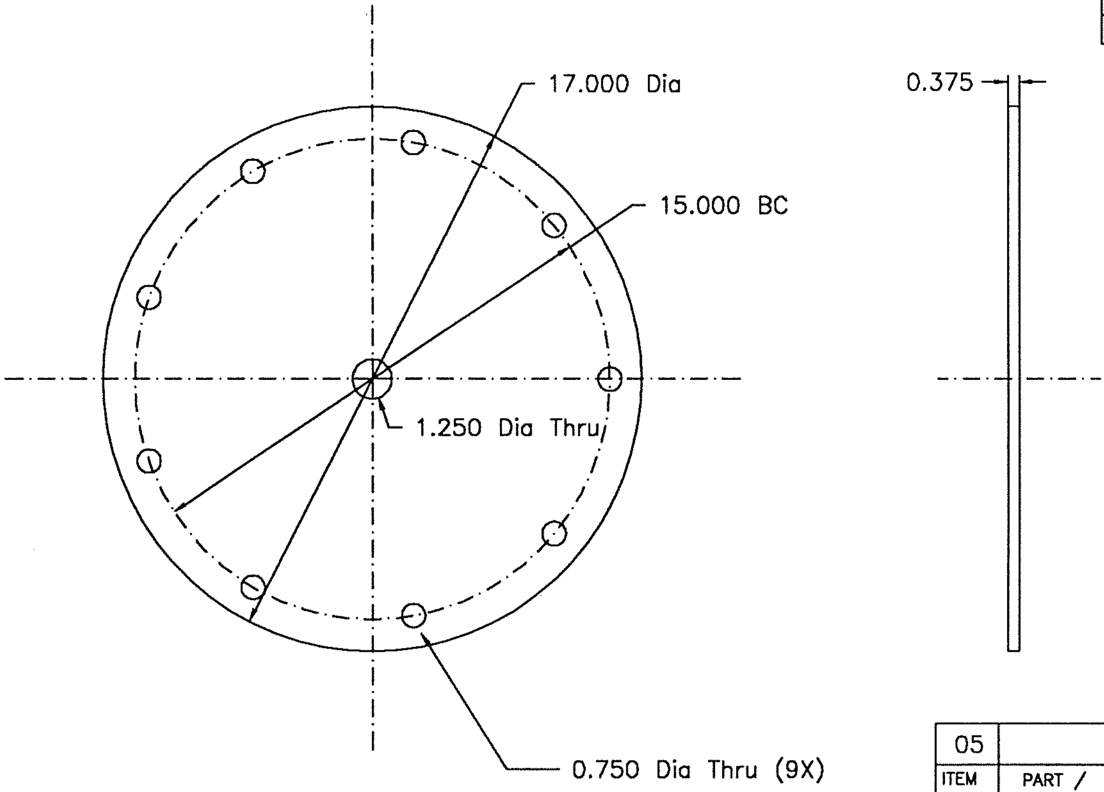
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE MAIN HOUSING

QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHP–ROUT–104
PROJECT SHRP 107–A

4 3 2 1

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP



05			304 S.S.	2
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5
.XXX ± .005 64√

DESIGN	DATE
DRAWN KJM	4/18/91
APPRV SV	4/22/91
RELEASE	

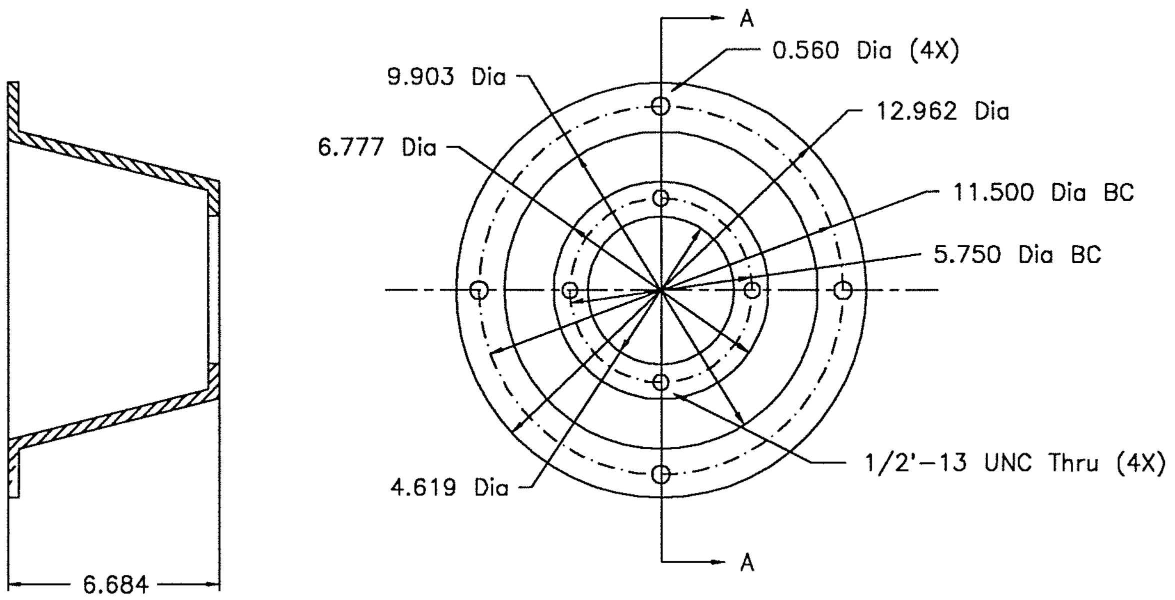
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE
HOLDING DISC

QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHP-ROUT-105
PROJECT SHRP 107-A

4 3 2 1

LTR	ZONE	REVISION DESCRIPTION	DATE	DRWN	APP



ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
09			304 S.S	1

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5
.XXX ± .005 64√

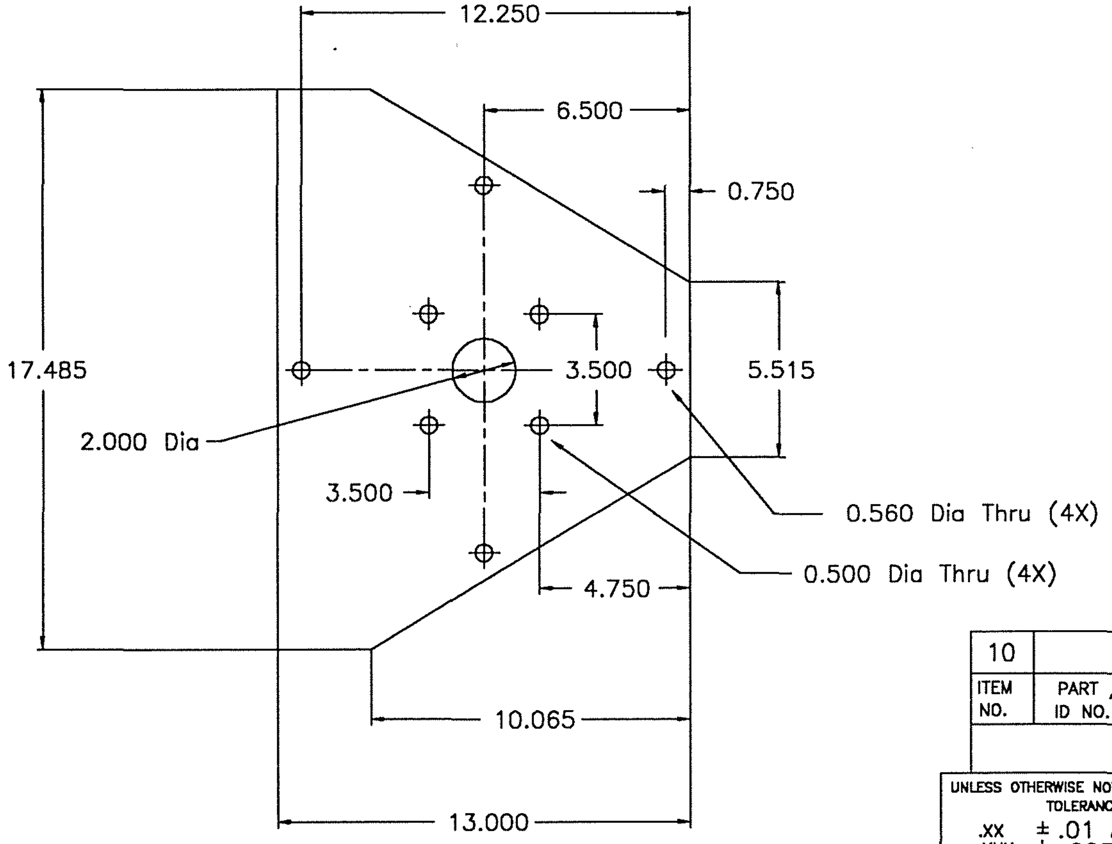
DESIGN	DATE
DRAWN KJM	4/18/91
APPRV SV	4/22/91
RELEASE	

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE
MOUNTING ADAPTOR

QTY 1
SCALE 1:1
DRAWING NO. SHP-ROUT-109
SIZE B
SHT
PROJECT SHRP 107-A

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP



10			304 S.S.	2
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5
.XXX ± .005 64√

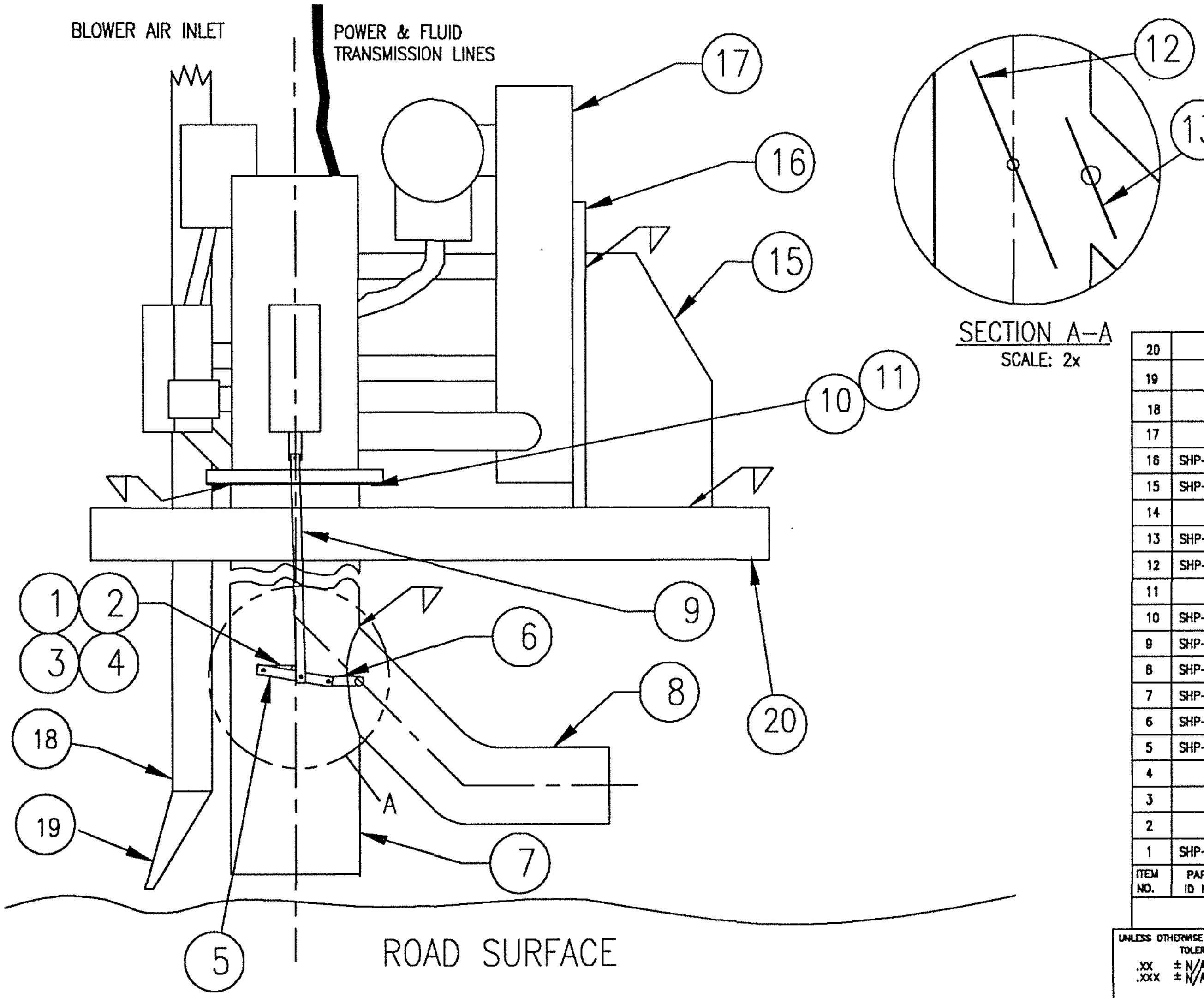
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

DESIGN		DATE
DRAWN	KJM	4/18/91
APPRV	SV	4/22/91
RELEASE		

TITLE BEARING PLATE

QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHP–ROUT–110
PROJECT SHRP 107–A

6.4 HEATING/CLEANING TECHNICAL DRAWINGS



REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN

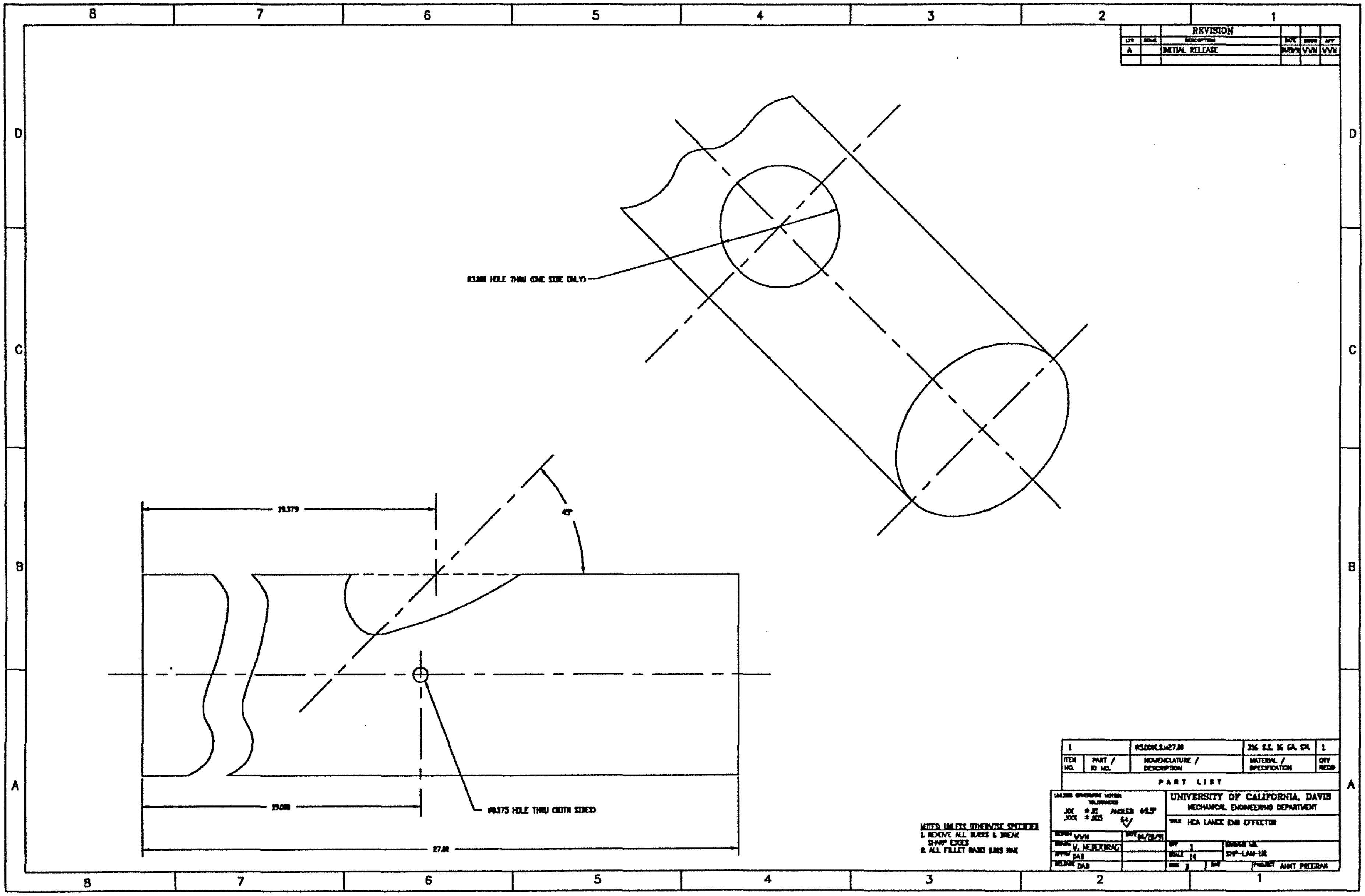
20		MOUNTING PLATE	PURCHASE	1
19		7/8 Dia NOZZLE	PURCHASE	1
18		3 in Dia AIR DUCT	PURCHASE	1
17		SUR-LITE 5" BURNER	PURCHASE	1
16	SHP-LAN-110	MOUNTING PLATE	STEEL	1
15	SHP-LAN-111	MOUNTING PLATE	STEEL	1
14		6-32x0.5" SCREWS S.S.	PURCHASE	6
13	SHP-LAN-104	SMALL BUTTERFLY VALVE	316 S.S.	1
12	SHP-LAN-103	LARGE BUTTERFLY VALVE	316 S.S.	1
11		1/4" BOLT/WASHER/NUT	PURCHASE	4
10	SHP-LAN-107	FLANGE	316 S.S.	1
9	SHP-LAN-109	CYLINDER CONNECTING ROD	316 S.S.	1
8	SHP-LAN-102	SECONDARY HEAT EXIT	316 S.S.	1
7	SHP-LAN-101	LANCE TUBE	316 S.S.	1
6	SHP-LAN-106	SMALL BUTTERFLY SHAFT	316 S.S.	1
5	SHP-LAN-108	CONNECTING ROD	316 S.S	1
4		RETAINER PIN	PURCHASE	4
3		3/8" WASHER	PURCHASE	4
2		SPRING PINS	PURCHASE	4
1	SHP-LAN-105	LARGE BUTTERFLY SHAFT	316 S.S.	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

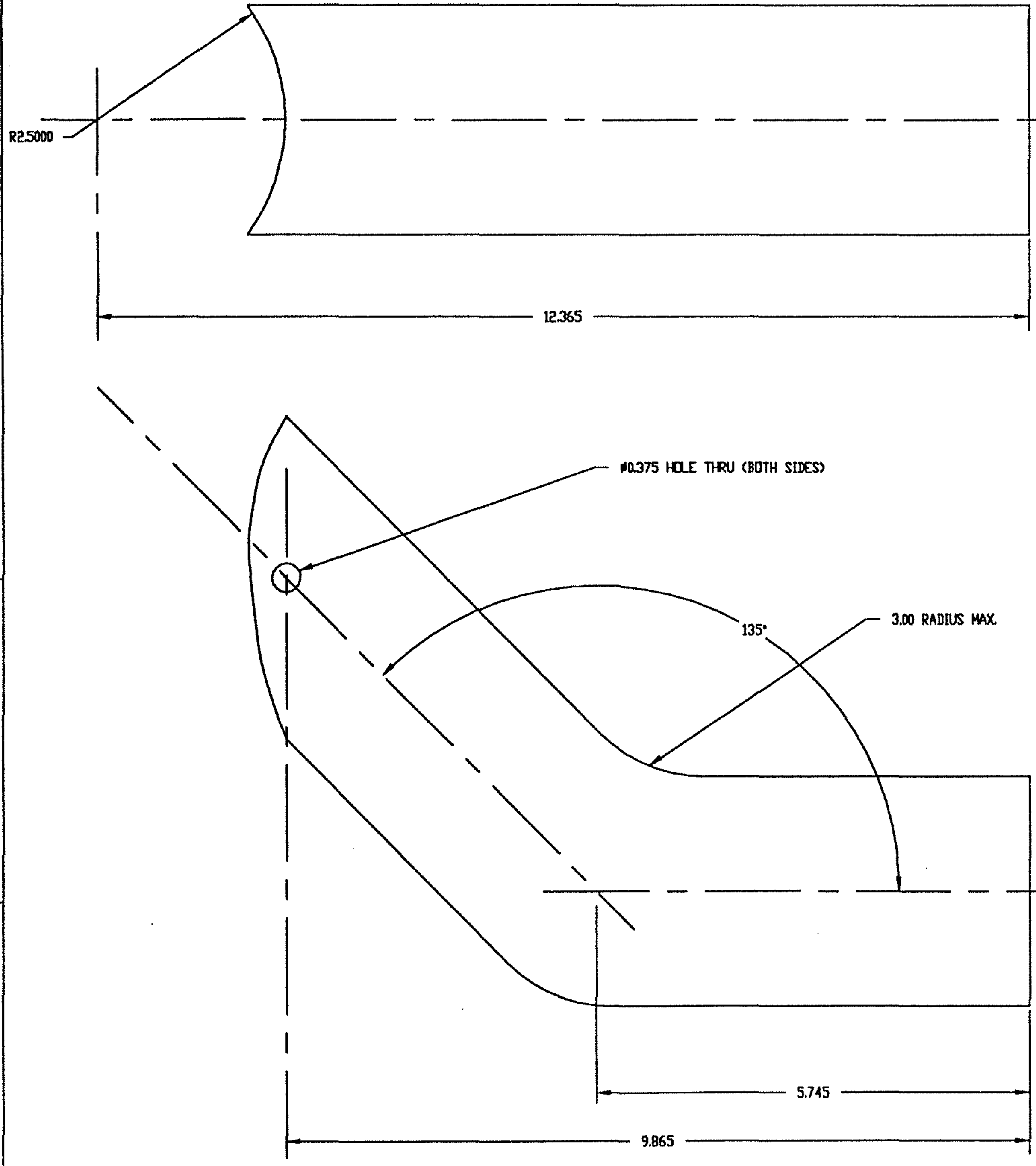
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± N/A ANGLES ±N/A
.XXX ± N/A N/A

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

DESIGN WWN	DATE 04/28/91	TITLE ASSEMBLY DRAWING FOR HEAT LANCE	
DRAWN W. NEDERBRAGT		QTY N/A	DRAWING NO. SHP-LAN-ASSY
APPRV DAB		SCALE 1/2:1	
RELEASE DAB		SIZE D SHT	PROJECT AHMT PROGRAM


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
A
INITIAL RELEASE
04/29/91
VVN
VVN
R1.000 HOLE THRU (ONE SIDE ONLY)
19.379
45°
19.000
Ø0.375 HOLE THRU (BOTH SIDES)
27.00
NOTES UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.03 MAX
1
Ø5.000I.D.x27.00
316 S.S. 16 GA. SH.
1
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED TOLERANCES
.XX ±.01 ANGLES ±0.5°
.XXX ±.005
63
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE HCA LANCE END EFFECTOR
DESIGN VVN
DATE 04/28/91
DRAWN V. NEDERBRAGT
APPRVD DAB
RELEASE DAB
QTY 1
SCALE 1:4
DRAWING NO.
EMP-LAN-101
SIZE B
SHT
PROJECT AHMT PROGRAM
8
7
6
5
4
3
2
1
D
C
B
A

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
1		ø3.00I.D.x12.00	316 S.S. 16 GA. SH.	1

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5°
.XXX ± .005
64√

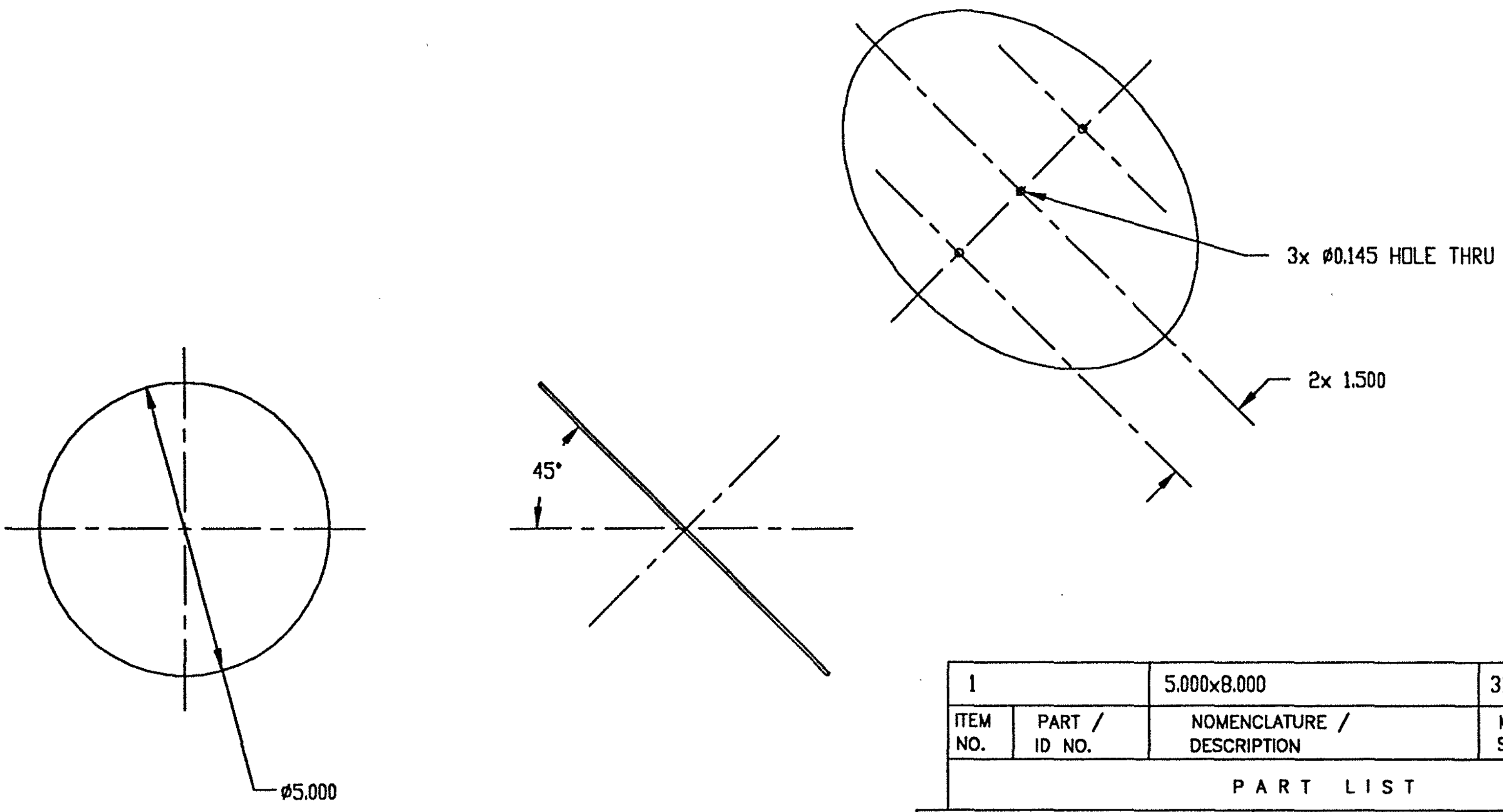
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE HCA LANCE SECOND OUTPUT

DESIGN WWN
DATE 04/28/91
DRAWN W. NEDERBRAGT
APPRV DAB
RELEASE DAB

QTY 1
SCALE 1:1
SIZE C
SHT
DRAWING NO. SHP-LAN-102
PROJECT AHMT PROGRAM

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
1		5.000x8.000	316 S.S. 16 GA. SM.	1

PART LIST

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

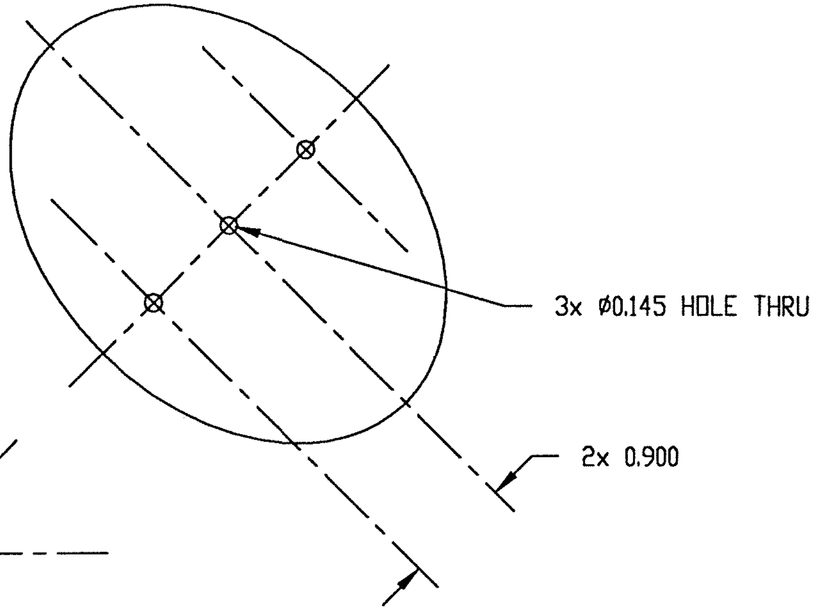
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5°
.XXX ± .005
64√

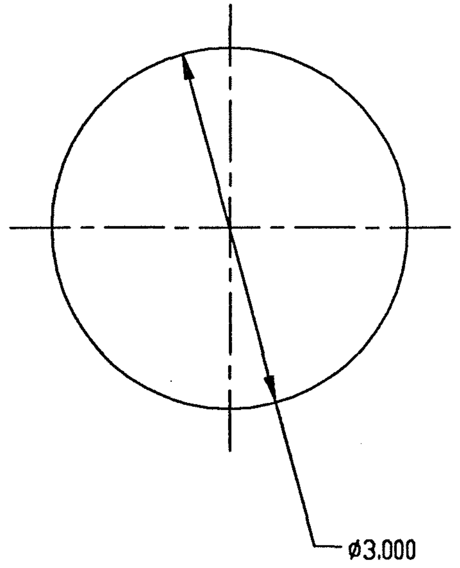
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

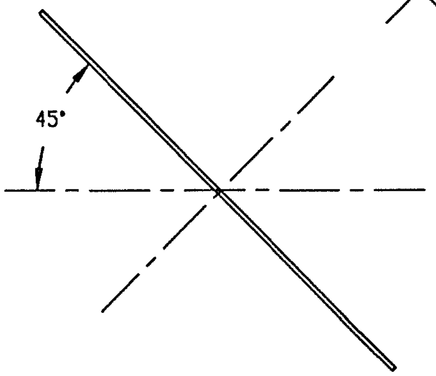
TITLE BUTTERFLY VALVE #1

DESIGN WWN
DATE 04/28/91
DRAWN W. NEDERBRAGT
APPRV DAB
RELEASE WWN
QTY 1
SCALE 1:1/2
SIZE B
SHT
DRAWING NO. SHP-LAN-103
PROJECT AHMT PROGRAM

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN







1		3.000x5.000	316 S.S. 16 GA. SM.	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5°
.XXX ± .005
64√

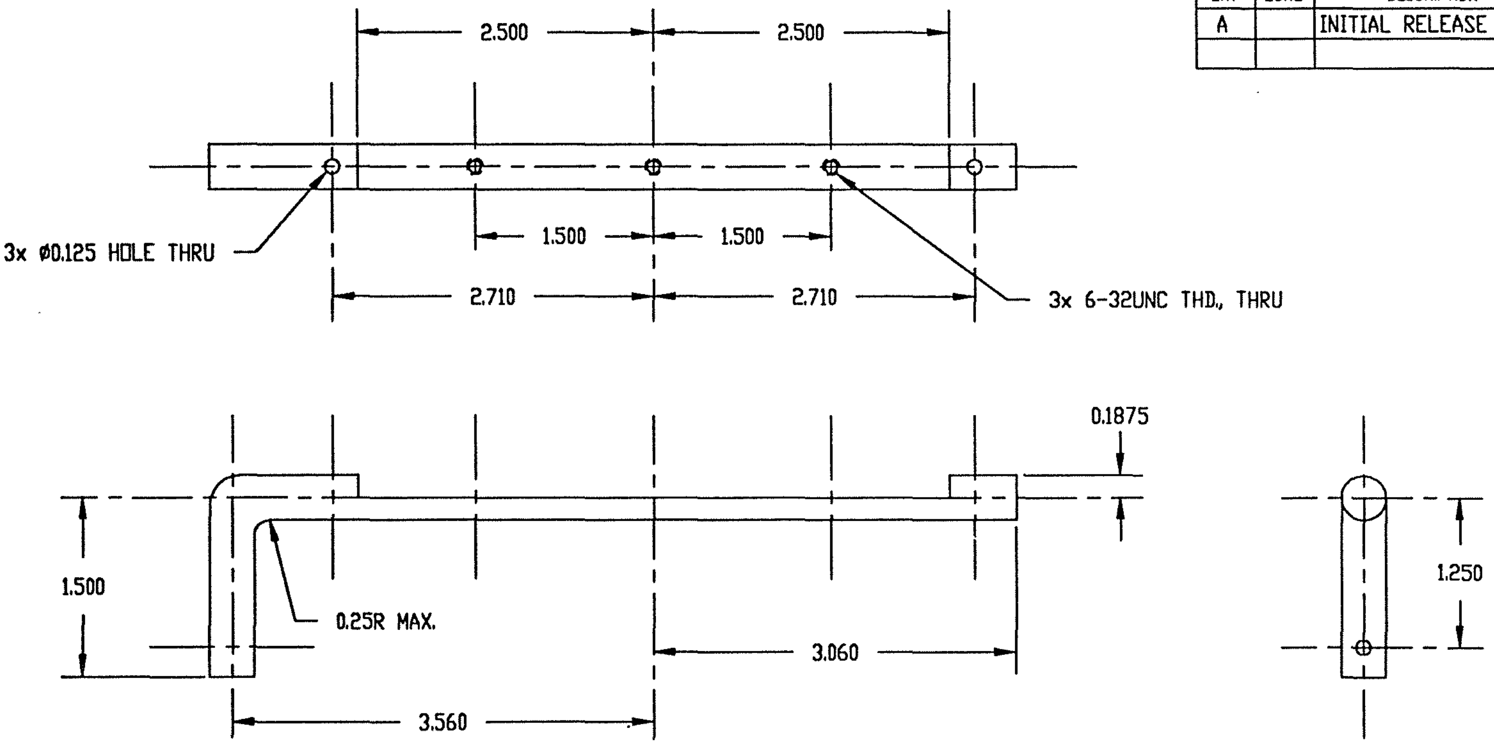
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE BUTTERFLY VALVE #2

DESIGN WWN	DATE 04/28/91		
DRAWN W. NEDERBRAGT		QTY 1	DRAWING NO. SHP-LAN-104
APPRV DAB		SCALE 1:1/2	
RELEASE WWN		SIZE B SHT	PROJECT AHMT PROGRAM

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



1		⌀0.375x8.00	316 S.S. ROD	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ±.01 ANGLES ±0.5°
.XXX ±.005
64√

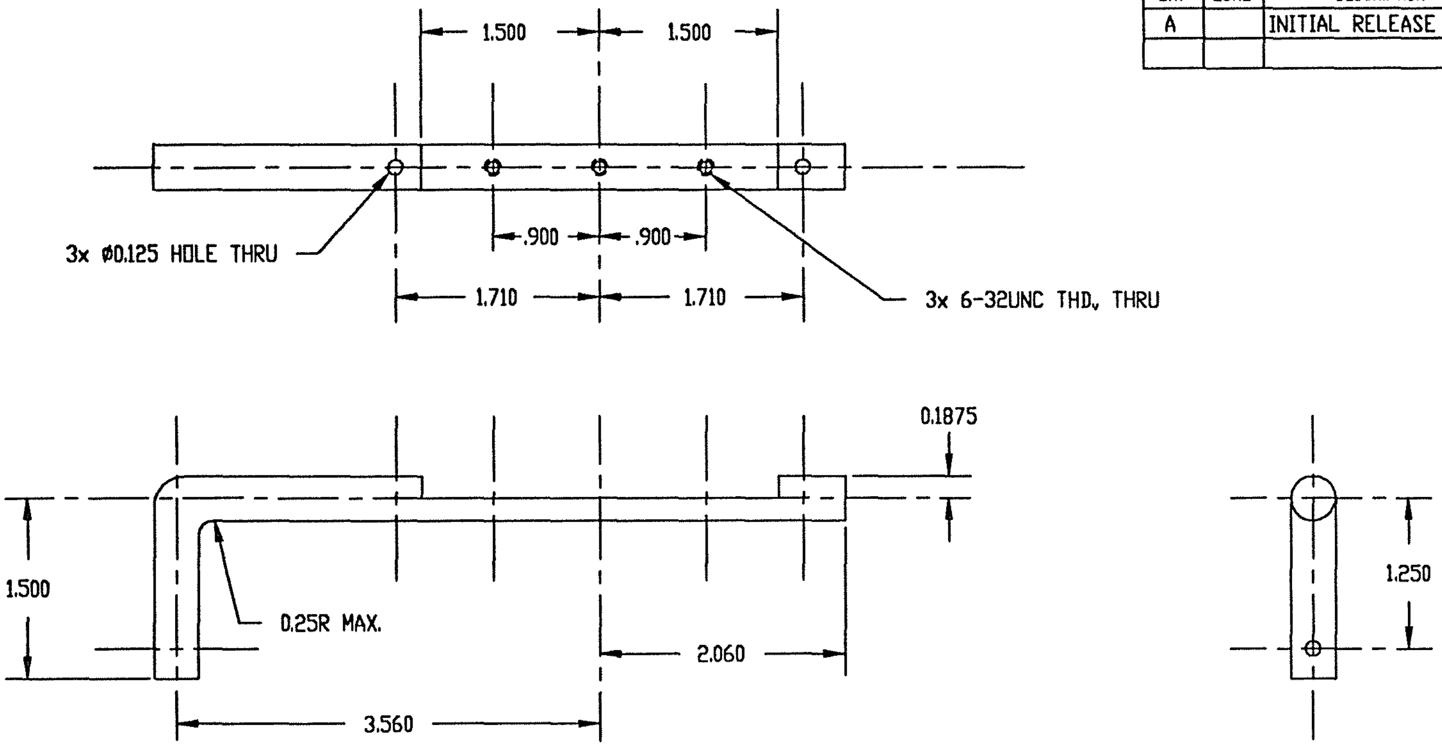
DESIGN WWN
DATE 04/28/91
DRAWN W. NEDERBRAGT
APPRV DAB
RELEASE DAB

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE LEVER FOR BUTTERFLY VALVE #1

QTY 1
SCALE 1:1
DRAWING NO. SHP-LAN-105
SIZE B
SHT
PROJECT AHMT PROGRAM

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



1		⌀0.375x7.00	316 S.S. ROD	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

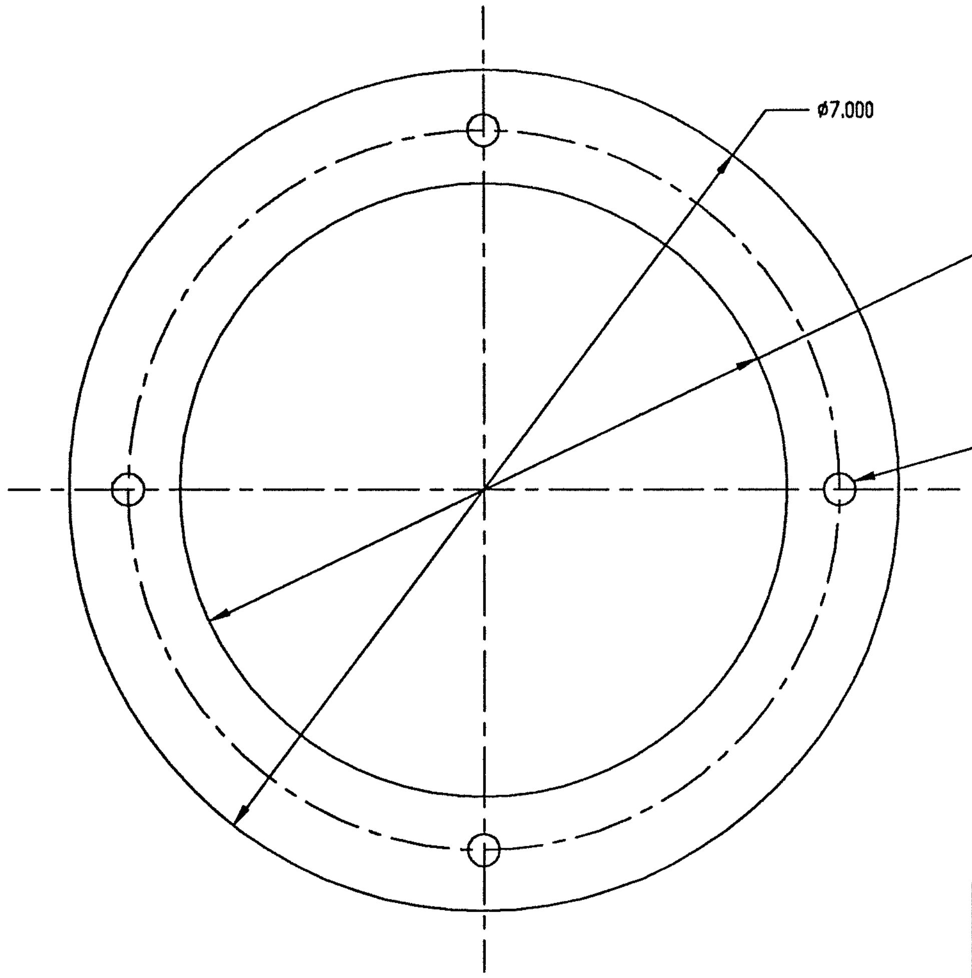
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ±.01 ANGLES ±0.5°
.XXX ±.005
64√

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE LEVER FOR BUTTERFLY VALVE #2

DESIGN WWN
DATE 04/28/91
DRAWN W. NEDERBRAGT
APPRV DAB
RELEASE DAB
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHP-LAN-106
PROJECT AHMT PROGRAM

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



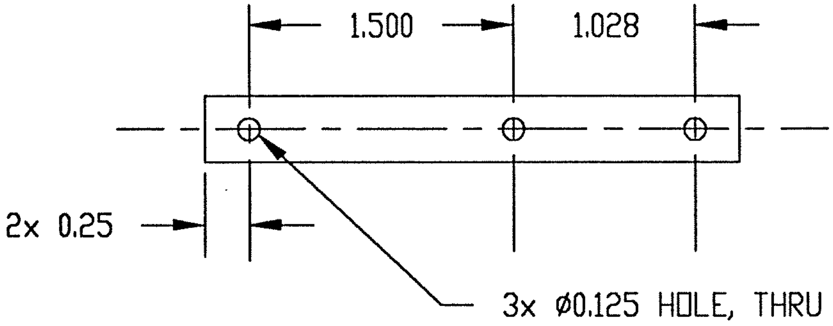
NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

1		⌀7.00	316 S.S. 16 GA. SM.	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED: TOLERANCES .XX ±.01 ANGLES ±0.5° .XXX ±.005 64		UNIVERSITY OF CALIFORNIA, DAVIS MECHANICAL ENGINEERING DEPARTMENT	
DESIGN WWN	DATE 04/28/91	TITLE FLANGE FOT MOUNTING LANCE TO TUBE BURNER	
DRAWN W. NEDERBRAGT		QTY 1	DRAWING NO. SHP-LAN-107
APPRV DAB		SCALE 1:1	
RELEASE DAB		SIZE B SHT	PROJECT AHMT PROGRAM

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



1		ø0.373x3.50 ROD	316 S.S.	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ±.01
.XXX ±.005
ANGLES ±0.5°
64

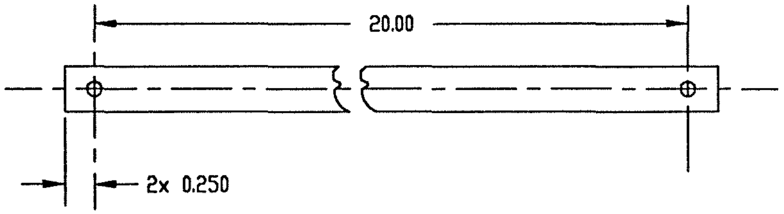
DESIGN WWN
DATE 04/28/91
DRAWN W. NEDERBRAGT
APPRV DAB
RELEASE DAB

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE CONNECTING ROD BETWEEN TWO BUTTERFLY VALVE SHAFTS

QTY 1
SCALE 1:1
DRAWING NO. SHP-LAN-108
SIZE A
SHT
PROJECT AHMT PROGRAM

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



1		ϕ0.375x21.00	316 S.S. ROD	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±0.5°
.XXX ± .005
64√

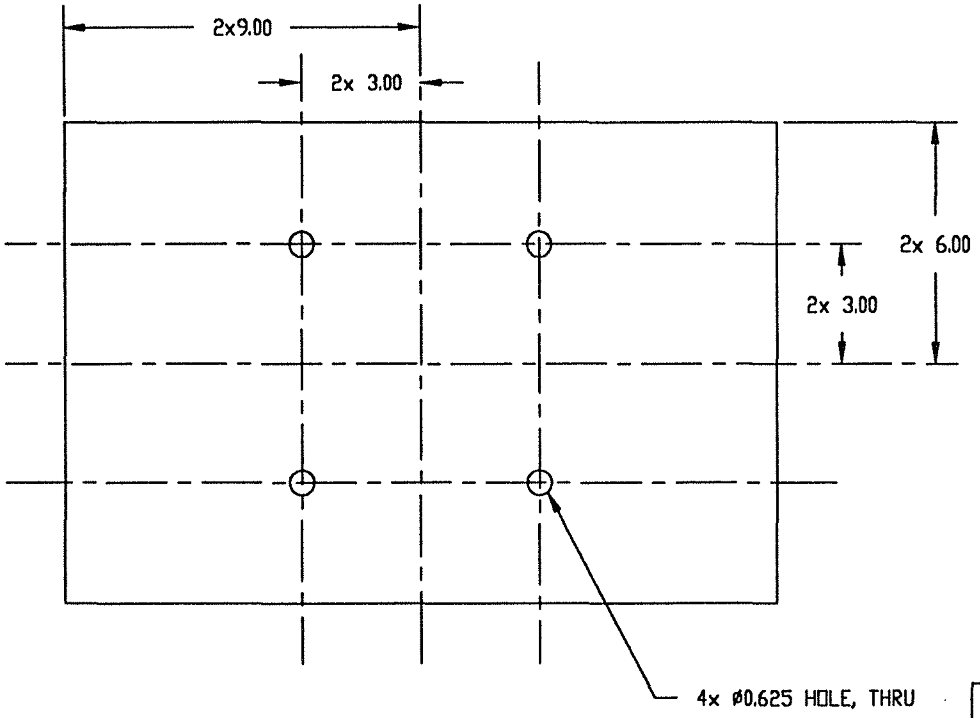
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE CONNECTING ROD BETWEEN VALVES AND CYLINDER

DESIGN WWN	DATE 04/28/91		
DRAWN W. NEDERBRAGT		QTY 1	DRAWING NO. SHP-LAN-109
APPRV DAB		SCALE 1/2:1	
RELEASE DAB		SIZE B	SHT	PROJECT AHMT PROGRAM

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
1		12.00x18.00x0.50	0.5' STEEL PLATE	1

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ±.01 ANGLES ±0.5°
.XXX ±.005 64√

DESIGN WWN DATE 04/28/91
DRAWN W. NEDERBRAGT
APPRV DAB
RELEASE DAB

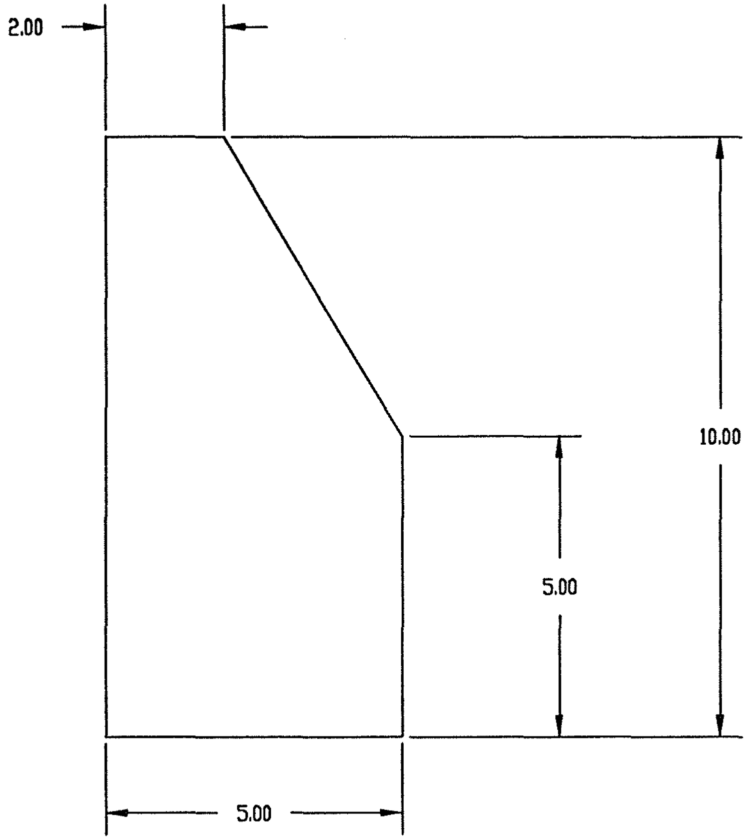
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE MOUNTING PLATE FOR BURNER

QTY 1
SCALE 1/3:1
SIZE B
SHT
DRAWING NO. SHP-LAN-110
PROJECT AHMT PROGRAM

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP
A		INITIAL RELEASE	04/28/91	WWN	WWN



1		10.00x5.00x0.500	0.5" STEEL PLATE	2
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ±.01 ANGLES ±0.5°
.XXX ±.005
64√

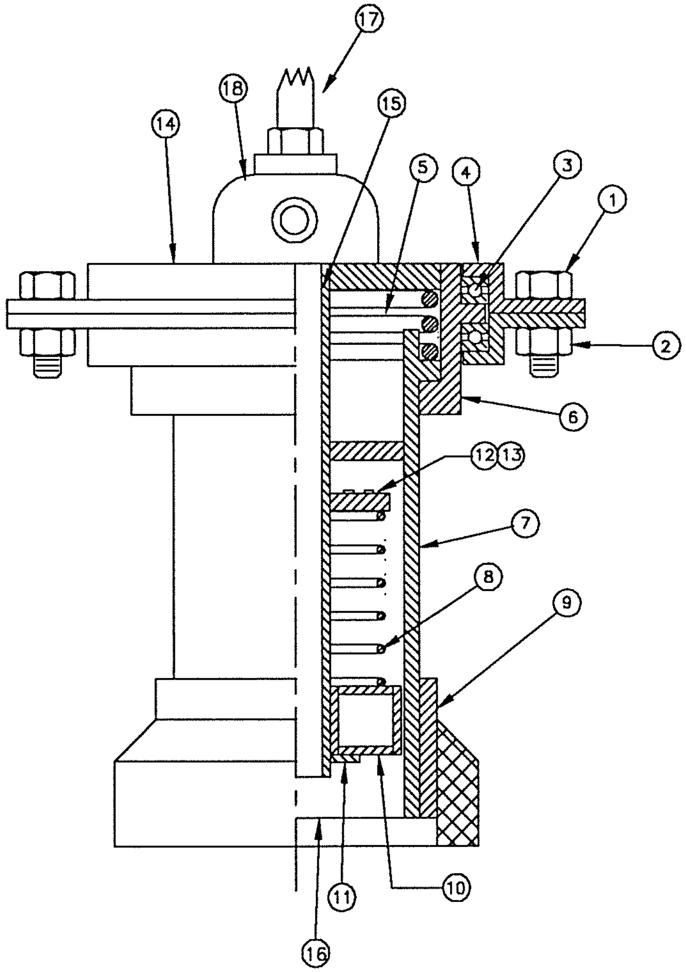
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

DESIGN WWN	DATE 04/28/91	TITLE MOUNTING PLATE FOR BURNER	
DRAWN W. NEDERBRAGT		QTY 2	DRAWING NO. SHP-LAN-111
APPRV DAB		SCALE 1/2:1	
RELEASE DAB		SIZE B	SHT	PROJECT AHMT PROGRAM

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & BREAK SHARP EDGES
2. ALL FILLET RADII 0.015 MAX

6.5 SEALANT APPLICATOR TECHNICAL DRAWINGS

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP

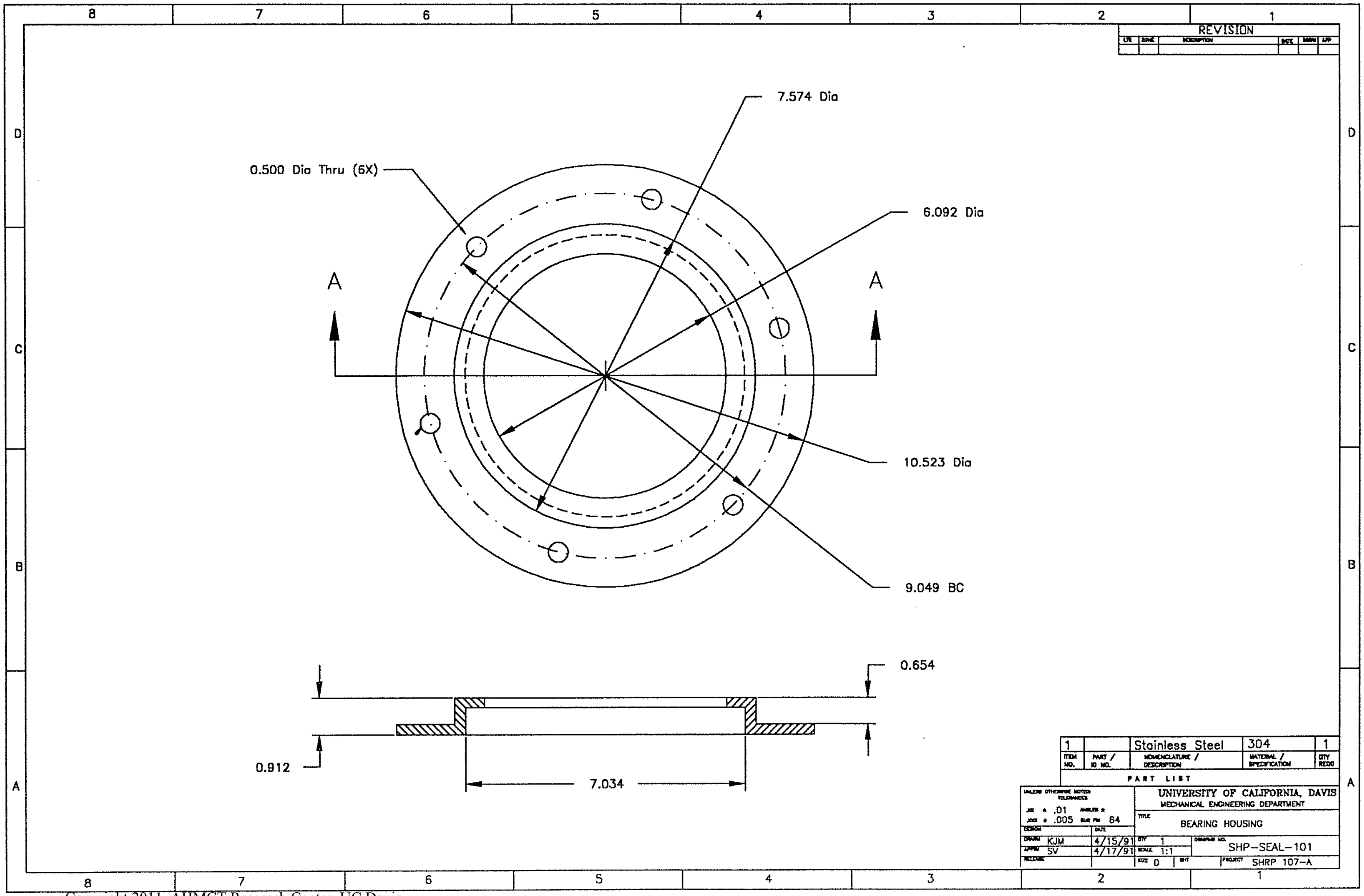


No.	Qty	DESCRIPTION	DWG No.
18	01	SHUTTLE VALVE	
17	01	SUPPLY HOSE	
16	01	SEALANT POCKET	
15	01	SEALANT PIPE	
14	01	TOP DISC	107
13	04	STRAIN GUAGE	
12	01	STRAIN RING	106
11	01	RETAINING RING	
10	01	LEVEL FLOATER	105
09	01	SEALING RING	104
08	01	HELICAL SPRING	
07	01	HOUSING CYLINDER	103
06	01	UPPER HOUSING	102
05	01	HELICAL SPRING	
04	02	BEARING HOUSING	101
03	02	THRUST BEARING	
02	06	1/2"-13 UNC NUT	
01	06	1/2"-13 UNC BOLT	

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.xx ± .01 ANGLES ±
.xxx ± .005 SUR FIN 64

DESIGN		DATE	UNIVERSITY OF CALIFORNIA, DAVIS MECHANICAL ENGINEERING DEPARTMENT		
			TITLE SEALANT APPLICATOR ASSEMBLY		
DRAWN	KJM	4/15/91	QTY 1	DRAWING NO. SHP-SEAL-100	
APPRV	SV	4/17/91	SCALE 1:1		
RELEASE			SIZE D	SHT	PROJECT SHRP 107-A



1		Stainless Steel	304	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

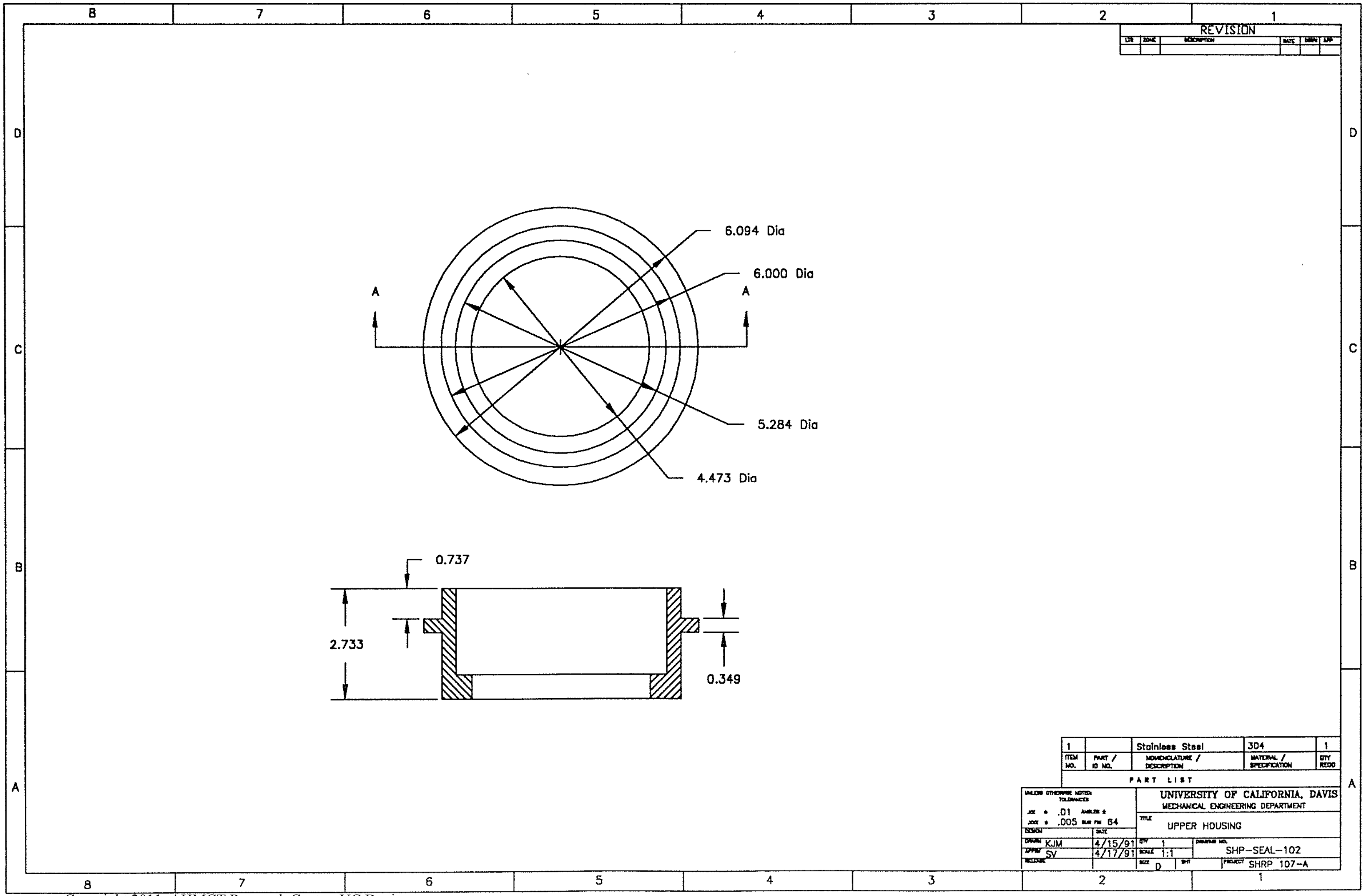
PART LIST

UNLESS OTHERWISE NOTED TOLERANCES
.XX ± .01 ANGLES ±
.XXX ± .005 SUR FIN 64

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE BEARING HOUSING

DESIGN
DATE
DRAWN KJM 4/15/91
APPRV SV 4/17/91
RELEASE
QTY 1
SCALE 1:1
DRAWING NO. SHP-SEAL-101
SIZE D
SHT
PROJECT SHRP 107-A



REVISION

LTR	ZONE	DESCRIPTION	DATE	DRWN	APP

ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
1		Stainless Steel	304	1

PART LIST

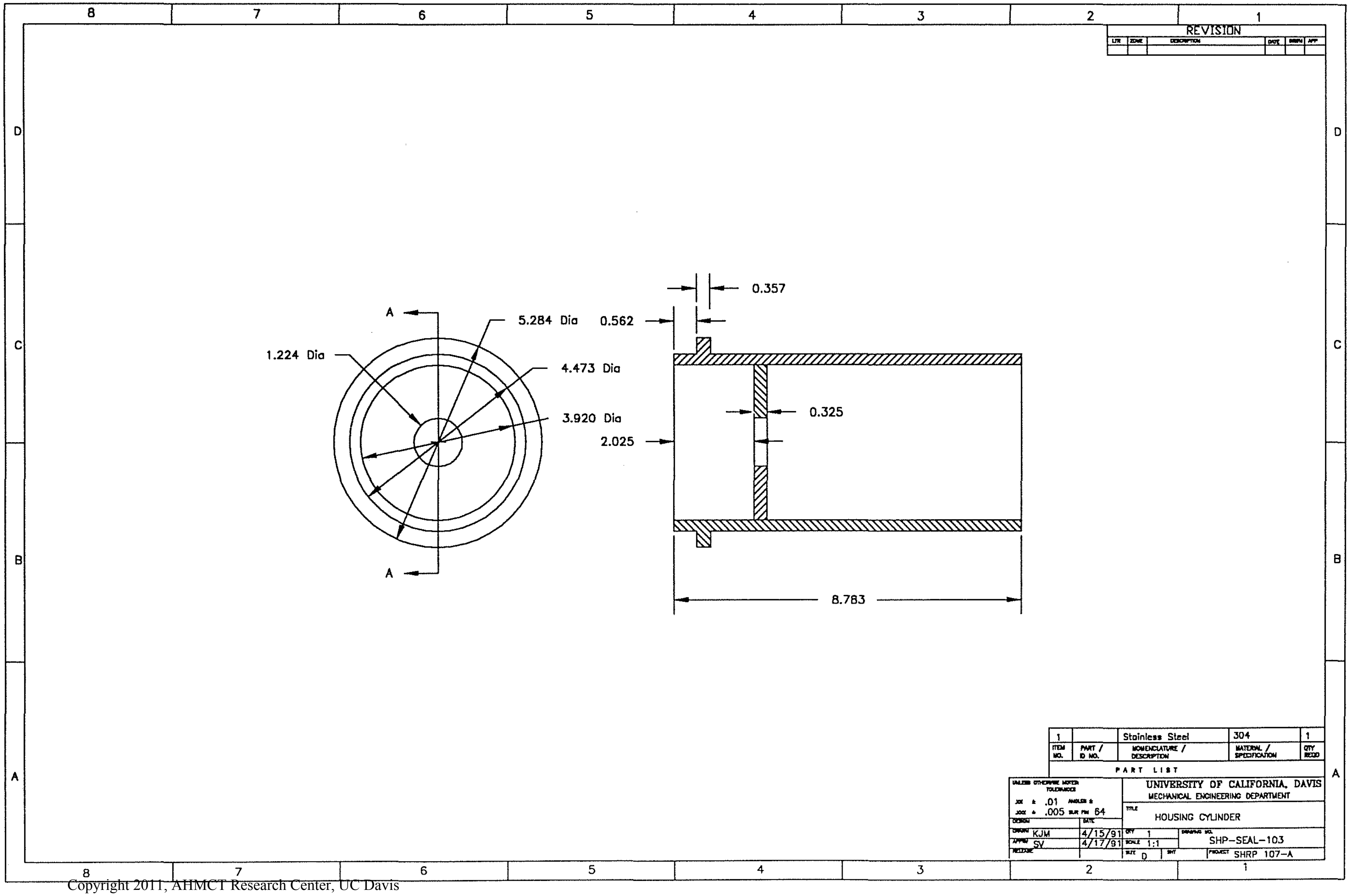
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .01 ANGLES ±
.XXX ± .005 SUR FIN 64

DESIGN
DRAWN KJM 4/15/91
APPR SV 4/17/91
RELEASE

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE UPPER HOUSING

QTY 1
SCALE 1:1
SIZE D
SHT
DRAWING NO. SHP-SEAL-102
PROJECT SHRP 107-A



REVISION

LTR	ZONE	DESCRIPTION	DATE	DRWN	APP

1		Stainless Steel	304	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

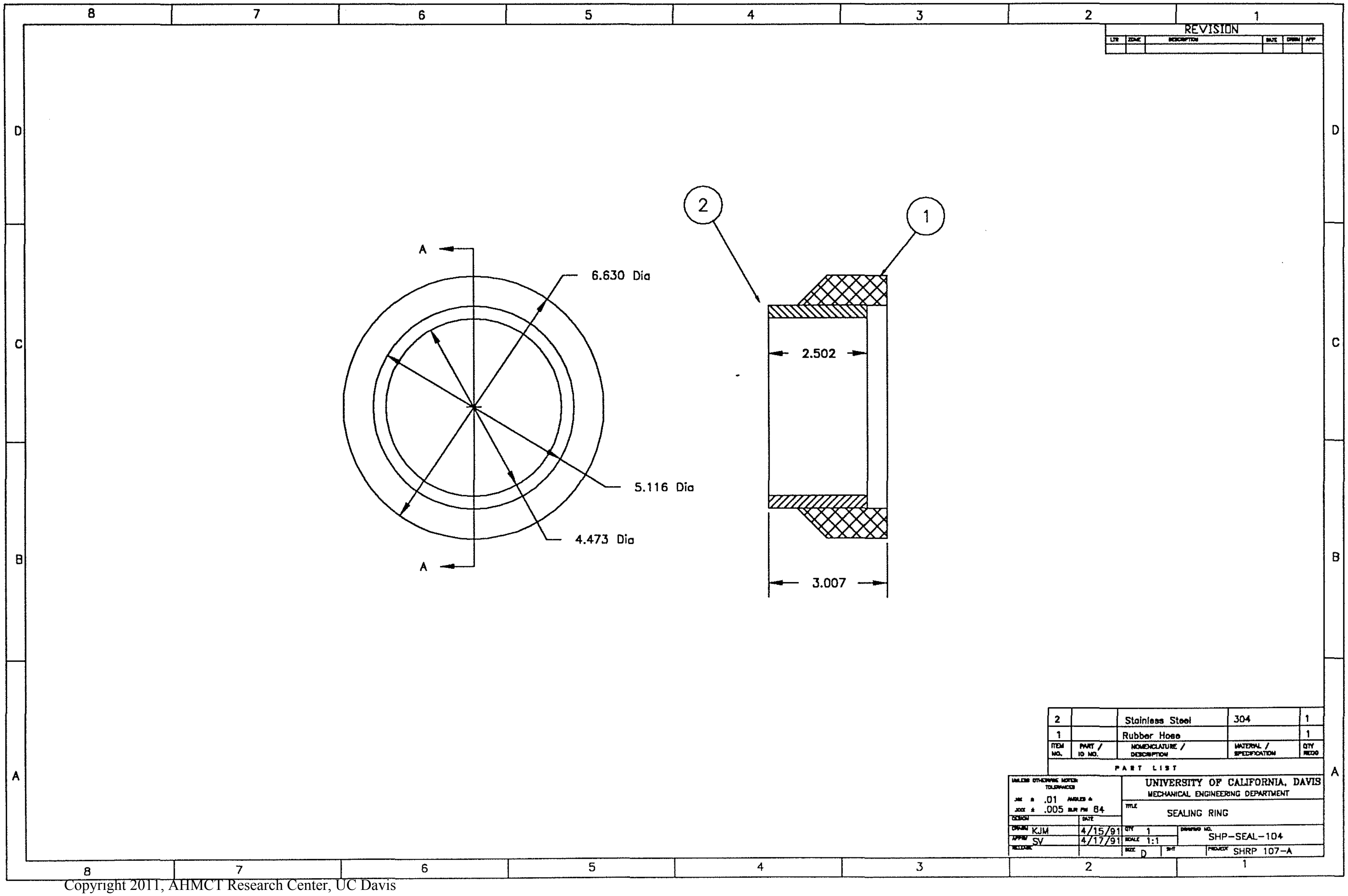
UNLESS OTHERWISE NOTED TOLERANCES
.XX ± .01 ANGLES ±
.XXX ± .005 SUR FIN 64

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE HOUSING CYLINDER

DESIGN	DATE
DRAWN KJM	4/15/91
APPRVD SV	4/17/91
RELEASE	

QTY 1
SCALE 1:1
SIZE D
SHT
DRAWING NO. SHP-SEAL-103
PROJECT SHRP 107-A



2		Stainless Steel	304	1
1		Rubber Hose		1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .01 ANGLES ±
.XXX ± .005 SUR FIN 64

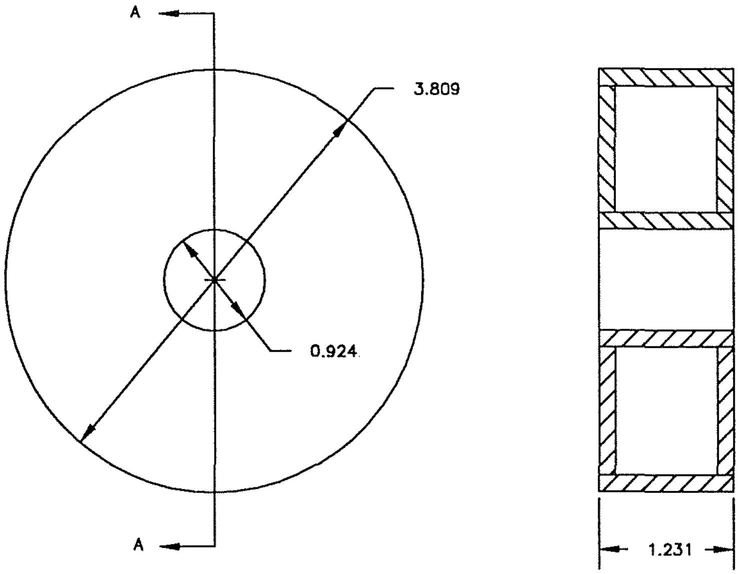
DESIGN
DATE
DRAWN KJM 4/15/91
APPRV SV 4/17/91
RELEASE

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE SEALING RING

QTY 1
SCALE 1:1
SIZE D
SHT
DRAWING NO. SHP-SEAL-104
PROJECT SHRP 107-A

		REVISION			
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP



1		Stainless Steel	304	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

P A R T L I S T

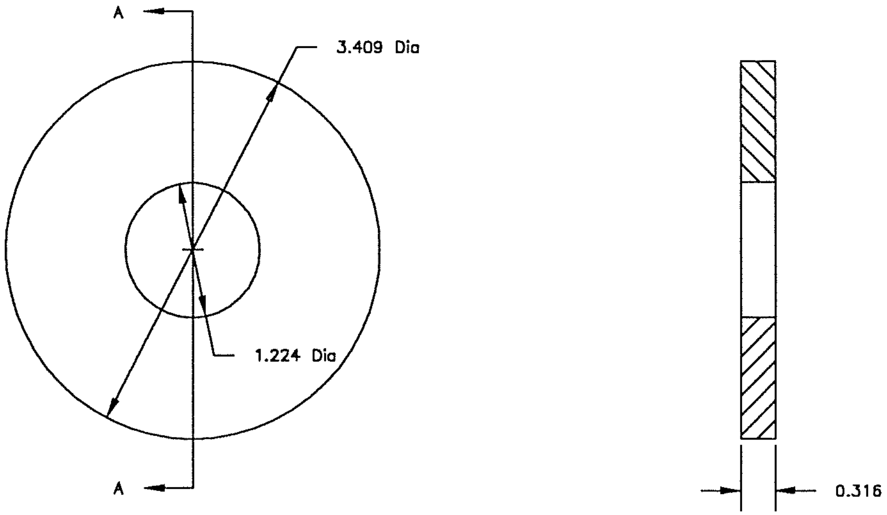
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±
.XXX ± .005 ✓ 65

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE
LEVEL FLOATER

DESIGN	DATE		
DRAWN KJM	4/16/91	QTY 1	DRAWING NO. SHP–SEAL–105
APPRV SV	4/18/91	SCALE 1:1	
RELEASE		SIZE B	SHT	PROJECT SHRP 107–A

REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP



ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
1		Stainless Steel	304	1

PART LIST

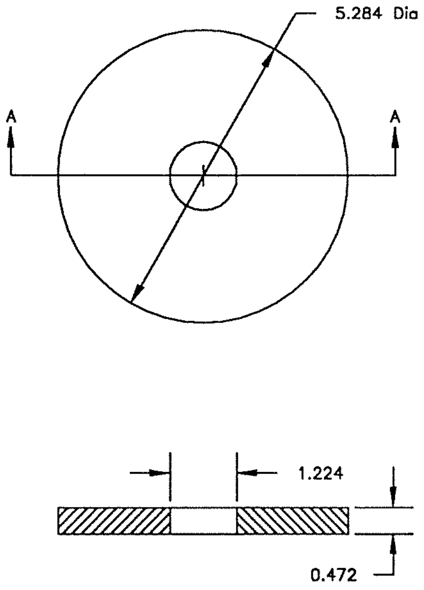
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±
.XXX ± .005 √ 65

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE STRAIN RING

DESIGN	DATE
DRAWN KJM	4/16/91
APPRV SV	4/18/91
RELEASE	

QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHP-SEAL-106
PROJECT SHRP 107-A



REVISION					
LTR	ZONE	DESCRIPTION	DATE	DRWN	APP

1		Stainless Steel	304	1
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD

PART LIST

UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01 ANGLES ±
.XXX ± .005 ✓ 65

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT

TITLE TOP DISC

DESIGN	DATE
DRAWN KJM	4/16/91
APPRV SV	4/18/91
RELEASE	

QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHP-SEAL-107
PROJECT SHRP 107-A

6.6 VENDOR TECHNICAL SPECIFICATIONS

AEROIL PRODUCTS COMPANY,INC.
69 Wesley Street
So. Hackensack, NJ 07606

CRACK & JOINT ROUTER MODEL CJR-24E-6
24HP Heavy Duty Machine Designed To Prepare Existing Cracks & Joints In Asphalt & Concrete Pavements For Filling & Sealing

July 1990

SPECIFICATION DESCRIPTION

THE FOLLOWING MINIMUM REQUIREMENTS ARE TO BE FURNISHED AS STANDARD

1. General Description

A portable, highly maneuverable pavement maintenance router with six carbide tipped cutters. Depth to be adjustable and gauged thru an electric linear actuator. 24 HP gasoline engine with triple band V-Belt drive for cleaning, widening, grooving or routing cracks and joints in asphalt or concrete roadways, airports, and parking lots.

2. Approximate Dimensions

Weight:	625 Lbs.	Overall Length:	75"
Width:	45"	Ht. to Handles:	32"

3. Tool System

Tool depth capability in pavement 0" - 1-1/2" depth. Maximum groove width - 2". Six 4-3/4" diameter, eight carbide tipped cutters, free spinning, mounted in double plate tool holding weldment. Cutters to be readily removable for replacement. Tool removal drive pin shall be provided. Debris from cutting action shall be thrown forward against chassis shield protecting traffic and pedestrians. A cut-out in the operating rear shield shall permit operator to view cutter in the groove for precise routing.

4. Engine & Drive System

24 HP Onan Engine with electric start alternator, ammeter and oil pressure gauge. The engine powers a three banded V-belt, three groove pulley system with adjustable take up plate. Plate to be adjustable without removing belt guard. Belt guard shall be provided. Engine throttle, emergency stop button and cutter depth switch shall be located on the operator's panel. 12V battery SAE 9AL or equal shall be provided.

5. Chassis

Electric welded construction using 1/4" plate on main chassis. Pivoting drop axle assemblies on the chassis shall permit raising and lowering cutters by means of power arms actuated by the 12 volt fused linear actuator and provide smooth operational action to the cutters. Position of the cutter plates and cutters to retard violent rearward action toward the operator. Router supplied with balanced hoisting yoke, pivotable for easy engine maintenance.

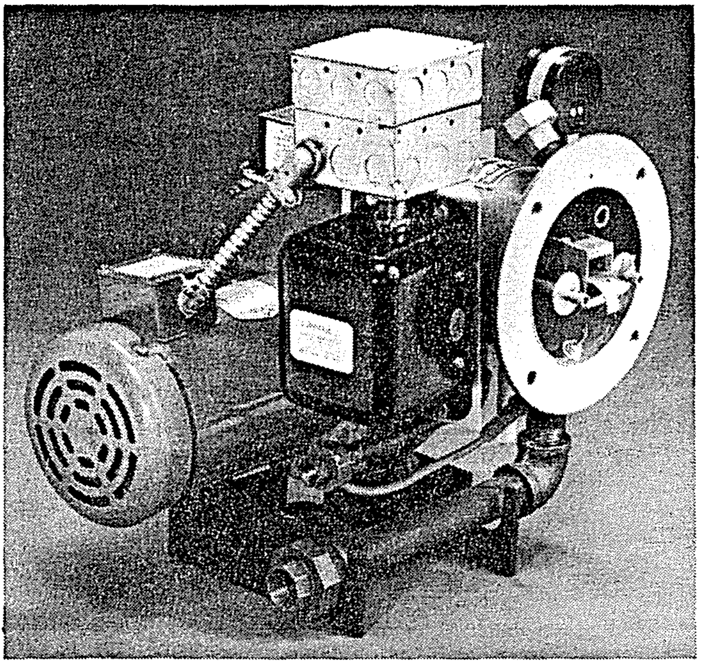
Two high-pressure pneumatic tires and wheels shall be provided for maximum stability and performance of cutters. Tire pressure: 60 PSI. Tires 4.80/4.00 x 8 load rating B. A steady rest mounted on handle shall hold same at the operating level. Handle shall be demountable for storage and handling.

An adjustable depth of cut gauge is to be positioned near the operators panel for easy viewing.

An abbreviated instruction shall be at the operator's panel. Unit to have a water resistant holder for detailed operating instructions and parts list.

5" Tube Burner

Models 12031-4, 300 CFM Blower; 12064-3, 530 CFM Blower; 12145, 600 CFM Blower



- 23,000 to 1,800,000 BTU/HR
- 1/3 HP - 3450 RPM
- 110 VAC, 240 VAC, 480 VAC
- Safe
- Compact
- Economical
- Self-Cleaning Radial Blade Fan
- Blower Wheel, Dynamically Balanced
- Complete Combustion

The Sur-Lite 5" Tube Burner is versatile, compact and economical. It gives **complete** combustion, saving you money by burning ALL YOUR FUEL. It features a radial blade, self-cleaning blower. Variable BTU output and a selection of operating voltages makes this burner ideal for many applications.

Includes 3/4" Bushed to 1" Main Gas Connection, 3/8" Pilot Gas Connection, Piping to the unions, 1/2" Site Glass, 1/2" Scanner Connection, Spark Ignitor, Blower with Manual Damper. Burner Electrical Assembly #12031-09, Ignition Transformer, Bracket, Air Flow Switch, Electrical Junction Box, Wiring, and Piping.

Gas fired applications include:

- Furnaces
- Ovens
- Holding & Melting Pots (150# to 1000# units)
- Boilers
- Any general usage power burner.
- Immersion Tube Heaters
- Afterburners

Options include:

- Modulating Damper
- Single or 3 Phase Motors
- Totally Enclosed Fan Cooled Motor
- Variable Sequence Functions

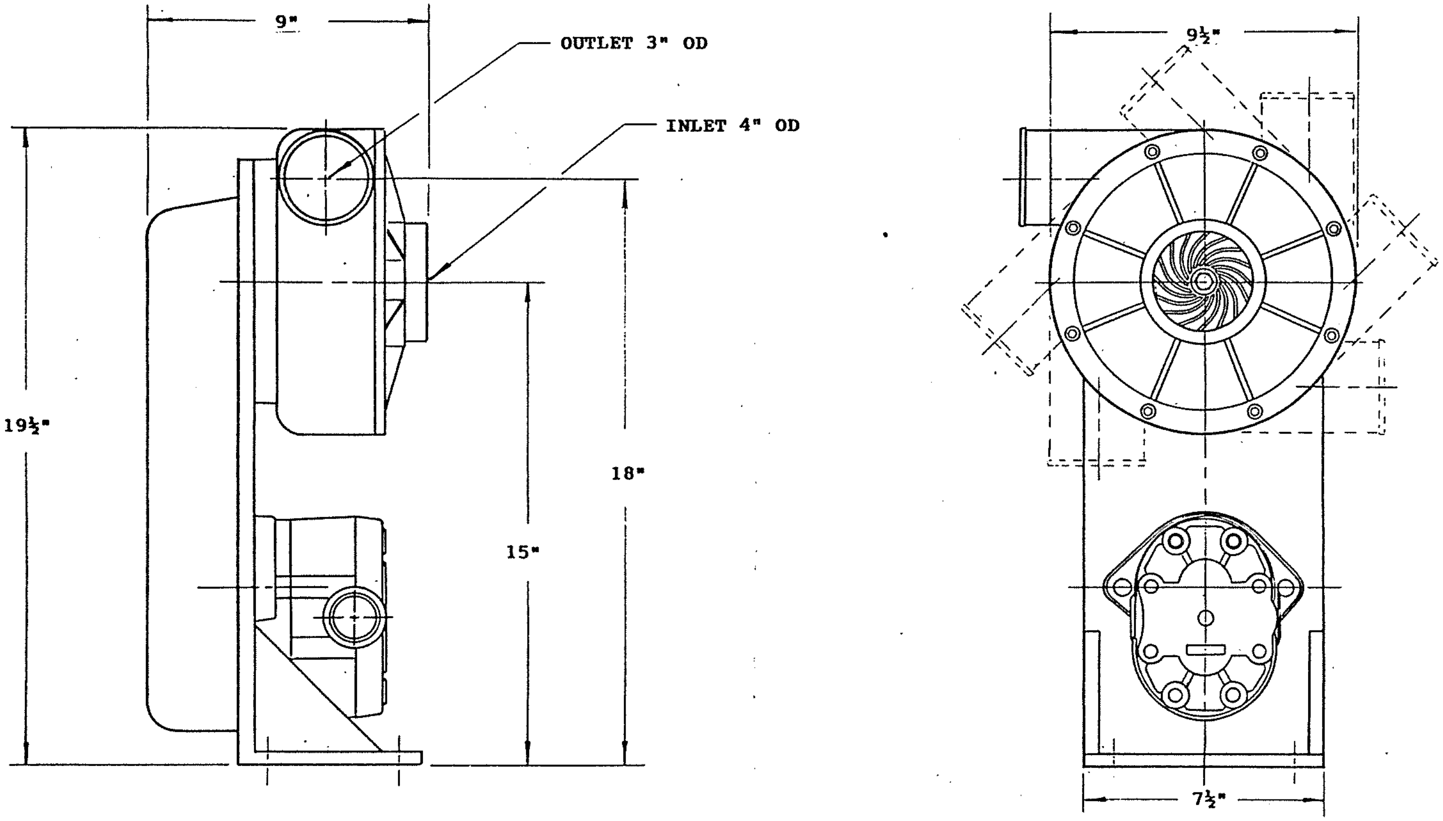
(213) 693-0796
(213) 698-9432
Telex: 67-7373

SUR-LITE CORPORATION

8124 Allport Avenue • Santa Fe Springs, California 90670

ADV-83-13

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED



HYDRAULIC LOAD = 1000 PSI AT 14 GPM

UNIT WT = 65 LBS

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
FRACTIONS ± — DECIMALS .XX ± — .XXX ± — ANGLES ± —

MATERIAL —

FINISH —

NEXT ASSY	USED ON
—	—

APPR	BY: DATE:
CHECKED	BY: KJW DATE: 1-18-91
DRAWN	BY: TR DATE: 1/18/91

SONIC AIR SYSTEMS
SANTA FE SPRINGS, CALIFORNIA

TITLE CENTRIFUGAL BLOWER
w/ 5 HP HYDRAULIC MOTOR

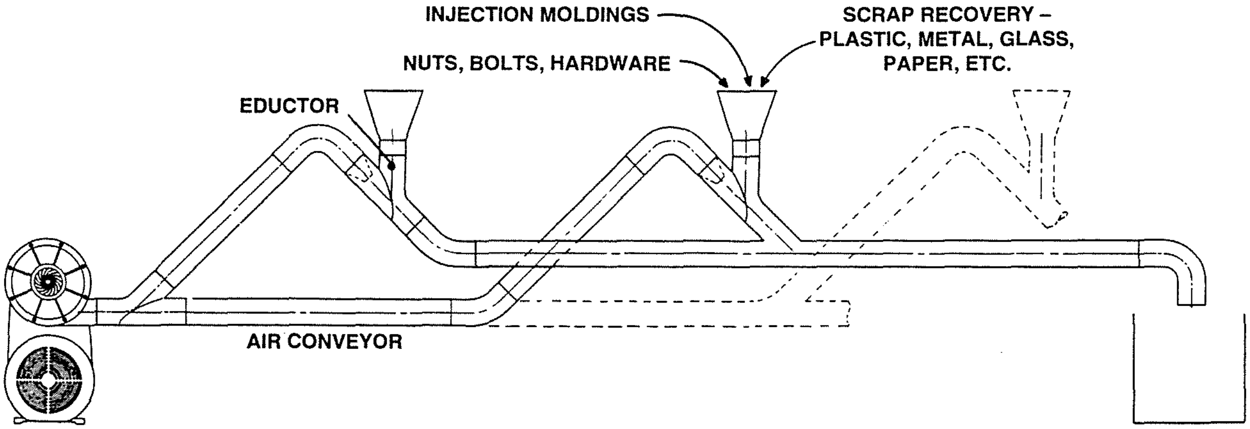
SIZE	FSCM NO.	DWG NO.	REV
		10090	

SCALE — SHEET 1 OF 1

SONIC AIR SYSTEMS

SANTA FE SPRINGS, CALIFORNIA, USA

- SINGLE AND MULTIPLE PORTS TO CONVEY FROM 2-200 FEET
- EDUCTOR NOZZLE INDUCES VACUUM AT PORT AND PROPELS PARTS TO DISCHARGE

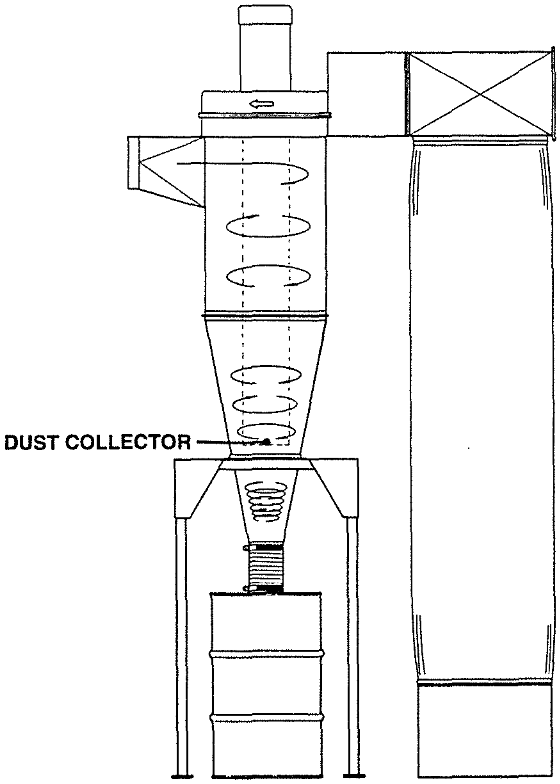


- SELF CONTAINED WITH ADJUSTABLE VELOCITY OF 1-15,000 FEET PER MINUTE
- SIMPLIFIED CONVEYOR DESIGN REQUIRES NO SEPARATORS OR ROTARY LOCK FEEDERS
- COMPLETE SYSTEMS CUSTOMIZED TO ANY APPLICATION

MATERIAL / PRODUCT AIR CONVEYORS

DUST COLLECTORS AND VACUUM SYSTEMS ENGINEERED TO ANY REQUIREMENT

- FILTER BAG DUST COLLECTORS
- CYCLONE SEPARATORS
- CARTRIDGE FILTER SYSTEMS WITH PULSE JET CLEANING BAG HOUSE UNITS
- AMBIENT AIR DUST EXTRACTORS
- WORKSTATION DOWNDRAFT TABLES



DUST COLLECTOR SYSTEMS

6.7 COST BENEFIT ANALYSIS SPREADSHEET

◦ COST SAVINGS ANALYSIS ◦

Crack Sealing System

	Current System Costs	Proposed System Costs
• Platform	$0	$250,000
• Additional Equipment	$0	$200,000
• Operational Cost	$45,000	$45,000
• Material Cost	$90,000	$90,000

ASSUMPTION

The differential cost between the two machines takes into consideration that the 'platform' and the 'additional equipment' categories of the current system do not need to be replaced or salvaged at this time. Thus, assuming that the 'operational cost' and the 'material cost' categories are equal for both systems, the differential cost incurred is due directly to the addition of another platform and additional equipment.

DIFFERENTIAL COST BETWEEN SYSTEMS = $450,000

◦ COST SAVINGS ANALYSIS ◦

CASE 1

ASSUMPTIONS

NO SPEED ADVANTAGE (1-2 Miles per Day)

(1) EXISTING AVERAGE NUMBER OF PERSONS / CREW	8
(2) AVERAGE LABOR COST / PERSON / YEAR	$50,000

PROPOSAL

(3) NEW AVERAGE NUMBER OF PERSONS/ CREW	4

RESULTS

(4) EXISTING AVERAGE LABOR COST / YEAR = [(1)*(2)]	$400,000
(5) NEW AVERAGE LABOR COST / YEAR = [(2)*(3)]	$200,000
AVERAGE LABOR COST SAVINGS / YEAR = [(5)-(4)]	**$200,000**

CASE 2

ASSUMPTIONS

SPEED ADVANTAGE (Up to 4 Miles per Day)

(6) NEW AVERAGE LABOR COST / YEAR	$200,000

PROPOSAL

(7) % LABOR COST REDUCTION DUE TO SPEED ADVANTAGE	30.00%

RESULT

ADDITIONAL NEW AVERAGE LABOR COST SAVINGS / YEAR = [(6)*(7)]	**$60,000**

◦ COST SAVINGS ANALYSIS ◦

CASE 3

ASSUMPTIONS

BETTER QUALITY OF PERFORMANCE (Reduced frequency of operation)

	Time	Year	% Time / Year
(8) AVERAGE FREQUENCY OF MAINTENANCE	1	2	50.00%
PROPOSAL			
(9) NEW FREQUENCY OF MAINTENANCE	1	3	33.33%

RESULTS

(10) % FREQUENCY MAINTENANCE SAVINGS / YEAR = [(9)-(8)]	16.67%
(11) MATERIAL COST / YEAR	$90,000
FREQUENCY MAINTENANCE MATERIAL COST SAVINGS / YEAR = [(10)*(11)]	**$15,000**

DESCRIPTION	*SAVINGS*
Average Labor Cost Savings / Year	$200,000
Additional New Average Labor Cost Savings / Year	$60,000
Frequency Maintenance Material Cost Savings / Year	$15,000
TOTAL PROPOSED SYSTEM SAVINGS / YEAR =	**$275,000**

CRACK SEALING SYSTEM

◦ SUMMARY ◦

ASSUMPTIONS

Inflation Rate (e) = 5.00%
Cost of Money (i) = 10.00%
Corrected Value (i') = i + e + ie = 15.50%

CASE 1

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
AVERAGE LABOR COST	$400,000	$420,000	$441,000	$463,000
LABOR COST SAVINGS	$200,000	$210,000	$221,000	$232,000
DIFFERENTIAL COST / YEAR	$450,000	($263,000)	($56,000)	
ACTUAL SAVINGS /YEAR	($250,000)	($53,000)	$165,000	$232,000
NET PRESENT VALUE = A(P/A, i'%, n) - Initial Investment	$537,000			

CASE 2

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
NEW AVERAGE LABOR COST	$200,000	$210,000	$221,000	$232,000
ADDITIONAL LABOR COST SAVINGS	$60,000	$63,000	$66,000	$70,000
DIFFERENTIAL COST / YEAR	$450,000	($200,000)		
ACTUAL SAVINGS /YEAR	($190,000)	$73,000	$287,000	$302,000
NET PRESENT VALUE = A(P/A, i'%, n) - Initial Investment	$833,000			

◦ SUMMARY ◦

CASE 1

	YEAR 5	YEAR 6	YEAR 7	YEAR 8
AVERAGE LABOR COST	$486,000	$510,000	$536,000	$563,000
LABOR COST SAVINGS	$243,000	$255,000	$268,000	$282,000
DIFFERENTIAL COST / YEAR				
ACTUAL SAVINGS /YEAR	$243,000	$255,000	$268,000	$282,000

CASE 2

	YEAR 5	YEAR 6	YEAR 7	YEAR 8
NEW AVERAGE LABOR COST	$244,000	$256,000	$269,000	$282,000
ADDITIONAL LABOR COST SAVINGS	$73,000	$77,000	$81,000	$85,000
DIFFERENTIAL COST / YEAR				
ACTUAL SAVINGS /YEAR	$317,000	$333,000	$350,000	$367,000

◦ SUMMARY ◦

CASE 1

	YEAR 9	YEAR 10
AVERAGE LABOR COST	$591,000	$621,000
LABOR COST SAVINGS	$296,000	$311,000
DIFFERENTIAL COST / YEAR		
ACTUAL SAVINGS /YEAR	$296,000	$311,000

CASE 2

	YEAR 9	YEAR 10
NEW AVERAGE LABOR COST	$296,000	$311,000
ADDITIONAL LABOR COST SAVINGS	$89,000	$93,000
DIFFERENTIAL COST / YEAR		
ACTUAL SAVINGS /YEAR	$385,000	$404,000

◦ SUMMARY ◦

CASE 3

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
LABOR COST SAVINGS	$200,000	$210,000	$221,000	$232,000
ADDITIONAL LABOR COST SAVINGS	$60,000	$63,000	$66,000	$70,000
MATERIAL COST	$90,000	$95,000	$100,000	$105,000
MATERIAL COST SAVINGS	$15,000	$16,000	$17,000	$18,000
SYSTEM SAVINGS / YEAR	$275,000	$289,000	$304,000	$320,000
DIFFERENTIAL COST / YEAR	$450,000	($184,000)		
ACTUAL SAVINGS /YEAR	($175,000)	$105,000	$304,000	$320,000
NET PRESENT VALUE = A(P/A, i'%, n) - Initial Investment	$907,000			

◦ SUMMARY ◦

CASE 3

	YEAR 5	YEAR 6	YEAR 7	YEAR 8
LABOR COST SAVINGS	$243,000	$255,000	$268,000	$282,000
ADDITIONAL LABOR COST SAVINGS	$73,000	$77,000	$81,000	$85,000
MATERIAL COST	$110,000	$116,000	$122,000	$128,000
MATERIAL COST SAVINGS	$18,000	$19,000	$20,000	$21,000
SYSTEM SAVINGS / YEAR	$334,000	$351,000	$369,000	$388,000
DIFFERENTIAL COST / YEAR				
ACTUAL SAVINGS /YEAR	$334,000	$351,000	$369,000	$388,000

◦ SUMMARY ◦

CASE 3

	YEAR 9	YEAR 10
LABOR COST SAVINGS	$296,000	$311,000
ADDITIONAL LABOR COST SAVINGS	$89,000	$93,000
MATERIAL COST	$134,000	$141,000
MATERIAL COST SAVINGS	$22,000	$24,000
SYSTEM SAVINGS / YEAR	$407,000	$428,000
DIFFERENTIAL COST / YEAR		
ACTUAL SAVINGS /YEAR	$407,000	$428,000