ON THE DEVELOPMENT OF A DESIGN CONCEPT FOR AUTOMATED PAVEMENT CRACK SEALING MACHINERY

Interim Report of

SHRP H-107A

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Strategic Highway Research Program

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ABSTRACT

Worldwide, a tremendous amount of resources are expended annually maintaining highway pavement. In the state of California alone, the Department of Transportation spends approximately $10 million per year of this maintenance budget to seal and fill cracks in the pavement. When properly performed, crack sealing and filling can help retain the structural integrity of the roadway and considerably extend the mean time between major rehabilitation.

Sealing and filling of cracks is a very labor-intensive and tedious operation. Approximately 2/3 of the cost is attributed to labor. A typical operation crew can seal or fill only approximately 2 lane-miles per day at a cost of about $1800 per lane-mile. Furthermore, the procedure is not standardized and there is a large distribution in the quality of the resultant seal. Additionally, the workers are exposed to a great deal of physical danger from moving traffic and dangerous equipment.

The goal of the SHRP H-107A project, of which this thesis project is a part, is to develop a prototype automated crack sealing machine that will sense, prepare, and seal (or fill) cracks and joints in road surfaces. The development of this machine is an attempt to eliminate or reduce the hazards and efficiencies as noted above. This thesis investigates the development of such a machine considering the topics of road surface preparation, positioning system (system for positioning the cleaning, heating, routing, and sealing/filling devices) configuration selection, and positioning system concept design selection. The investigation was structured by the function synthesis (orderly creative inventing) and brainstorming methods of development and design.

A literature search was performed to determine the road surface cleaning methods that were currently being employed in the United States and other countries. Feasibility experiments of various cleaning methods were also conducted and presented. Cleaning

method selection criteria were then developed. From the literature review and feasibility experiments, the advantages and disadvantages of each method were discussed. Following the discussion, it was determined that the abrasive vacuum blasting has the potential of producing the best results. However, considerable development would be required to make it commercially feasible for the crack sealing machine prototype. It was decided that a centrifugal blower/vacuum system will do a satisfactory job of removing most *loose* debris from the road surface and cracks if controlled properly. Furthermore, the use of the air blower method will be sufficient to demonstrate the main objectives of the SHRP H-107A project. The blower/vacuum system will be incorporated into the prototype machine.

The basic positioning system configurations were discussed (e.g. "array" and "crack following" configurations). These configurations relate to the manner in which the cleaning, heating, and sealing devices are positioned over the cracks in the road surface. The inherent advantages and disadvantages of each configuration were then discussed. Based of the information that was generated during this discussion, the best crack following configuration was selected. It was determined that the "crack following" system was the best positioning system configuration. This configuration will be incorporated into the prototype machine.

After the positioning system configuration was selected, the best "concept design" for the positioning system was considered. Design criteria were specified. Numerous concept designs were generated and the advantages, disadvantages, and significant design features of each design were discussed. The best concept design was chosen based on the information generated. It was determined that the Truck-Mounted Manipulator Arm system (Fig. 6.5) was the best concept design. This concept design will be incorporated into the prototype crack sealing machine. Finally, conclusions of this project were noted and recommendations for future study were presented.

CHAPTER 1

INTRODUCTION

1.1 - Problem Description

Worldwide, a tremendous amount of resources are expended annually maintaining highway pavement. In the state of California alone, the Department of Transportation (Caltrans) spends approximately $100 million per year maintaining about 33,000 lane-miles of Asphalt Concrete (AC) pavement and 13,000 lane-miles of Portland Cement Concrete (PCC) pavement. Approximately $10 million of this maintenance budget is used to seal and fill cracks in the pavement. When properly performed, crack sealing and filling can help retain the structural integrity of the roadway and considerably extend the mean time between major rehabilitation.

Sealing and filling of cracks is a labor-intensive and tedious operation. A typical operation for sealing cracks in AC pavement involves a crew of eight persons. This crew can seal approximately 2 lane-miles per day at a cost of about $1800 per lane-mile. 66% of this cost is 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. Additionally, the workers must be on the road surface adjacent to moving traffic, thus exposing them to a great deal of physical danger.

1.2 - The Need for an Automated Crack Sealing/Filling Machine

The final goal of the SHRP H-107A project, of which this thesis project is a part, is to develop a prototype automated crack sealing machine that will sense, prepare, and seal (or fill) cracks and joints in AC and PCC pavement. The goal of this project is to investigate the development of such a machine considering only the topics of road surface preparation, positioning system (system for positioning the cleaning, heating, routing, and sealing/filling devices) configuration selection, and positioning system concept design selection. The primary objectives of the project are to:

- Increase the cost-effectiveness of the crack sealing and filling operations,
- Increase the quality, consistency, and life of the resultant seals and fills,
- Increase the safety of work crews and highway users, and
- Increase the use of remote equipment operation and control to attain the above.

A machine that can satisfy the objectives listed above will have the added benefits of reducing lane and highway closures and thus, will play a significant role in the reduction of traffic congestion, a considerable problem in major urban regions around the world. The cost effectiveness of such a machine will be realized through a combination of increased speed and reduced manpower, in addition to the higher quality seal which will reduce the frequency of major highway rehabilitations.

1.3 - Machine Specifications

To have the greatest impact, such a machine should satisfactorily perform the following tasks automatically:

- Sense the occurrence and location of cracks in pavement.
- Prepare the crack and pavement surface for sealing/filling. This task includes the removal of vegetation, loose debris, dirt film, and moisture. In addition, preheating of the road surface may be necessary to ensure maximum sealant adhesion and refacing of reservoirs (routing) may be required.

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

In addition, the overall functional (performance) specifications of the machine should be:

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

Furthermore, the equipment prototypes may be derived from modifying existing equipment or from the development of new equipment (with preference given to suitable commercially available equipment), and each equipment design may include one or more pieces of equipment.

1.4 - Literature Review of Road Surface Cleaning Methods

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 widely accepted 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 widely accepted standards to evaluate crack cleanliness nor are there generally accepted cleaning procedures (Belangie, 1990).

In order to develop a robotic crack sealing machine for repairing cracks in road surfaces, it is necessary to determine a method of efficiently and effectively cleaning the road surface cracks prior to the application of sealant. Various possible methods for cleaning road surfaces are discussed below and the purpose of this portion of the project is to choose 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 alternative 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 brushes, brooms, 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 form 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.

1.4.1 - Compressed Air Jets

Compressed air is widely used as a primary method of cleaning cracks and pavement surfaces. Its wide acceptance seems due mainly to its ease of use and relatively low cost. While compressed air jets are useful and are capable of removing loose 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 be due mainly to the fact that there is no widely accepted standard as to the "acceptable level-of-cleanliness" of cracks and road surfaces prior to sealing.

Because of the discrepancies in the published literature concerning the effectiveness of compressed air jets, this cleaning method will be addressed in the following research work as a series of feasibility experiments. These experiments will provide the necessary information to make an educated assessment of the compressed air jet technology.

1.4.2 - Hot Air 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 difference 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 heat lance as the preferred tool for cleaning cracks prior to sealant application since they are capable of producing approximately 3,000 degrees F (1650 degrees C) air with operating velocities of approximately 3,000 fps (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", compressed air jet cleaning effectiveness decreases. Other methods were therefore examined.

1.4.3 - Low Pressure-High Volume Blowers

There has been a recent trend in the street sweeping industry. Cities across the nation are gradually shifting towards 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 an air 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 in pavement. 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" wide strip (+/- 1/2") 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 cleaning 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 traveling 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" nozzle could provide the needed air power to clean out a crack and the path cut by the router.

1.4.4 - 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 clean to bare metal prior to bridge painting (Perkins, 1990).

Abrasive vacuum blasting has been found to perform well also but is slow, and relatively expensive in terms of paint preparation (Perkins, 1990). Abrasive 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 abrasive 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 sandblast 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" 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 problem with sandblasting include: the amount of equipment necessary for the operation, 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 the 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 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.

Based on information gathered from the literature, it is concluded that abrasive blasting using a blast media of either aluminum oxide, steel shot, or cut steel wire should produce the best results. These blast media should be reusable many times (as opposed to sand which is only reusable several times) and they should provide a very clean road surface and crack that is dry and free of all loose debris, dirt film, and oil film.

In addition to the information obtained from the published literature, a feasibility experiment will be conducted as part of this research work to gain a better understanding of the sandblast and abrasive vacuum blast methods so that a more educated assessment of these methods can be formulated.

1.4.5 - 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 can 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 strip 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 toad 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.

1.4.6 - Water 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 through 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. These cleaning methods are discussed in detail by Appleman and Bruno (1985) and Davidson and Callahan (1987).

In short, various types of wet blasting systems showed much promise in surface preparation and may prove valuable to future generation crack sealing machinery. However, since it is currently desirable to apply a non-emulsion based sealant to very dry pavement and to perform the crack sealing in a single pass operation, wet blasting is unfeasible. Other drawbacks are the large support equipment needed and their associated high 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.

1.4.7 - 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 was 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).

1.5 - Purpose and Outline of Report

The purpose of this project is to investigate the development of a machine considering only the topics of road surface preparation, positioning system configuration selection, and positioning system concept design selection. More specifically, these three interrelated tasks of the machine development follow:

- Determine the best and most practical method(s) for cleaning the road surface and cracks.
- Determine the best positioning system configuration to accommodate the crack detection, cleaning, preparation, and sealing operations.
- Determine the positioning system concept design, based on the chosen positioning system configuration, that will best perform the entire operation.

This report is organized into seven chapters. In Chapter 2, a feasibility study is conducted to determine the effectiveness of using high pressure air jets to remove vegetation, loose debris, and dirt film from road surfaces and cracks.

In Chapter 3, a similar, but more qualitative feasibility study is conducted to determine the effectiveness of cleaning road surfaces and cracks using a sandblasting method and an abrasive vacuum blasting method.

Chapter 4 combines the information gathered through the literature search and the feasibility studies of Chapters 2 and 3. This chapter begins by outlining the cleaning method selection criteria. That is, the criteria by which each of the cleaning methods will be evaluated and compared to the others. The major advantages and disadvantages of each of the methods are then discussed. Finally, the best cleaning method(s) is selected based on the selection criteria. This method(s) will be incorporated into the prototype machine.

In Chapter 5, the basic positioning system configuration is discussed. This discussion focuses on two basic configurations including the "array" and the "crack following" configurations. Each of the configurations is described in detail and the advantages and disadvantages of each is noted. The configurations are compared to each other and the best positioning system configuration is chosen. This configuration will be incorporated into the prototype machine.

Chapter 6 contains a description and discussion of several concept designs (based on the crack following configuration) for the basic positioning system. The advantages, disadvantages, and significant design features of each design are noted. The designs are compared to each other and the best design is chosen to be incorporated into the prototype machine.

In Chapter 7, major conclusions and recommendations will be discussed.

1.6 - Methodology

At this point, it is useful to discuss the methods and processes on which various decisions of this project will be based. In general, the methods used throughout this project are a combination of "functional synthesis" (orderly creative inventing) and brainstorming techniques as described by Middendorf (1986) and Walton (1991). As described, functional synthesis can best be applied by individual effort. The sought-after device must be described in terms of functional requirements rather than by descriptive adjectives. By doing this, the problem can be approached from a fresh perspective without any unnecessarily imposed constraints on the final design of the device which may inhibit the creativity of the developer or designer. This method consists of six steps:

1. Define the problem.
2. Gather information.
3. Divide the system into subunits.
4. Describe each subunit with a complete list of functional requirements.
5. List all ways that the functional requirements of each subunit can be realized. Each of these is a partial solution to the problem.
6. Study all combinations of partial solutions.

Brainstorming is another method for generating creative ideas. This is an activity in which a group of people get together specifically to think of ideas. A group of people knowledgeable in various aspects of the problem can usually generate more and better ideas in a shorter period of time than can a single individual. As people hear an idea, no matter how impractical, from another person in the group, it often triggers a new idea. By continuing this process, a large number of ideas can be generated in a very short period of time. The good and more practical parts of each idea can than be considered and combined to produce a final solution to the problem. The main rule for such a brainstorming session is that no one should be permitted to be critical of another persons idea during the this period. This would tend to inhibit the free flow of ideas within the group. Brainstorming can be most useful in step five of the functional synthesis process described above. During step five, it is necessary to list all of the partial solutions to the problem at hand.

In the case of this crack sealing machine project, step one, definition of the problem was accomplished above. The project was then researched on a global level and was subsequently divided into manageable subunits. This project will deal with the subunit problems of road surface cleaning method selection, positioning system configuration selection, and positioning system concept design selection. In the case of road surface cleaning methods, more detailed information was gathered on the state of existing technology and practices. This information is provided in the literature review above and in the feasibility studies described in Chapters 2 and 3. More detailed discussions of how the functional synthesis and brainstorming methods were applied to the investigation of this project are provided in the introductions to Chapters 4 and 6.

The problem solving methods of functional synthesis and brainstorming were extremely valuable and necessary at this conceptual stage of the project development, although the information generated during these processes is not necessarily scientifically based. It may be quite easy for someone to review the text and analysis of Chapters 4, 5, and 6 and dismiss it as only tedious documentation of the project development or simple recordings of the development process that only organize the knowledge of the present so that it may be referenced in the future. This is far from the case. The proceedings of Chapters 4, 5, and 6 were used as a major tool in the development process to select the best cleaning method(s), positioning system configuration, and positioning system concept design. The process used in these chapters helped establish the functional requirements for the problem at hand, generate numerous ideas, analyze each idea thoroughly, and record the entire process on paper. This process made it possible to evaluate each of the possible solutions in a clear, concise, and very organized manner. In addition, the process helped to assure that the widest diversity of solutions was proposed, thus making it more likely that the "best" solution was found.

CHAPTER 2

ROADWAY CRACK DEBRIS REMOVAL USING A COMPRESSED AIR JET

(A FEASIBILITY STUDY)

2.1 - Introduction

The purpose of this experiment was to gain a better understanding of the effectiveness of using compressed air jets to remove loose debris (e.g. dirt, sand, and small gravel) vegetation, and dirt film from road surface cracks. More specifically, it was necessary to determine the conditions under which compressed air jets can be used to clean road surfaces. This was achieved through a series of controlled laboratory tests and field tests under more realistic conditions. Data (written data, photos, and video tape) such as air nozzle orientations, air nozzle speeds, air pressures, air flow rates, amount of debris removed from cracks, etc. was obtained to develop technical specifications for the implementation of compressed air jets nozzles on an automated crack sealing machine. This information was necessary from the perspective of the global development and design of the crack sealing machine. For instance, data concerning nozzle orientation with respect to road cracks, speed, and effectiveness at various distances and angles with respect to cracks (nozzle effectiveness zone) was needed to design the positioning system and applicator assemblies to operate within effective limits. Knowledge about the nozzle effectiveness zone was also required to establish the accuracy and precision requirements of the global vision system and local sensing system. Furthermore, knowledge of required air pressures, air flow rates, and power requirements help to determine air compressor specifications, air hose specifications, etc. All of the data was used to determine the general effectiveness and efficiency of the cleaning method so that it can be compared with other methods based on sound judgement.

2.2 - Objective

The purpose of this experiment, as described in the introduction above, was to gain a better understanding of the effectiveness of using compressed air jets to remove loose debris, vegetation, and dirt film from road surface cracks. The conditions under which compressed air jets can be used to clean road surfaces were determined. It is useful at this point to present the list of objectives which were used as an aid to obtain the required data. The objectives of this experiment follow:

1. Perform realistic field tests to determine (qualitatively) the effectiveness of using a compressed air jet for removing vegetation, loose debris, and dirt film from actual road surface cracks.
2. Perform controlled laboratory tests to obtain written data for developing technical specifications for the implementation of air nozzles on the crack sealing machine. This data includes;
    - air nozzle orientations,
    - air nozzle speeds,
    - air pressures,
    - air flow rates,
    - amount of debris removed from road surface cracks, and
    - other data.
3. Obtain detailed, slow motion video tape of the local crack area during the debris removal process to gain an understanding of the local dynamics of the debris removal process.
4. Determine the effect of an air jet on different sizes of debris material.

5. Compare the "Air Knife" nozzle with less sophisticated orifices.

As noted above, these objectives were achieved through a series of controlled laboratory tests and realistic field studies. The laboratory test setup basically consisted of a stationary, cracked pavement test specimen (filled with debris) over which an air nozzle passed at various speeds, orientations, air pressures, and air flow rates. The nozzle was attached to the tip of variable velocity testing machine "whirlybird machine". A 185 CFM (maximum), 100 PSI (maximum) compressor supplied compressed air to the nozzle. The field studies were conducted on a section of lightly used roadway outside the city of Davis, California.

2.3 - Definitions

To better understand the compressed air jet experiment presented in this chapter, the following definitions are provided to clarify specific technical terms.

crack approach angle - The acute angle measured between the line of the direction of travel of the crack and the direction of travel of the air nozzle (see Fig. 2.1). This angle can be varied from 0-90 degrees. These tests were concerned with the angles of 0 and 90 degrees.

nozzle approach angle - The acute angle, measured from a vertical axis with respect to the road surface to the angle of a line parallel to the nozzle, in the vertical plane of the nozzle direction of travel (see Fig. 2.1). This angle can be varied from -90 to +90 degrees (At these extreme angles, the nozzle would be parallel to the plane of the road surface). These tests were concerned with the angles of 0, +15 and +30 degrees (where the "+" indicates the that jet of air "leads" the nozzle as the nozzle moves in its direction of travel.

nozzle angle of incidence - The acute angle, measured from a vertical axis with respect to the road surface to a line parallel to the nozzle, in the vertical plane perpendicular to the nozzle direction of travel (see Fig. 2.1). This angle can be varied from 0 to 90 degrees (At 90 degrees, the nozzle would be parallel to the plane of the road surface). These tests were concerned with the angles of 0, 15, and 30 degrees.

nozzle eccentricity - The horizontal distance (measured perpendicular to the line of action of the crack) from the center line of the crack to the tip of the air nozzle. The crack approach angle must be zero (0) degrees for the nozzle eccentricity to have any relevance (see Fig. 2.1). These tests were concerned with the eccentricities of 0, 1/2", 1", and 1 1/2".

dirt film - The thin film of debris (usually fine dirt or oil) that coats the inside of roadway cracks and the area surrounding cracks. This dirt film usually remains in the crack after another debris removal method (such as a high pressure air jet) removes the loose debris from the crack. It is thought that a better sealant bond (to the road surface) could be achieved if this dirt film were removed from the crack and the local crack area.

VVTM - (Variable Velocity Testing Machine) ("whirlybird machine") This is an item of equipment used for producing relative motion between the air nozzle and the pavement test specimen during the controlled laboratory tests.

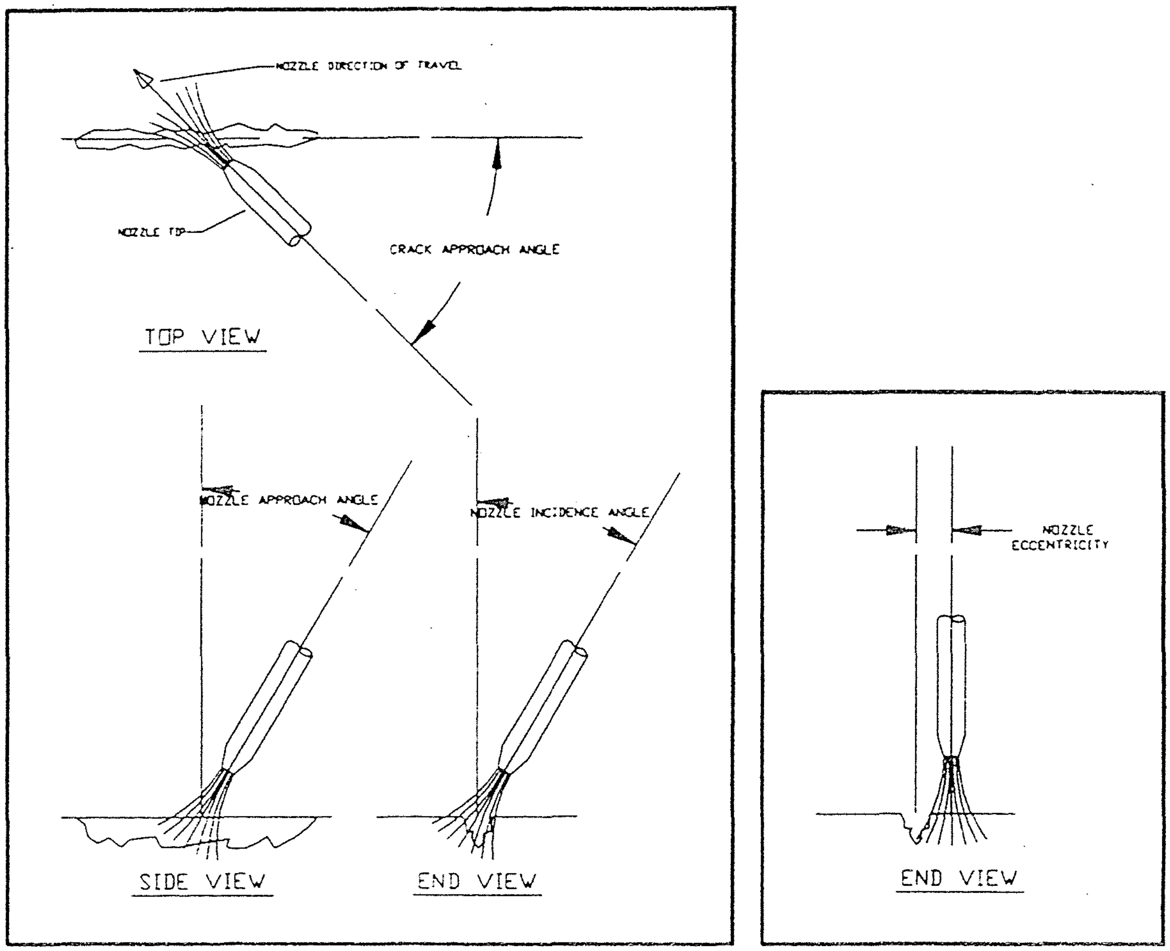


Figure 2.1 - Views of Air Nozzle Tip with Respect to Crack

2.4 - Equipment and Materials Required

The equipment and materials necessary to perform this experiment generally include the VVTM, air compressor, hoses, nozzles, air flow meters, air pressure gages, pavement test specimen, test specimen table, still camera, video camera, and other miscellaneous equipment. Please refer to Appendix A.1 for a detailed list.

2.5 - Debris Material

Three different sizes of debris material were used for this experiment. These included small, medium, and large sand particles. All three sizes of debris were mixed thoroughly, in equal volumes, to obtain the final debris mixture that was used for each of the test runs. The debris material (sand) consisted primarily of quartz and feldspar. The chemical analysis (on a dry basis) and the size description of the debris is shown in Table 2.1.

DEBRIS MATERIAL SIZE DESCRIPTION / CHEMICAL ANALYSIS	
TYPE: Lapis Lustre, Clementina Dried Sand (sandblasting sand)	
CHEMICAL ANALYSIS	
Aluminum as Al2O3	8.630%
Calcium as CaO	0.570%
Chlorine as Cl	0.018%
Fluorine as F	0.010%
Iron as Fe2So3	0.610%
Magnesium as MgO	0.180%
Potassium as K2O	3.170%
Combined Silica as SiO2	85.750%
Sodium as Na2O	1.630%
Sulfur as SO3	0.080%
Titanium as TiO2	0.010%
Chloride	0.027%
Asbestos	none
Loss on Ignition	0.440%
OTHER DATA	
Specific Gravity	2.610%
Absorption	0.500%
MOH Hardness	6
SAND SIZE DESCRIPTION	
Small	#60, 40 x 70
Medium	#1C, 16 x 40
Large	#3, 8 x 20

Table 2.1 - Debris Material (Size Description and Chemical Analysis)

2.6 - "Air Knife" Description

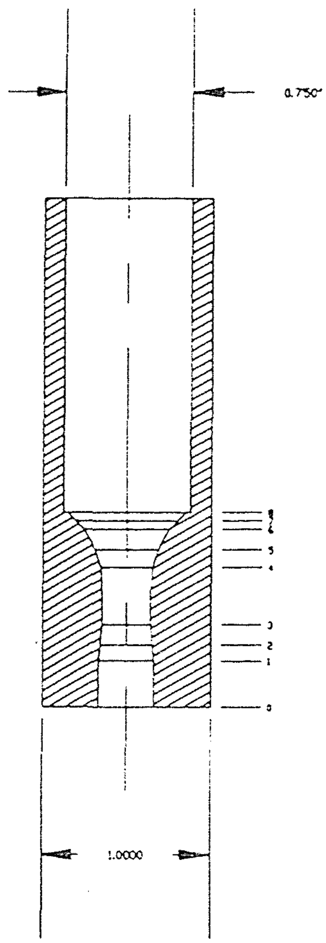
The model X-1, "SupAir Knife" air nozzle used in this experiment is a product of the ACB Technology Corporation. Air flow requirements for this nozzle are 125 CFM at 100 PSI. An illustration of the nozzle tip profile as some of its pertinent dimensions is shown in Fig. 2.2. Additional literature about the "SupAir Knife" and a video tape of its operation is available from the local distributor.

The "Air Knife" used in this experiment was borrowed from the following company (local distributor).

Air Knife of California
6930 26th Street
Rio Linda, CA 95673
(916) 991- 0732
FAX (916) 991 - 0458
Point of Contact - Mr. Tony Fletcher - Sales

An additional contact follows.

Air Knife of California
5525 Oakdale Ave., Suite 150
Woodland Hills, CA 91364
(818) 702 - 9766
FAX (818) 702 - 8752
Point of Contact - Mr. Stephen C. Dorfman - Manager



POSITION	'Y' DISTANCE FROM REFERENCE (INCHES)	NOZZLE INSIDE DIAMETER (INCHES)
0	0	0.330
1	0.275	0.330
2	0.370	0.310
3	0.490	0.290
4	0.825	0.312
5	0.930	0.375
6	1.050	0.507
7	1.100	0.600
8	1.150	0.705

Figure 2.2 - "Air Knife" Nozzle Tip Profile

2.7 - Crack Filling Procedure

The procedure used to fill the crack in the pavement test specimen (with debris) follows:

1. Mix equal volume amounts of small, medium, and large debris (dry) in a container.
2. Fill pavement test specimen crack with debris until debris is flush with the specimen surface.
3. Remove excess debris from the test specimen and the surrounding area with the whisk broom and/or low pressure sir nozzle.

2.8 - Procedure / Observations / Conclusions

2.8.1 - Experiment Setup

Fig. 2.3 is an illustration of the experiment setup. Photos 2.1 - 2.4 depict the actual test setup. Any test setup that makes it possible to produce a relative velocity of the air nozzle laterally with respect to a road surface specimen while varying the nozzle orientation angles would be acceptable. This particular test setup was used because it served the purpose adequately and the VVTM was already available and operational at a Caltrans facility. A detailed procedure for setting up the basic experiment follows can be found in Appendix A.2.

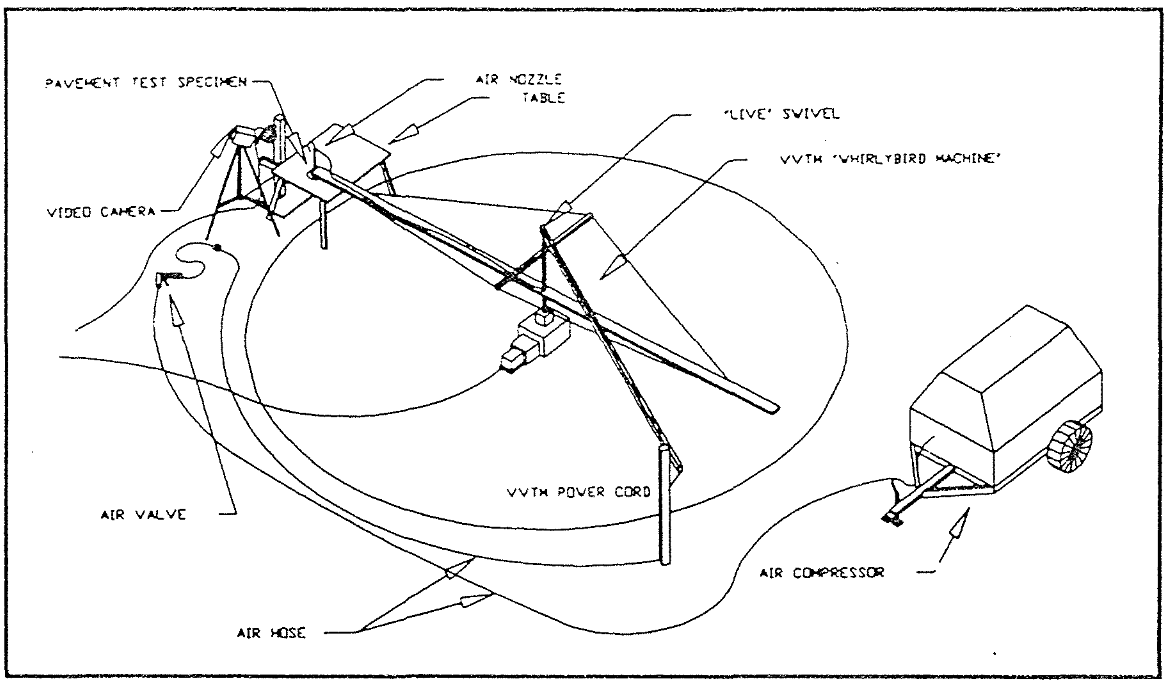


Figure 2.3 - Air Jet Experiment Test Setup Schematic

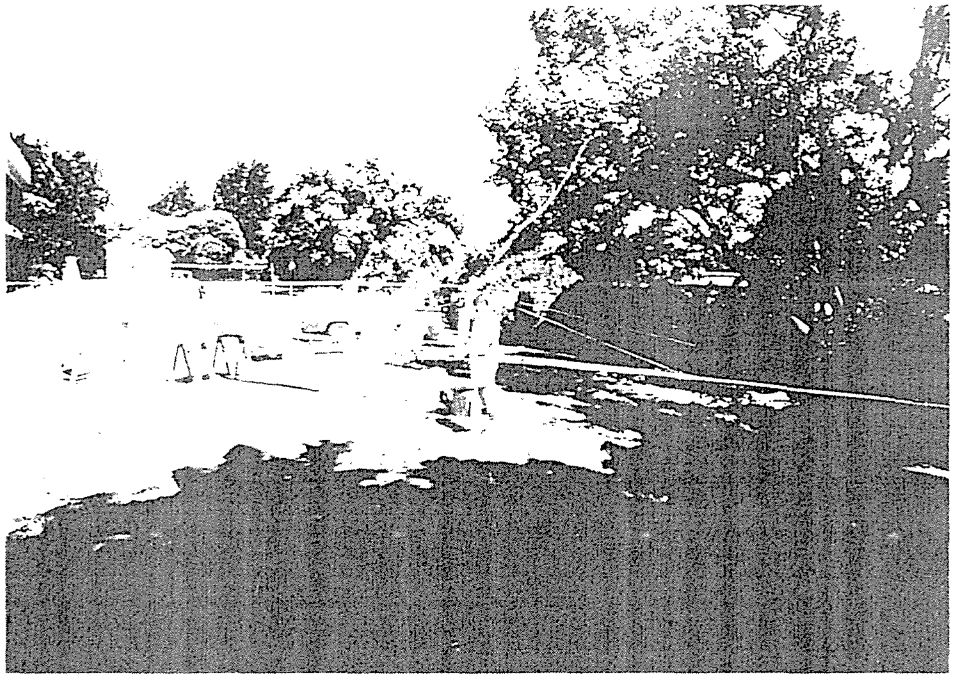


Photo 2.1 - Air Jet Experiment Test Setup

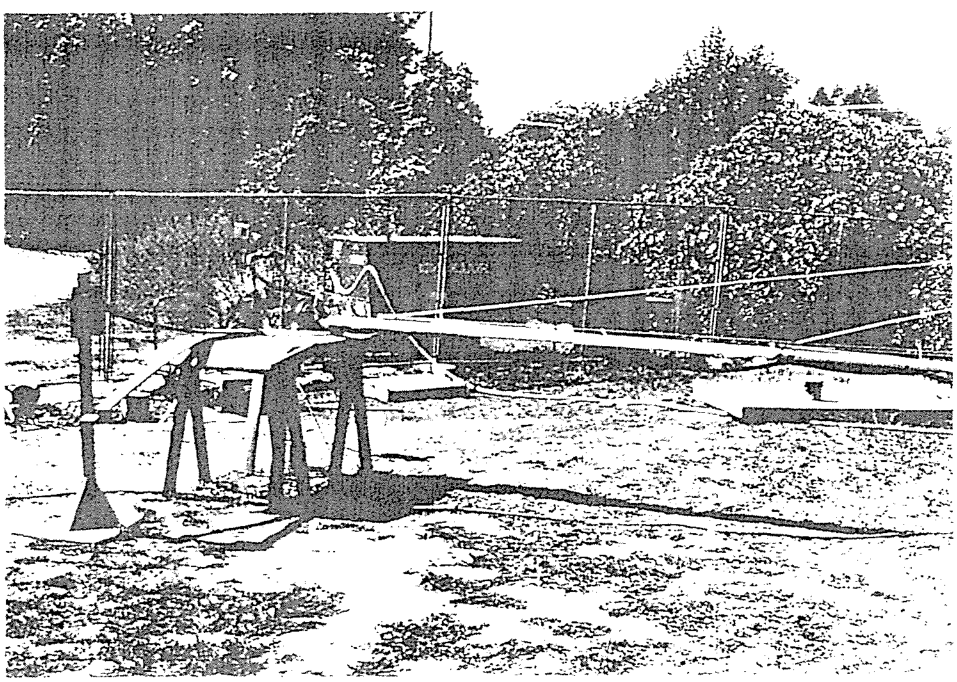


Photo 2.2 - Air Jet Experiment Test Setup

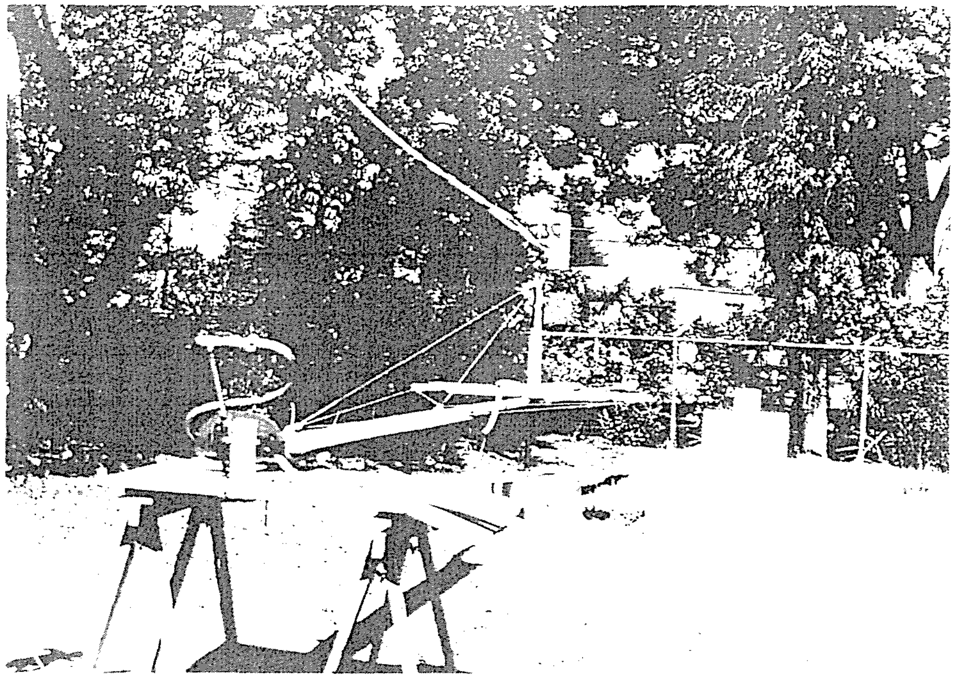


Photo 2.3 - Air Jet Experiment Test Setup

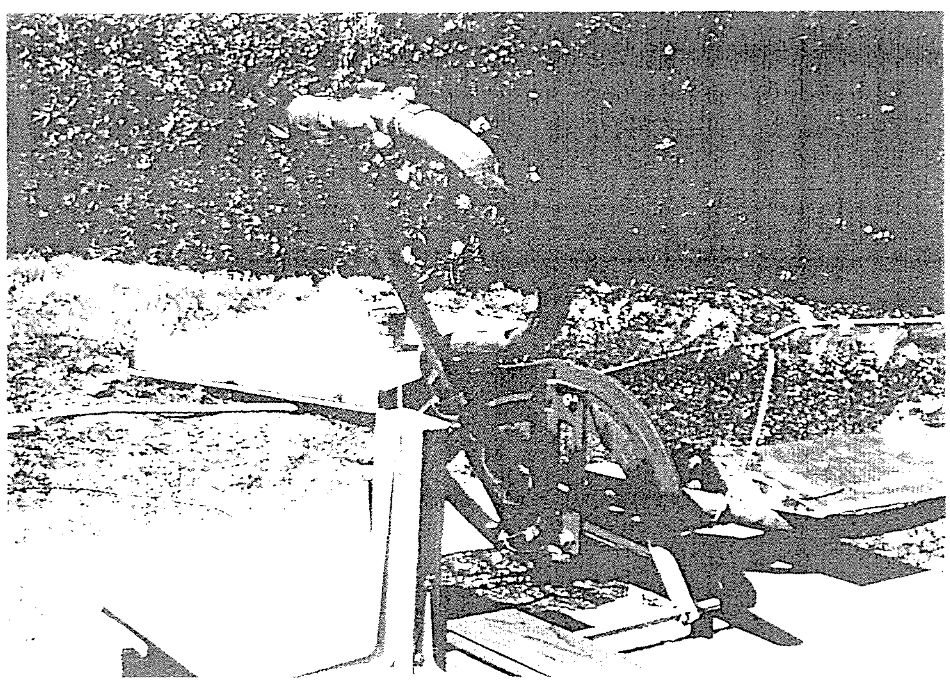
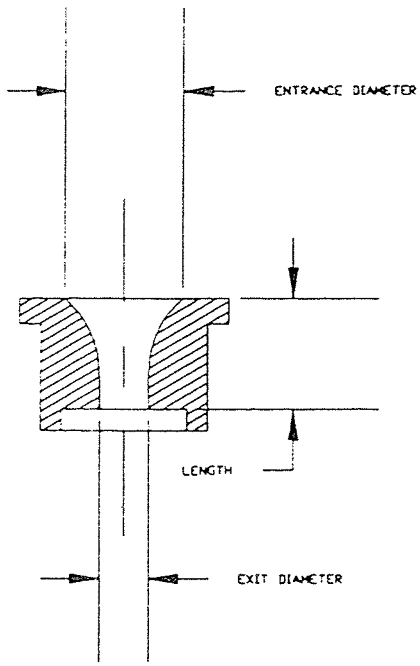


Photo 2.4 - Air Jet Experiment Test Setup

2.8.2 - Part One - Air Flow Rate Calibration Test

The purpose of this test was to obtain sufficient data to produce performance curves of nozzle air pressure vs. air hose length and air flow rate vs. air hose length for the air compressor and hose used in these experiments. The flow meter and test nozzles used for this test were obtained from the "SupAir Knife" distributor as they were specially designed for use with the "SupAir Knife". Four nozzle sizes (N1, N2, N3, and N4) were used for the test. An Illustration of the nozzle shapes and overall dimensions are shown in Fig. 2.4. Five air hose lengths (hose length = 0, 50', 100', 150', and 200') were used for the test. For hose length = 0, the flow meter was attached directly to the output valve on the air compressor. The compressor was then loaded to full capacity and air pressure and air flow rate were recorded. A similar procedure was followed for all combinations of nozzles and hose lengths. A summary of the test data is shown in Appendix A.3, Table A.1. A plot of air pressure vs. hose length, for each of the nozzles, is shown in Fig. 2.5. A plot of air flow rate vs. hose length, for each of the nozzles, is shown in Fig. 2.6.



NOZZLE DESCRIPTION	ENTRANCE DIAMETER (INCHES)	EXIT DIAMETER (INCHES)	LENGTH (INCHES)
N1	0.789	0.1885	1.0
N2	0.789	0.2665	1.0
N3	0.789	0.3305	1.0
N4	0.789	0.3815	1.0

Figure 2.4 - "Air Knife" Air Flow Meter Calibration Nozzles

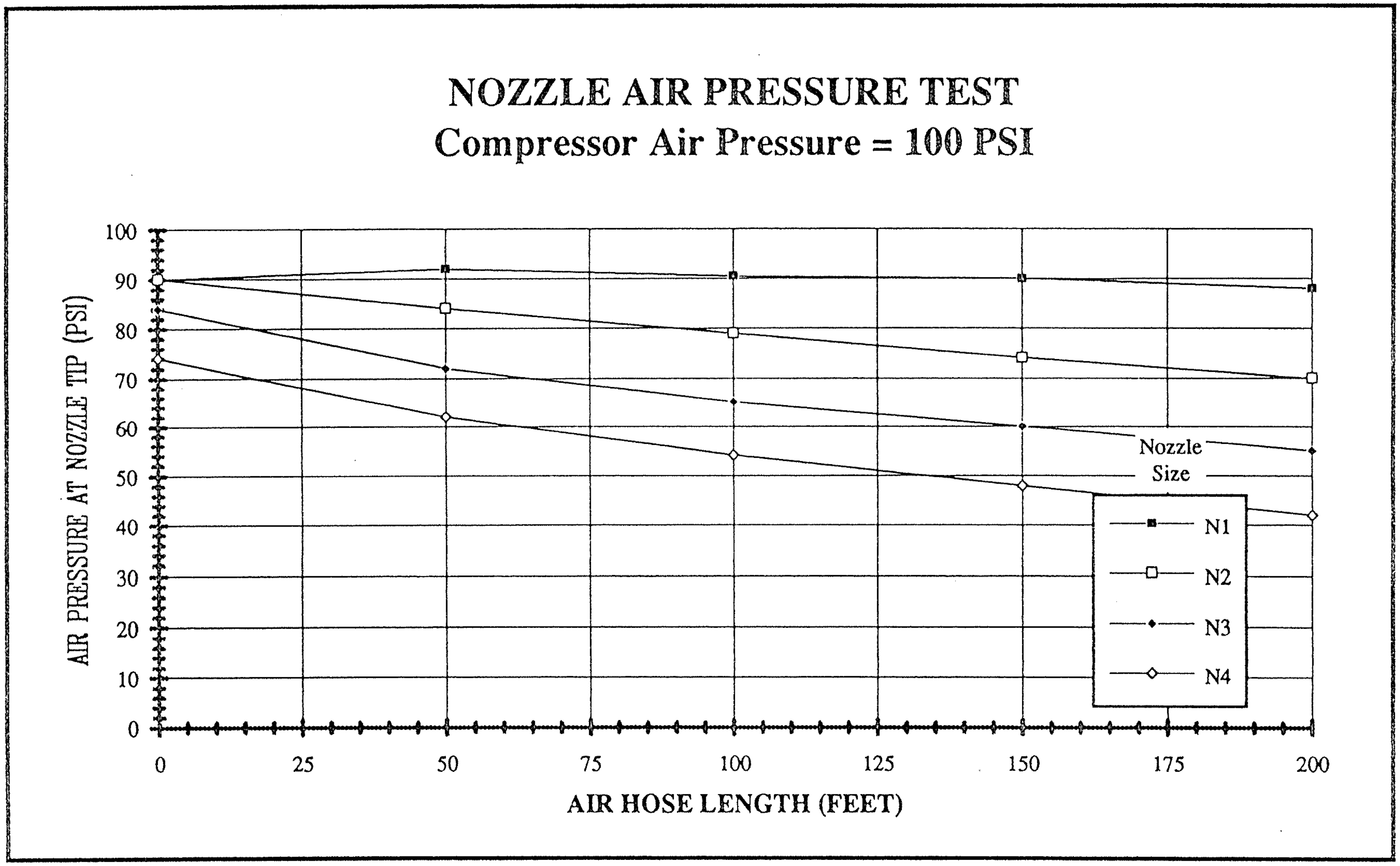


Figure 2.5 - Nozzle Air Pressure Test - Nozzle Air Pressure vs. Air Hose Length

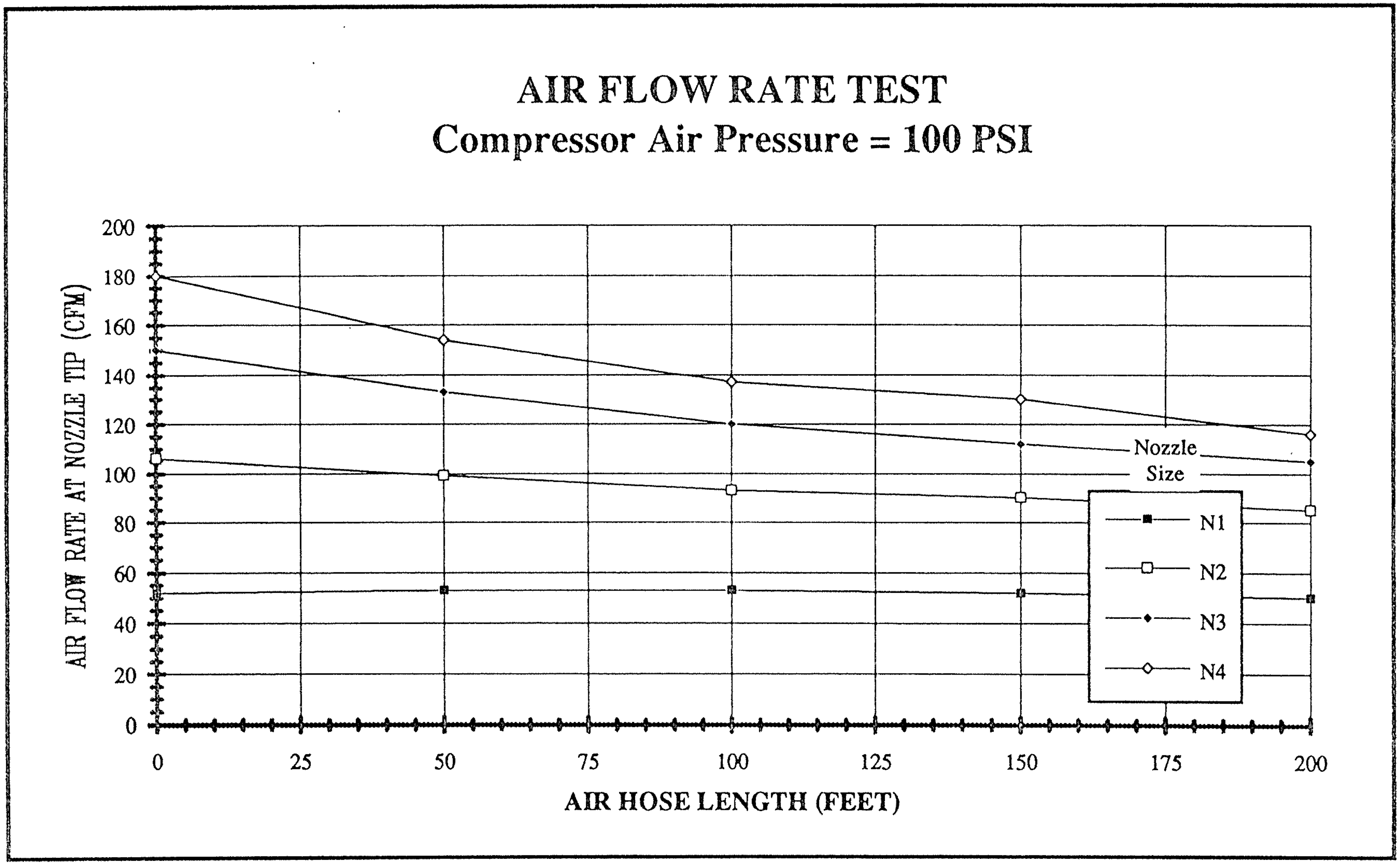


Figure 2.6 - Nozzle Air Flow Rate Test - Nozzle Air Flow Rate vs. Air Hose Length

2.8.3 - Part Two - Nozzle Eccentricity Test

Basic Test Description

This test simulated the use of an air jet for cleaning cracks in which the nozzle direction of travel was the same as the crack direction of travel (i.e. crack approach angle = 0 degrees). Data was obtained for many combinations of nozzle approach angles, angles of incidence, eccentricities, speeds, and air pressures. This data is especially applicable to the development of a machine for sealing "longitudinal" road surface cracks. Refer to Photos 2.5 - 2.10 for typical results of this test. A detailed general procedure for this test is provided in Appendix A.4. An illustration of the air nozzle orientation parameters for the nozzle eccentricity test was previously presented in Fig. 2.1.

It should be noted that debris material for all tests consisted of thoroughly mixed, equal volume amounts of small, medium, and large debris. During preliminary tests, it was observed that the amount of each size of debris material removed by the air jet was not significantly dependant on the size of the debris material (for the particular sizes of small, medium, and large debris selected for this experiment). Therefore, in all subsequent tests, no attempt was made to separate the debris into its respective sizes (following a particular test) for the purpose of recording the respective amounts of small, medium, and large debris removed by the air jet during that test.

It should also be noted that several preliminary tests were conducted to determine the effect of debris moisture content on the ability to remove debris from cracks (No data is available for these tests.). During these tests, it was observed that there were not measurable differences in the ability of the air jet to remove debris from the test crack. This observation could in part be due to the fact that only "sand" debris was used for this experiment. Because of this, the debris did not "cake together" as it probably would have if a dirt and sand debris mixture was used. In the interest of time, a debris mixture of dirt and sand was not investigated.

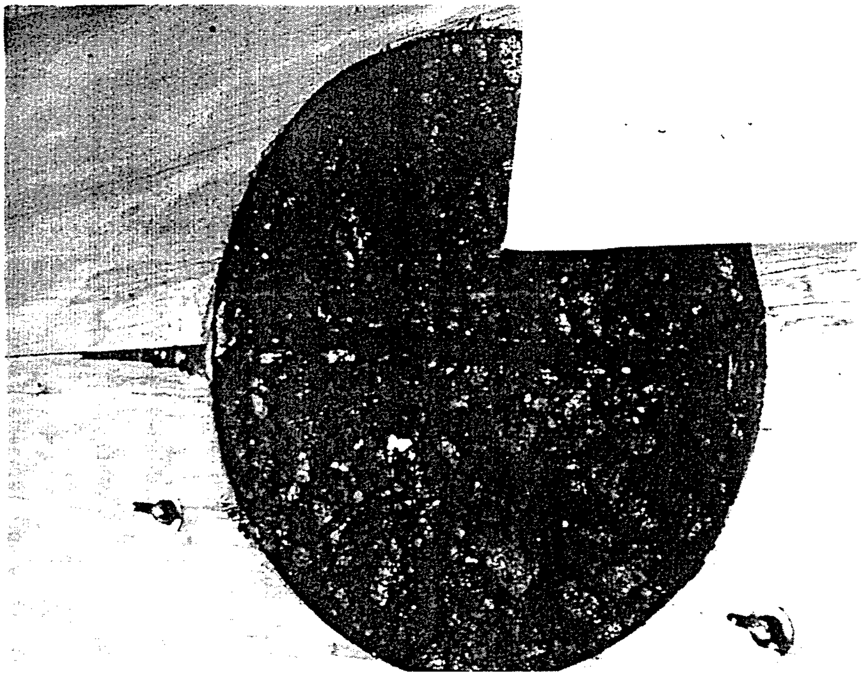


Photo 2.5 - 1/2" Nozzle Eccentricity, 5 MPH Nozzle Speed

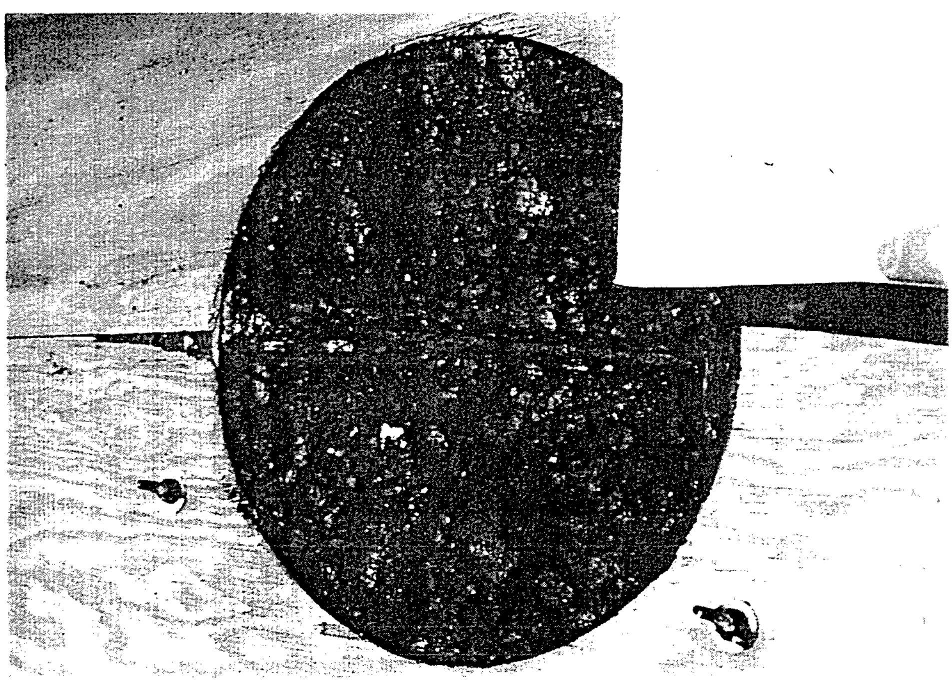


Photo 2.6 - 1/2" Nozzle Eccentricity, 10 MPH Nozzle Speed

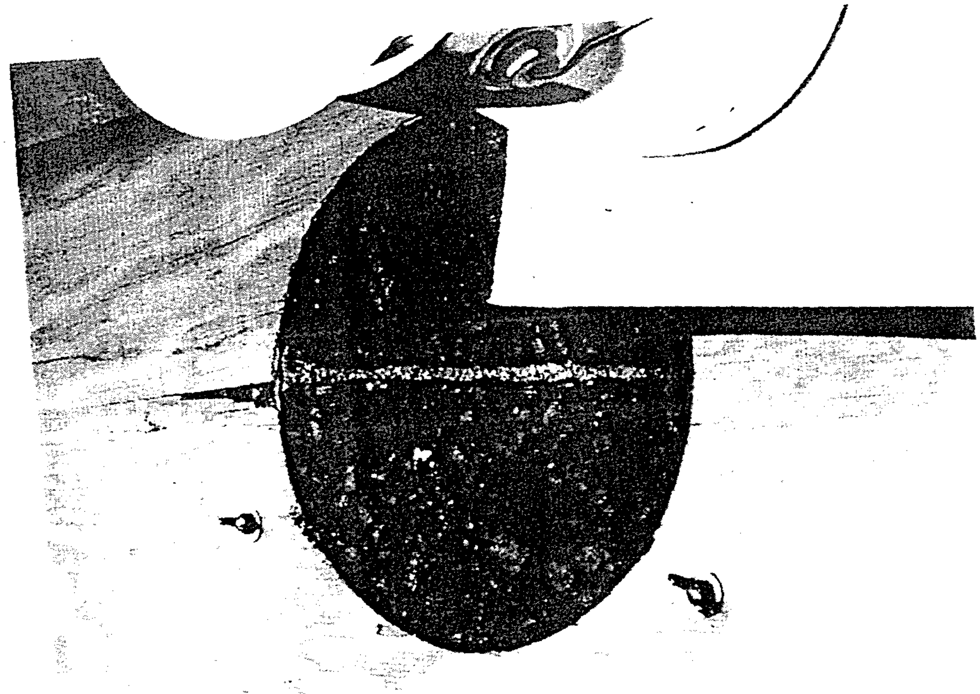


Photo 2.7 - 1" Nozzle Eccentricity, 5 MPH Nozzle Speed

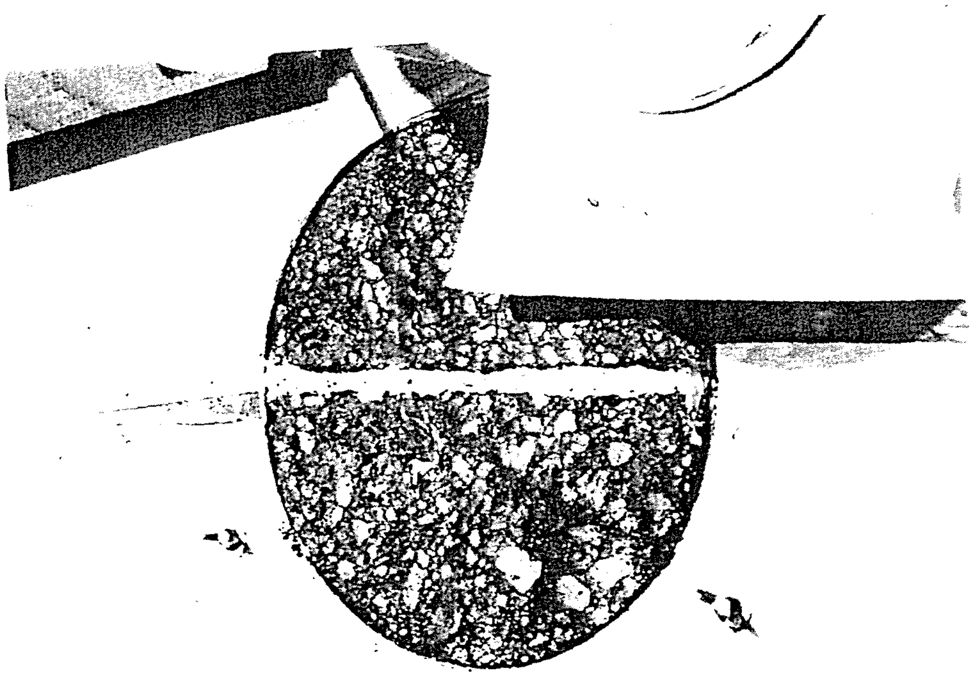


Photo 2.8 - 1" Nozzle Eccentricity, 10 MPH Nozzle Speed

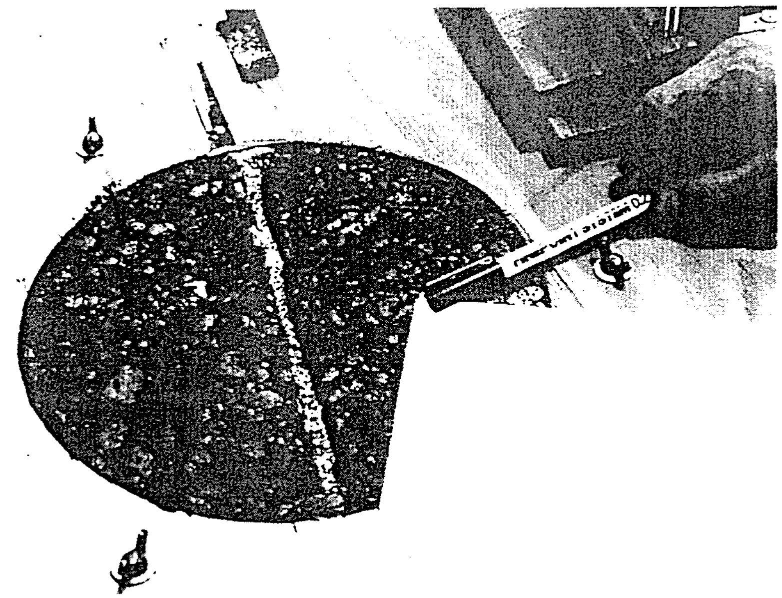


Photo 2.9 - 1 1/2" Nozzle Eccentricity, 5 MPH Nozzle Speed

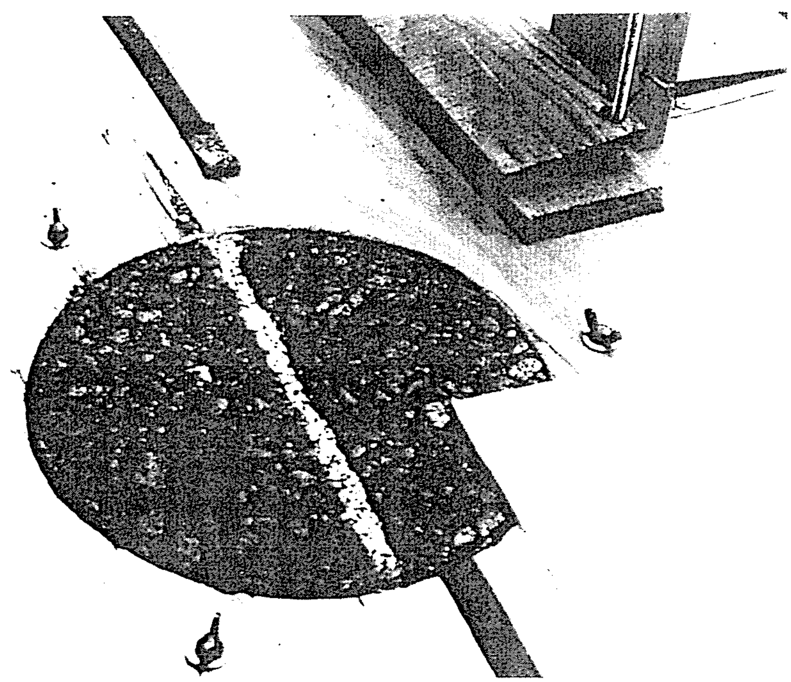


Photo 2.10 - 1 1/2" Nozzle Eccentricity, 10 MPH Nozzle Speed

2.8.3.1 - Part Two (A) - Nozzle Approach Angle Variations

In an effort to reduce that amount of data to be taken, a small test was conducted to determine whether variations in nozzle approach angle had a significant effect on the amount of debris removed from the crack. Nozzle settings for this test were as follows.

- crack approach angle = 0 degrees
- nozzle angle of incidence = 0 degrees
- nozzle eccentricity = 0 inches
- nozzle speed = 25 mph

Data was then obtained for all combinations of nozzle approach angles (0, 15, and 30 degrees) and nozzle air pressures (45, 65, and 80 psi). For a summary of the data obtained, refer to Appendix A.4, Table A.2. For a plot of depth of debris removed from the crack vs. nozzle approach angle, for each nozzle pressure, refer to Fig. 2.7.

Observations and Conclusions

Observing the plot of Fig. 2.7, it was concluded that nozzle approach angle has a relatively insignificant effect on the amount of debris removed from a crack (for nozzle approach angle variations from 0 - 30 degrees). Therefore, subsequent nozzle eccentricity tests were conducted with the nozzle approach angle set to 0 degrees.

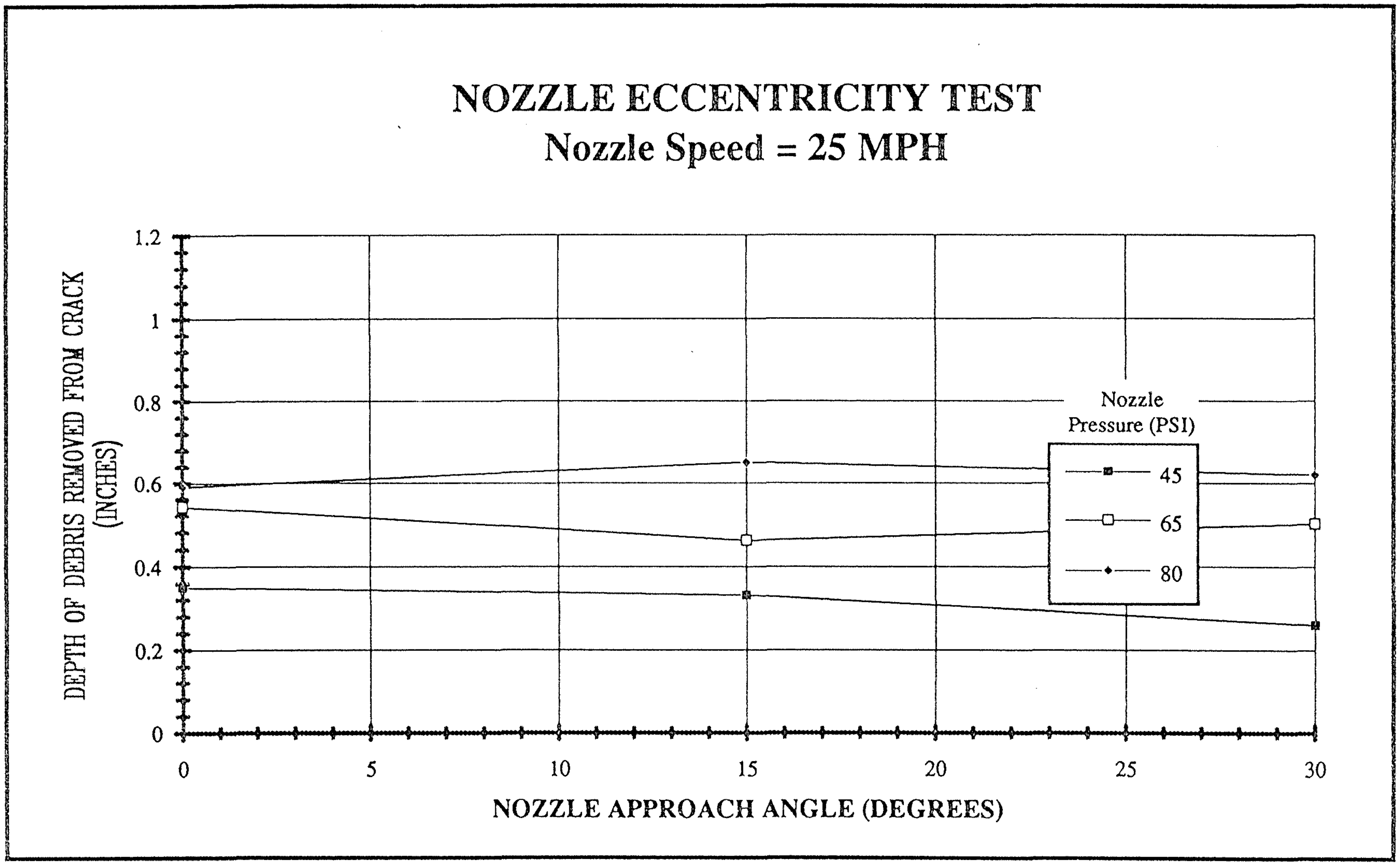


Figure 2.7 - Nozzle Eccentricity Test - Depth of Debris Removed From Crack vs. Nozzle Approach Angle

2.8.3.2 - Part Two (B) - Subsequent Nozzle Eccentricity Tests

Nozzle settings for this test were as follows.

- crack approach angle = 0 degrees
- nozzle approach angle = 0 degrees
- nozzle angle of incidence = 0 degrees
- nozzle pressure = 80 psi

Data was obtained for all combinations of nozzle eccentricities (0, 1/2", 1", and 1 1/2") and nozzle speeds (2, 5, 10, 15, 20, and 25 mph). For a summary of the data obtained, refer to Appendix A.4, Table A.3. For a plot of depth of debris removed from the crack vs. nozzle speed, for each nozzle eccentricity, refer to Fig. 2.8. Photos 2.5 - 2.10 show the results of tests at nozzle eccentricity variations of 1/2", 1", and 1 1/2" and at speeds of 5 and 10 mph.

Observations and Conclusions:

It was concluded from this test that nozzle eccentricities greater than approximately 1/2" clean the crack relatively poorly as compared with eccentricities less than approximately 1/2". It may also be noted that the size of crack used for this experiment may have had some effect on these test results. Cracks of smaller width *may* require a smaller (maximum) nozzle eccentricity to clean the crack effectively and larger cracks *may* be effectively cleaned when the (maximum) nozzle eccentricity is greater that 1/2". In the interest of time, the effects of nozzle eccentricity on smaller and larger cracks was not explored further.

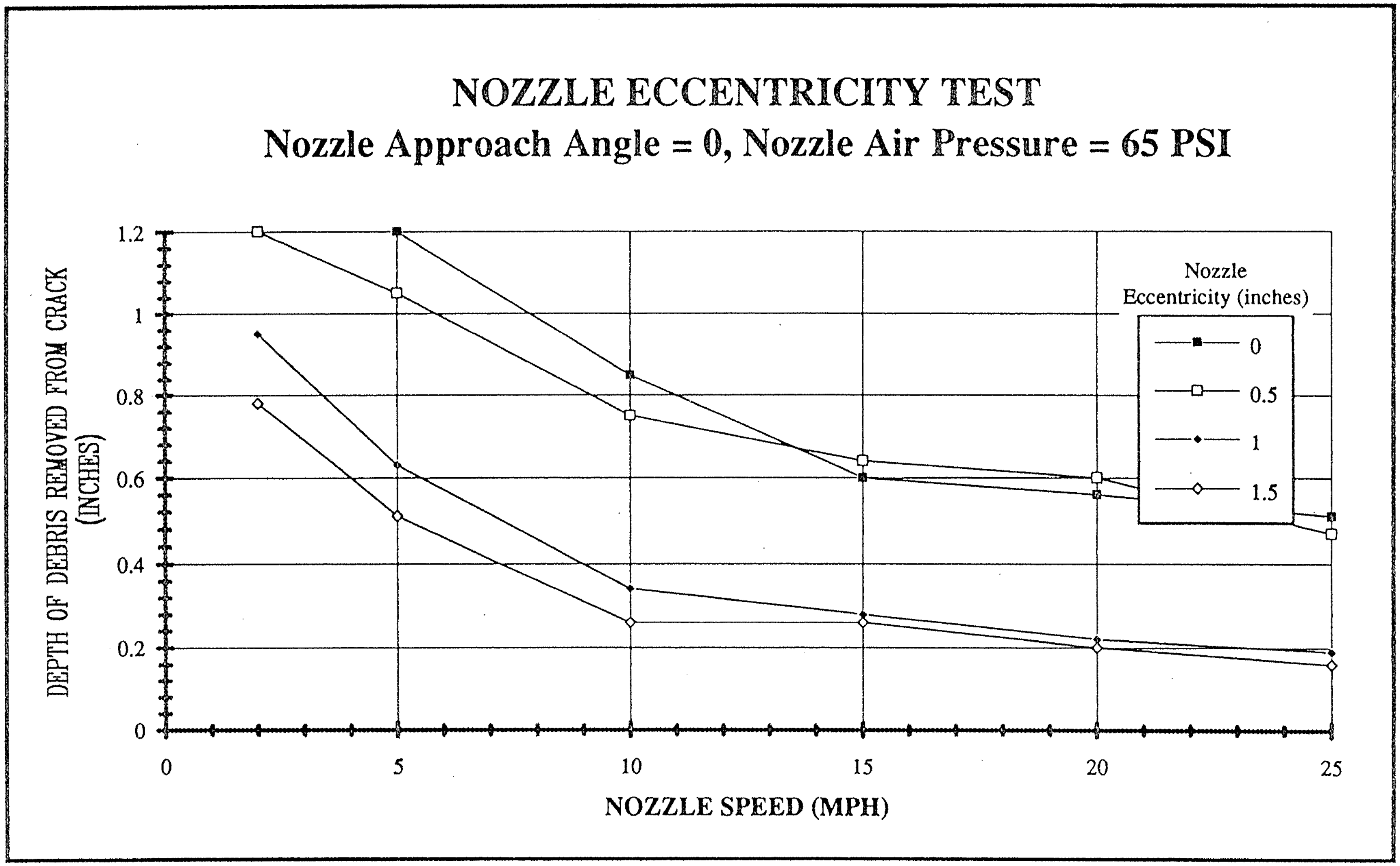


Figure 2.8 - Nozzle Eccentricity Test - Depth of Debris Removed From Crack vs. Nozzle Speed

2.8.3.3 - Part Two (C) - Effects of Small Amounts of Gravel in the Crack

Limited tests (four tests total) were conducted to obtain a rough idea of the effects of the presence of small amounts of gravel (1/4"-3/8" screen grid) in the crack on the removal of the debris from the crack. Nozzle settings for this test were as follows.

- crack approach angle = 0 degrees
- nozzle approach angle = 0 degrees
- nozzle eccentricity = 0 inches
- nozzle angle of incidence = 0 degrees
- nozzle pressure = 80 psi

Data was obtained for nozzle speeds of 2, 5, 10, and 15 mph. However, the data was not sufficient to make a meaningful plot of the depth of debris removed form the crack vs. the nozzle speed.

Observations and Conclusions

It can be observed from the photos and video tape for this test that the presence of small gravel in the crack sometimes hindered the removal of the other (sand) debris. This effect is mainly the result of the gravel becoming lodged in the crack and thus disrupted the air flow in the crack which made it more difficult to remove the smaller debris. These four tests were the only ones of the entire experiment which included small gravel in the debris material.

2.8.3.4 - Part Two - Summary of Observations and Conclusions

A brief summary of the observations and conclusions for part two follows.

- The amount of debris material removed by the air jets is not significantly dependent on the size of the debris material (for the three sizes of debris (sand) used in this experiment).

- Nozzle approach angle has a relatively insignificant effect on the amount of debris material removed from the crack (for angles of 0-30 degrees).
- Nozzle eccentricities greater than approximately 1/2" clean the crack relatively poorly as compared with eccentricities less than approximately 1/2".
- A large amount a detailed data was obtained which will significantly aid in understanding and optimizing the following parameters:
  - nozzle air pressures,
  - nozzle air flow rates,
  - nozzle orientations,
  - nozzle speeds,
  - air compressor requirements, and
  - air pressure loss in 3/4" supply hoses.

2.8.4 - Part Three - General Crack Test

Basic Test Description and Purpose

With the crack approach angle set at 90 degrees, many tests were run for various combinations of nozzle approach angles, incidence angles, speeds, and air pressures. The purpose of this test was to evaluate the feasibility of an "array" type crack sealing machine. More generally, the purpose of this test was to evaluate the performance of an air jet in cases where the jet must cross the crack at a 90 degree angle (i.e. crack approach angle = 90 degrees). Refer to Fig. 2.1 for an illustration of the air nozzle orientation parameters for the general crack test. Refer to Photo 2.11 for a typical result of this test. A detailed general procedure for this test is provided in Appendix A.5.

2.8.4.1 - Part Three (A) - Variations in Nozzle Air Pressure, Angle of Incidence, and Speed

Nozzle settings for this test were as follows.

- crack approach angle = 90 degrees
- nozzle approach angle = 0 degrees
- nozzle eccentricity - not applicable

Data was obtained for all combinations of nozzle angles of incidence (0, 15, and 30 degrees), nozzle air pressures (45, 65, and 80 psi), and nozzle speeds (2, 5, and 10 mph). For a summary of the data obtained, refer to Appendix A.5, Table A.4. A sample of the plots constructed from this data is shown below in Fig. 2.9. The complete set of plots of debris removal for the various nozzle settings is shown in Appendix A, Figures A.1 - A.6.

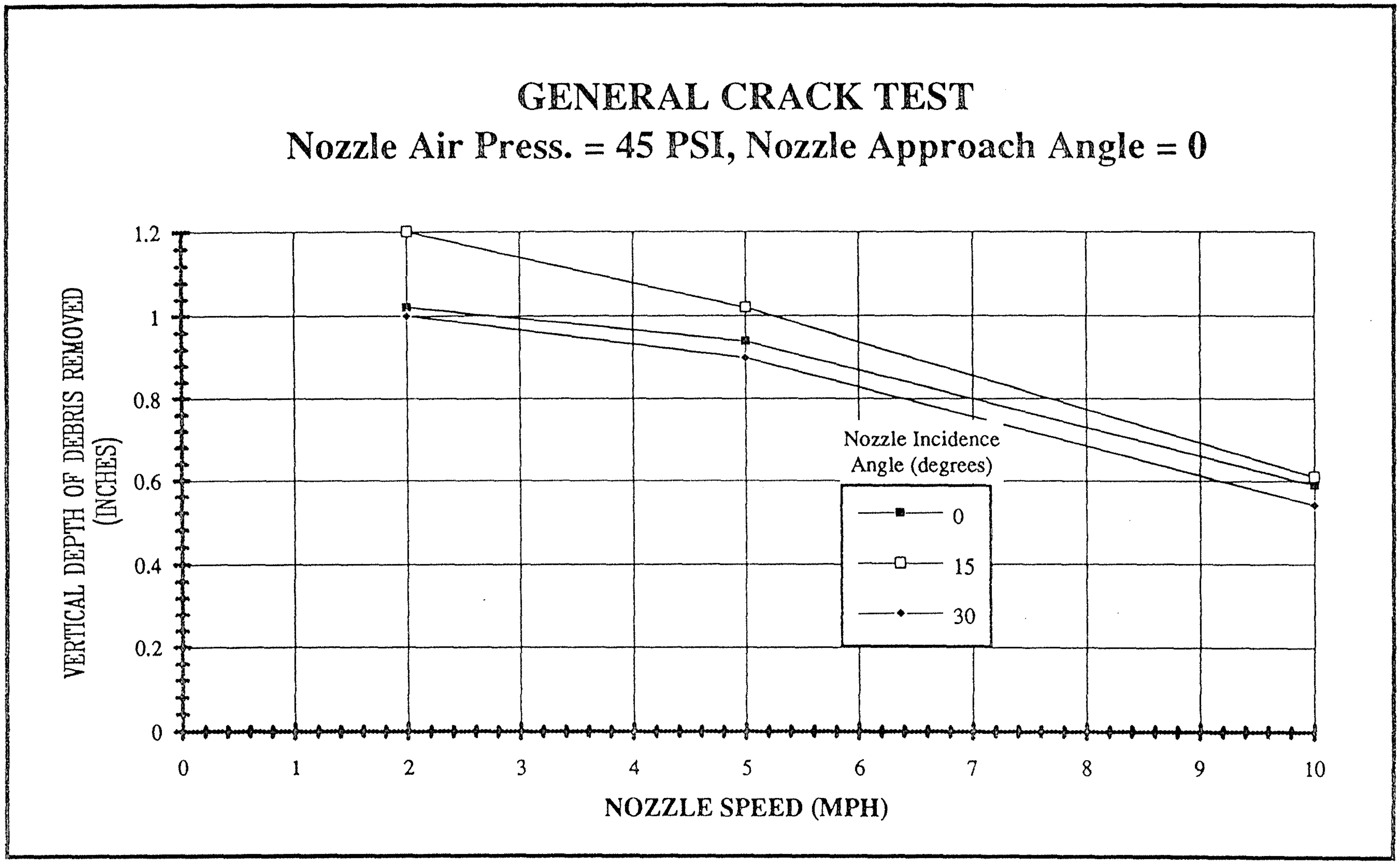


Figure 2.9 - General Test - Depth of Debris Removed From Crack vs. Nozzle Speed

2.8.4.2 - Part Three (B) - Variations in Nozzle Approach Angle, Angle of Incidence, and Speed

Nozzle settings for this test were as follows.

- crack approach angle = 90 degrees
- nozzle air pressure = 65 psi
- nozzle eccentricity - not applicable

Data was obtained for all combinations of nozzle approach angles (0, 15, and 30 degrees), nozzle angles of incidence (0, 15, and 30 degrees), and nozzle speeds (2, 5, and 10 mph). For a summary of the data obtained, refer to Appendix A.5, Table A.5. A sample of the plots constructed from this data is shown below in Fig. 2.10. The complete set of plots of debris removal for the various nozzle settings is shown in Figures A.7 - A.12.

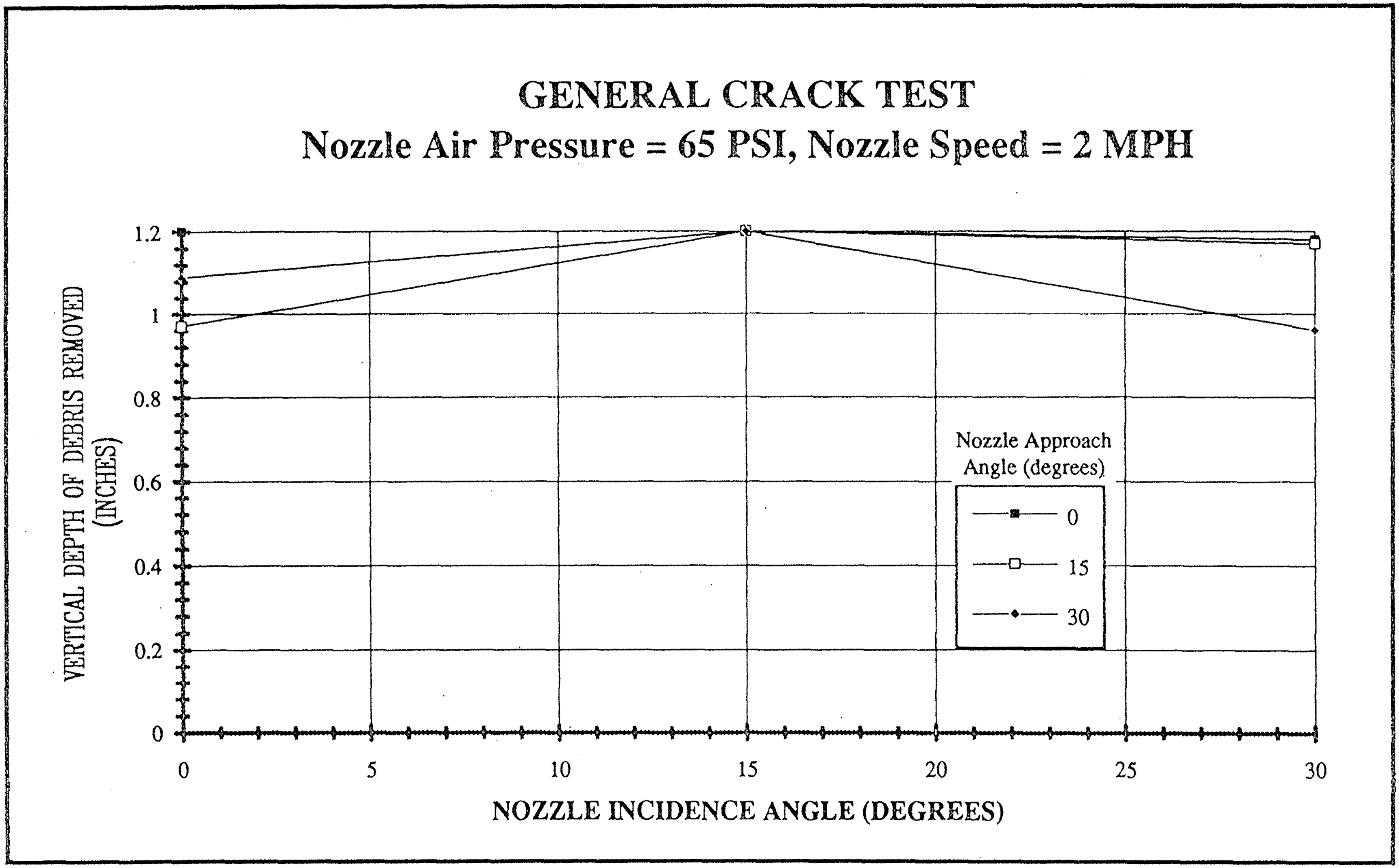


Figure 2.10 - General Test - Depth of Debris Removed From Crack vs. Nozzle Incidence Angle

2.8.4.3 - Part Three - Observations and Conclusions

A list of observations and conclusions obtained from these tests follows.

- The amount of debris removed from a transverse crack is reduced very significantly as the nozzle speed is increased.
- A nozzle incidence angle of approximately 15 degrees may optimize the depth of debris removal.
- Air flow characteristics in the local crack area are quite complex, thus making it more difficult to predict/control the exit path of the debris from the crack.
- For optimum air jet performance, it is preferable for the nozzle direction of travel to be aligned with the crack direction of travel (i.e. crack approach angle = 0 degrees).

2.8.5 - Part Four - Field Tests

Basic Test Description and Purpose

In this test, the "Air Knife" and other less sophisticated orifices were tested under actual, relatively worst case, field conditions. The purpose of this test was to;

- evaluate the performance of the "Air Knife" nozzle under actual field conditions,
- compare the "Air Knife" nozzle with other, less sophisticated orifices,
- evaluate the feasibility of using high pressure air to remove "dirt film" from the sides of cracks, and
- evaluate the performance of an air jet for cleaning cracks with weeds growing in them.

2.8.5.1 - Test Results

Photos 2.12 and 2.13 show the other less sophisticated orifices and wand and the "air knife" wand and compressor. Photos 2.14 - 2.16 show "before and after" shots of actual cracks that were cleaned using the "Air Knife" and the other orifices. Photos 2.17 - 2.19 show "before and after" shots of the "Air Knife" being used to remove weeds and debris from road cracks. As can be seen from the photos, the air jet satisfactorily removed loose debris from the cracks. However, the air jet had very little effect on the removal of the thin "dirt film" on the sides of cracks or the removal of live weeds from the cracks.

2.8.5.2 - Part Four - Observations and Conclusions

The following is a list of the observations and conclusions which were drawn from the tests that were conducted.

- The "Air Knife" performed quite satisfactorily for removing all sizes of loose debris from cracks.
- It was difficult to observe a difference between the cleaning performance of the "Air Knife" and the other, less sophisticated orifices (assuming air pressures and flow rates were approximately equal).
- It was not possible to remove a significant amount of "dirt film" from the sides of the cracks with a high pressure / flow rate air jet.
- The air jet was unsuccessful in removing weeds from cracks unless the plant roots were dead.

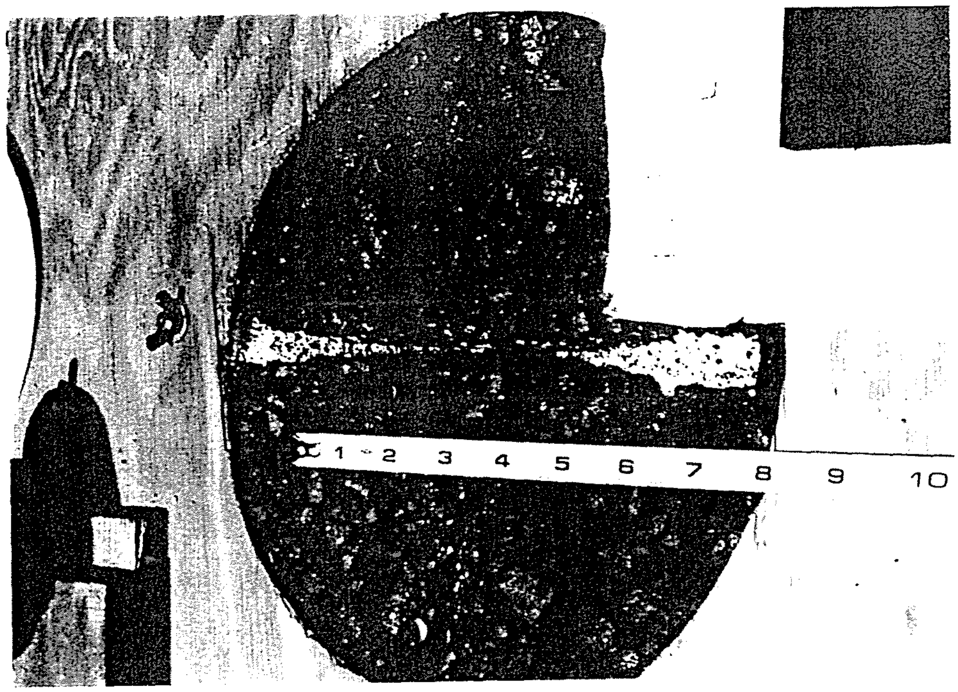


Photo 2.11 - Typical Result of General Crack Test

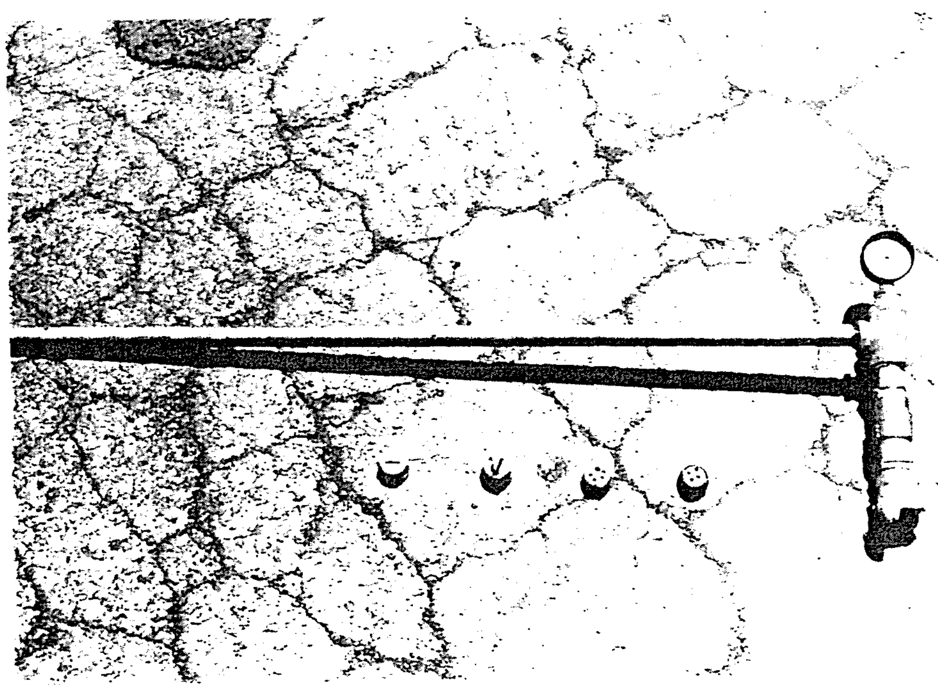


Photo 2.12 - Less Sophisticated Orifices and Wand

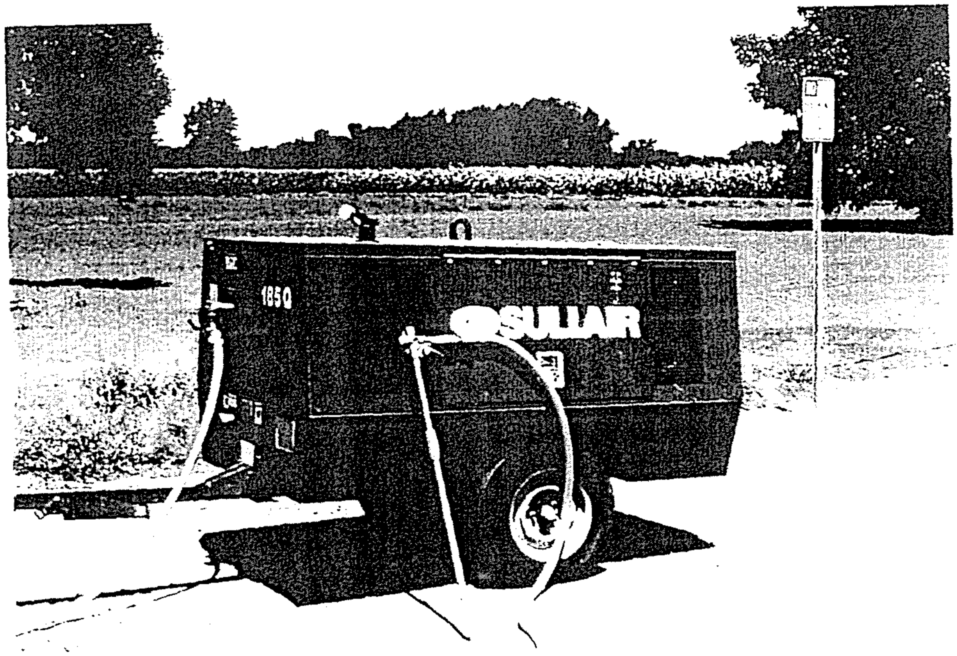


Photo 2.13 - "Air Knife" Wand and Air Compressor

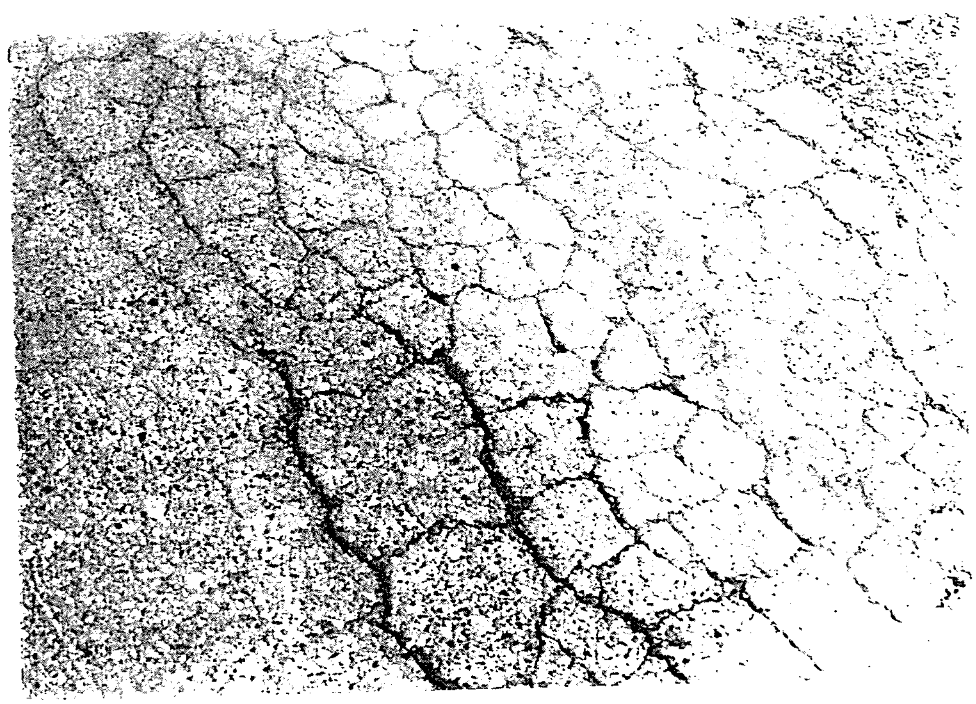


Photo 2.14 - "Before and After" - Cracks Cleaned with Compressed Air

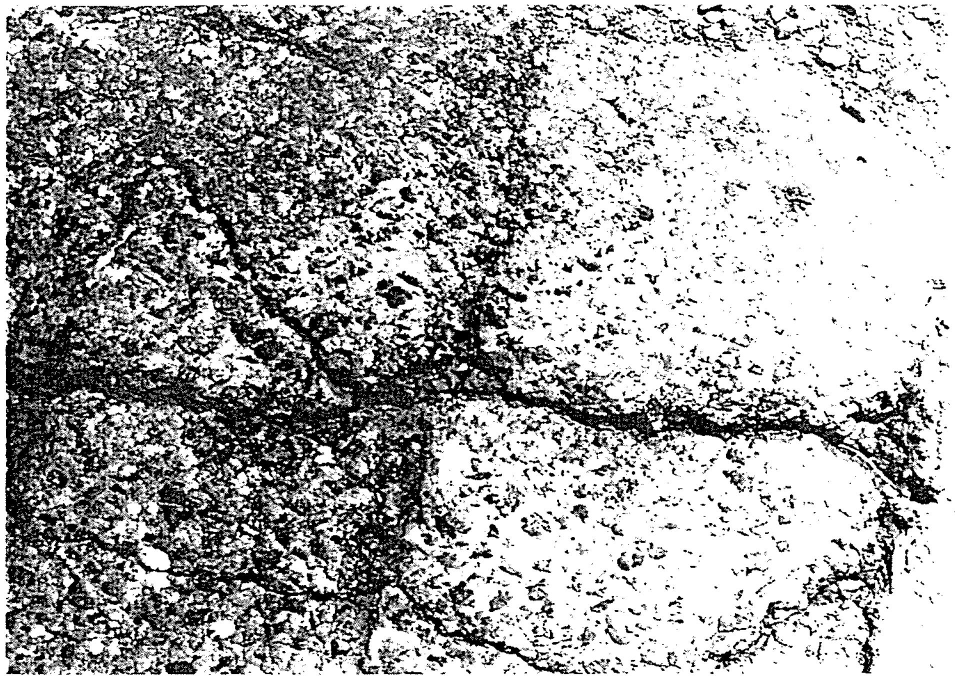


Photo 2.15 - "Before and After" - Cracks Cleaned with Compressed Air

Photo 2.16 - "Before and After" - Cracks Cleaned with Compressed Air

Photo 2.17 - "Before and After" - Removing Vegetation with Compressed Air

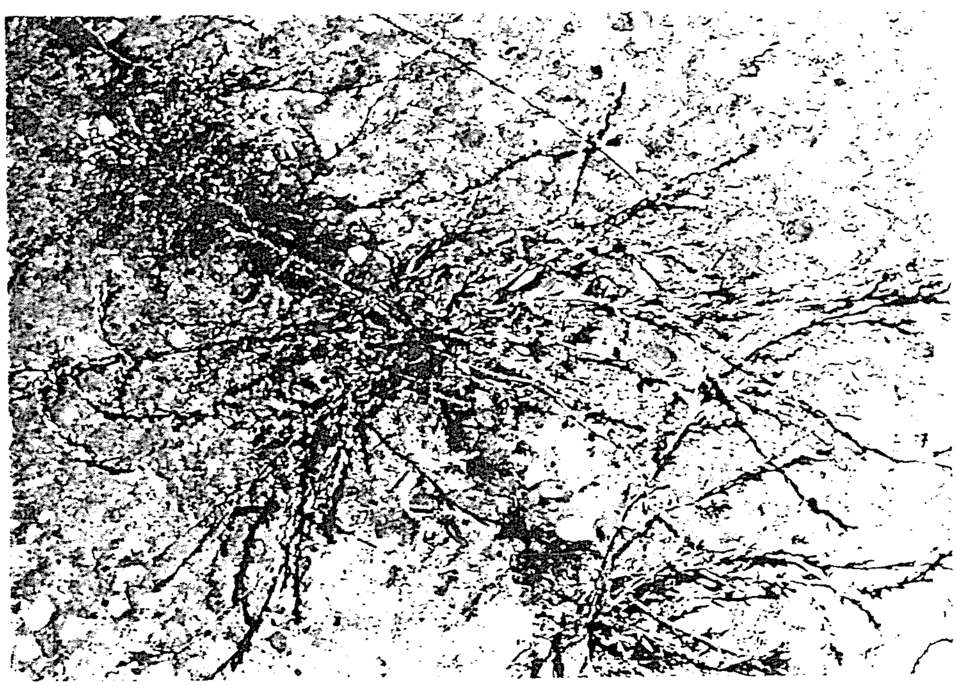


Photo 2.18 - "Before and After" - Removing Vegetation with Compressed Air

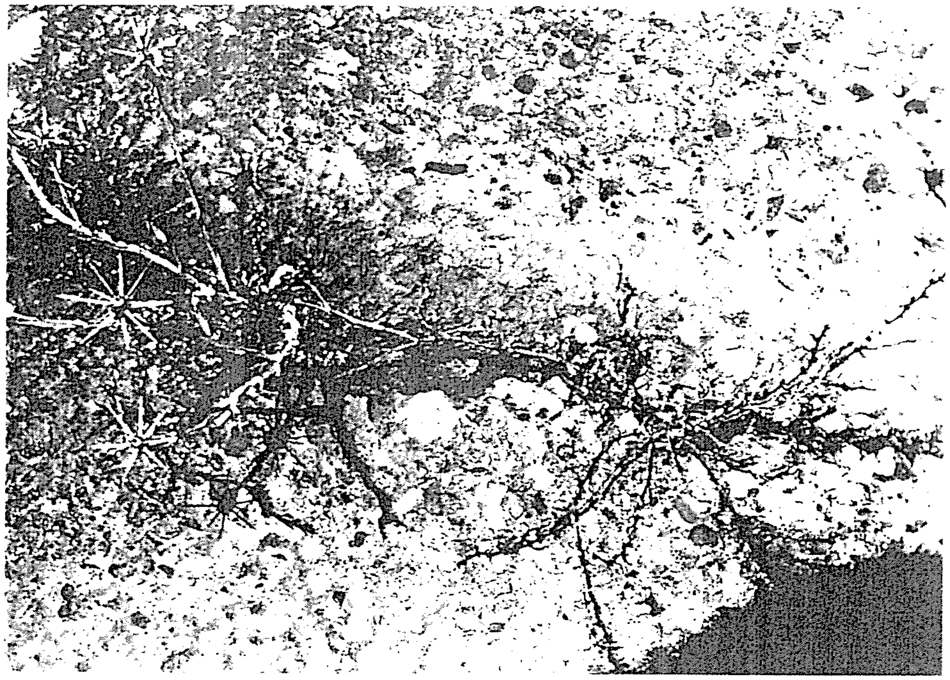


Photo 2.19 - "Before and After" - Removing Vegetation with Compressed Air

2.9 - Overall Conclusions and Recommendations

This experiment was necessary to gain a better understanding of the effectiveness of and the conditions for using compressed air jets to clean road surfaces. The data of this experiment was achieved through a series of controlled laboratory tests and field tests under more realistic conditions. Data (written data, photos, and video tape) such as air nozzle orientations, air nozzle speeds, air pressures, air flow rates, amount of debris removed from cracks, etc. were obtained to develop technical specifications for the implementation of compressed air jets nozzles on the prototype automated crack sealing machine. Such data will be used to compare this cleaning method with other cleaning methods. In addition, the data will be used to develop technical specifications pertaining to such machine subsystems as the positioning system, applicator assemblies, global vision system, local sensing system, and air compressor requirements.

A list of the conclusions and recommendations which were drawn from this experiment follows:

- It was not possible to remove a significant amount of "dirt film" from the sides of the cracks with an air jet. Therefore, if "dirt film" removal is necessary, another cleaning method is required. Several recommended methods for further research follow:
    - abrasive blasting
    - abrasive vacuum blasting
    - high pressure water jets
    - steam cleaning
    - mechanical means, such as rotary brushes
- The air jet was unsuccessful in removing weeds from cracks unless the plant roots were dead. Therefore, another method of removing weeds is required. Several recommended methods for further research follow:

- cutting weeds with high pressure water jets
- burning weeds propane burners
- spraying weeds (with herbicide)
- abrasive blasting
- abrasive vacuum blasting

· Observing the results of cleaning actual road surface cracks, it can be concluded that an air jet should satisfactorily remove all sizes of *loose* debris from cracks at slow speeds (approximately 0-5 mph). 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. This information will be useful for developing specifications for the positioning system and applicator assemblies.

· Nozzle eccentricities greater than approximately 1/2" clean the crack relatively poorly as compared with eccentricities less than approximately 1/2". This phenomenon may be a function of the crack width. Therefore, it may be useful to perform additional tests on cracks of smaller width (The crack width used for this experiment was assumed to be representative of a worst case road crack.) to determine if a 1/2" nozzle eccentricity is acceptable for cleaning all sizes of road cracks. This information will be useful for developing specifications for the positioning system and applicator assemblies as well as requirements for the vision system and local sensing system.

· For optimum air jet performance, it is preferable for the nozzle direction of travel to be aligned with the crack direction of travel (i.e. crack approach angle = 0 degrees). Therefore, it is recommended that the air jet direction of travel be continuously aligned with the crack direction of travel during the cleaning procedure. This finding indicates that an "array" type crack sealing machine would probably not be a viable design since this design would require that the crack approach angle vary from 0-90 degrees.

- It was difficult to observe a difference between the cleaning performance of the "Air Knife" and the other, less sophisticated orifices (for similar air pressures and flow rates). Therefore, it is concluded that the air nozzle/orifice design is not a significant factor in the performance of an air jets when cleaning cracks similar to those studied in this experiment. In addition, air pressures of approximately 65-80 PSI and air flow rates of approximately 60-90 CFM seem to be adequate for cleaning most road cracks.

CHAPTER 3

ROADWAY CRACK DEBRIS REMOVAL USING THE SANDBLASTING METHOD AND THE ABRASIVE VACUUM BLASTING METHOD (A FEASIBILITY STUDY)

3.1 - Introduction

The purpose of this experiment was to gain a better understanding of the effectiveness of using the sandblasting method and abrasive vacuum blasting method to remove vegetation, loose debris (e.g. dirt, sand, and small gravel), and dirt film from road surface cracks. More specifically, it was necessary to determine the conditions under which sand blasters and abrasive vacuum blasters can be used to clean road surfaces. This was achieved through a series of very qualitative field tests under realistic conditions. Data including photos and video tape was obtained to determine whether sandblasting or abrasive vacuum blasting could be used on an automated crack sealing machine. Operation parameters including air and blast media flow rate, air pressure, blast media size, and nozzle orientation angles (with respect to the road surface) was examined briefly and peripherally to gain a better understanding of how these parameters effect the success of the operation. The purpose of this experiment was to obtain entirely qualitative information. This experiment was only meant to provide a basic overall assessment of the sandblasting and abrasive vacuum blasting technologies as they would apply to the automated crack sealing project. It *was not* the purpose of this experiment to *fully* evaluate the significance of each of the operation parameters. If either the sandblasting or abrasive vacuum blasting methods were found to produce satisfactory results, then the knowledge gained from this experiment may be used to develop test procedures for a more extensive studies.

Although not part of this study, the knowledge that would be gained from more extensive and quantitative study of these cleaning methods would be necessary from the perspective of the global development and design of the crack sealing machine. For instance, data concerning blast nozzle orientation with respect to road cracks, speed, and effectiveness at various distances and angles with respect to cracks (nozzle effectiveness zone) would be used to design the positioning system and applicator assemblies to operate within effective limits. Knowledge of the blast nozzle effectiveness zone would be required to establish the accuracy and precision requirements of the global vision system and local sensing system. Furthermore, knowledge of required air pressures, air and blast media flow rates, and power requirements would help to determine air compressor specifications, abrasive blasting machine size, air hose specifications, etc. All of the data would be used to determine the general effectiveness and efficiency of the sandblast and abrasive vacuum blast cleaning methods so that they can be compared with other methods based on sound judgement.

3.2 - Objective

The purpose of this experiment, as described in the introduction above, was to gain a better understanding of the effectiveness of using the sandblasting and abrasive vacuum blasting cleaning methods to remove vegetation, loose debris, and dirt film from road surface cracks. The conditions under which these methods can be used to clean road surfaces were examined very generally. It is useful at this point to present a list of objectives which were used as an aid to obtain the required qualitative data. The objectives of this experiment follow:

1. Determine the effectiveness of sand blasting and abrasive vacuum blasting methods for removing vegetation from road cracks, both alone and in combination with a vegetation burning process.
2. Determine the effectiveness of the sand blasting and abrasive vacuum blasting methods for removing loose debris from roadway cracks and the local crack area.
3. Determine the effectiveness of the sand blasting and abrasive vacuum blasting method for removing dirt film from roadway cracks and the local crack area.
4. Gain a reasonable understanding of the significance of each of the machine operation parameters to the overall performance of the sand blasting and abrasive vacuum blasting methods. More specifically;
   - determine which, if any, of the air compressor operation parameters (including air pressure and air flow rate) are significant to overall performance,
   - determine which, if any, of the blaster operation parameters (including sand flow rate and sand size) are significant to overall performance,
   - and determine which, if any, of the nozzle orientation parameters (including nozzle speed, nozzle approach angle, incidence angle, and eccentricity) are significant to overall performance.

As noted above, these objectives were achieved through a series of realistic field studies. The field studies were conducted on a section of lightly used roadway outside the city of Davis, California.

Once again, it *was not* the purpose of this experiment to *fully* evaluate the significance of each of the operation parameters. If either the sandblasting or abrasive vacuum blasting methods were found to produce satisfactory results, then the knowledge gained from this experiment may be used to develop test procedures for a more extensive studies.

3.3 - Definitions

To better understand the sandblast and abrasive vacuum blast experiments presented in this chapter, the following definitions are provided to clarify specific technical terms.

sand blast method - A cleaning method which employs a high velocity stream of sand, projected by air,to clean a surface or object. The stream of sand cleans the surface or object by impinging on it and abrading unwanted material from the outer surface.

abrasive vacuum blast method - A cleaning method which employs a high velocity stream of blast media (usually sand, aluminum oxide, steel shot, cut wire, etc.), projected by air, to clean a surface or object. The stream of blast media cleans the surface or object by impinging on it and abrading unwanted material from the outer surface. Immediately after the blast media impinges upon the surface or object, the blast media and debris (remove from the surface or object) are vacuumed up through a small housing which surrounds the blast nozzle. The blast media and debris may then be filtered and separated to recycle the reusable blast media.

crack approach angle - The acute angle measured between the line of the direction of travel of the crack and the direction of travel of the air nozzle (see Fig. 2.1). This angle can be varied from 0-90 degrees. These tests were concerned with the angles of 0 and 90 degrees.

nozzle approach angle - The acute angle, measured from a vertical axis with respect to the road surface to the angle of a line parallel to the nozzle, in the vertical plane of the nozzle direction of travel (see Fig. 2.1). This angle can be varied from -90 to +90 degrees (At these extreme angles, the nozzle would be parallel to the plane of the road surface). These tests were concerned with the angles of 0, +15 and +30 degrees (where the "+" indicates the that jet of air "leads" the nozzle as the nozzle moves in its direction of travel.

nozzle angle of incidence - The acute angle, measured from a vertical axis with respect to the road surface to a line parallel to the nozzle, in the vertical plane perpendicular to the nozzle direction of travel (see Fig. 2.1). This angle can be varied from 0 to 90 degrees (At 90 degrees, the nozzle would be parallel to the plane of the road surface). These tests were concerned with the angles of 0, 15, and 30 degrees.

nozzle eccentricity - The horizontal distance (measured perpendicular to the line of action of the crack) from the center line of the crack to the tip of the air nozzle. The crack approach angle must be zero (0) degrees for the nozzle eccentricity to have any relevance (see Fig. 2.1). These tests were concerned with the eccentricities of 0, 1/2", 1", and 1 1/2".

dirt film - The thin film of debris (usually fine dirt or oil) that coats the inside of roadway cracks and the area surrounding cracks. This dirt film usually remains in the crack after another debris removal method (such as a high pressure air jet) removes the loose debris from the crack. It is thought that a better sealant bond (to the road surface) could be achieved if this dirt film were removed from the crack and the local crack area.

3.4 - Equipment and Materials Required

The equipment and materials necessary to perform this experiment generally include a sand blast machine, abrasive vacuum blasting machine, air compressor, hoses, nozzles, pavement test surface, still camera, video camera, appropriate safety equipment and other miscellaneous equipment. Please refer to **Appendix B.1** for a detailed list of the equipment and materials required for this experiment.

3.5 - Experiment Setup

Photos 3.1 - 3.6 show the equipment used for the abrasive vacuum blasting test. Photo 3.1 shows a general shot of the vacuum blasting support truck, the air compressor, air hoses, and the vacuum blast head. Photos 3.2 and 3.3 are closeups of the LTC 1060Pn vacuum blasting machine and air/moisture separator system. Photos 3.4 - 3.6 are closeups of the vacuum blast cart, the blast head, and the blast nozzle, respectively. Note in Photo 3.5 that the air and blast media was propelled to the road surface through the center, conically-shaped enclosure. After the blast media impinges on the road surface, it and the loosened debris was vacuumed up through the outer, surrounding, conically-shaped enclosure. The material was then separated and the reusable blast media is recycled back into the blast media supply line. In Photo 3.5, also note the heavy-bristled brush ring that surrounds the enclosure. This brush ring slid along the road surface and contained the blast media and debris. Photo 3.6, the blast nozzle, was similar for both the abrasive vacuum blast machine and the sandblast machine. Photo 3.7 is representative of the sandblasting operation.

Prior to starting the experiment, a representative roadway test area was selected. The test area included representative amounts of crack vegetation, loose debris and dirt film. All machinery including abrasive blasting equipment and the air compressor was set up and tested thoroughly for proper operation and safety considerations.

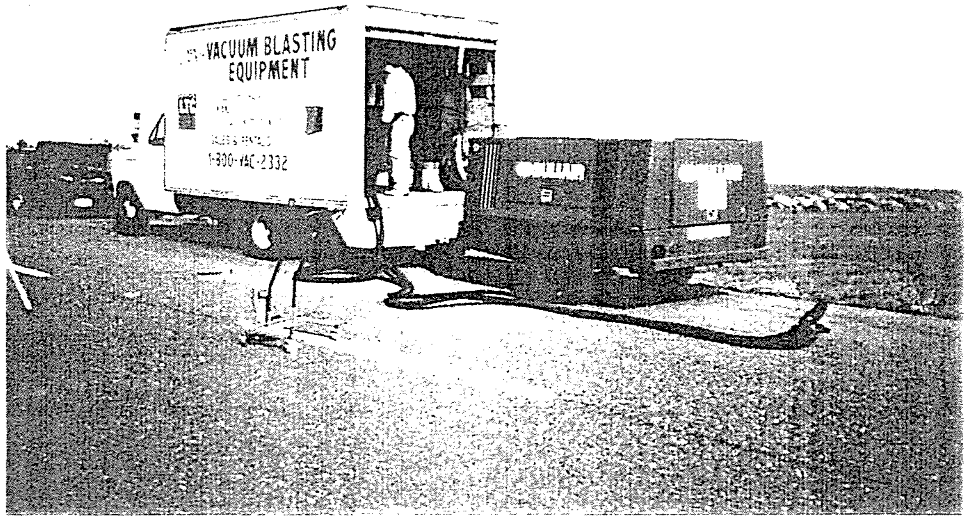


Photo 3.1 - Abrasive Vacuum Blast Experiment Setup

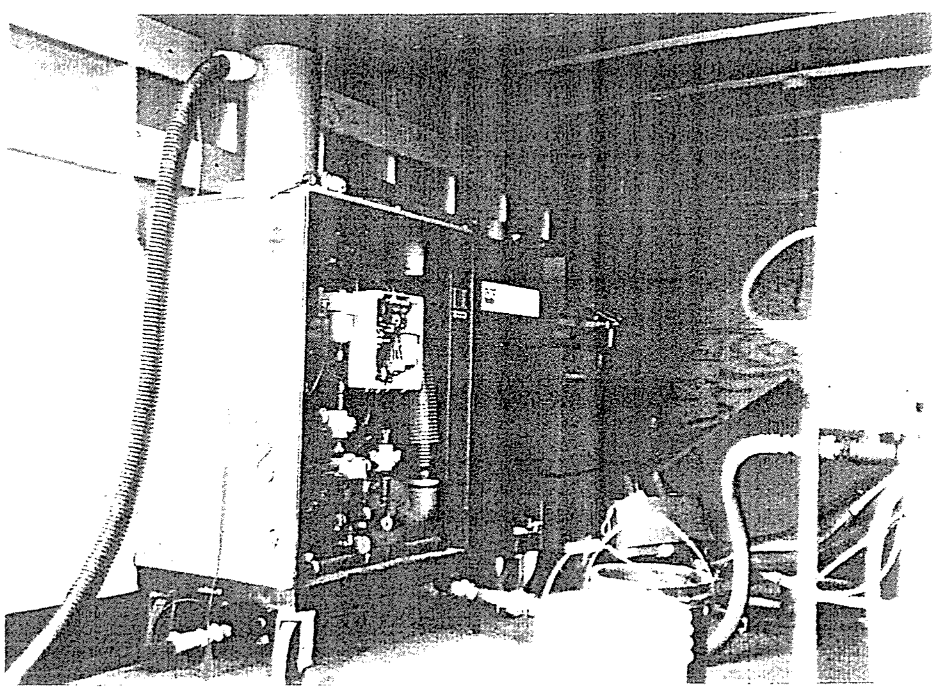


Photo 3.2 - LTC 1060Pn Abrasive Vacuum Blast Machine

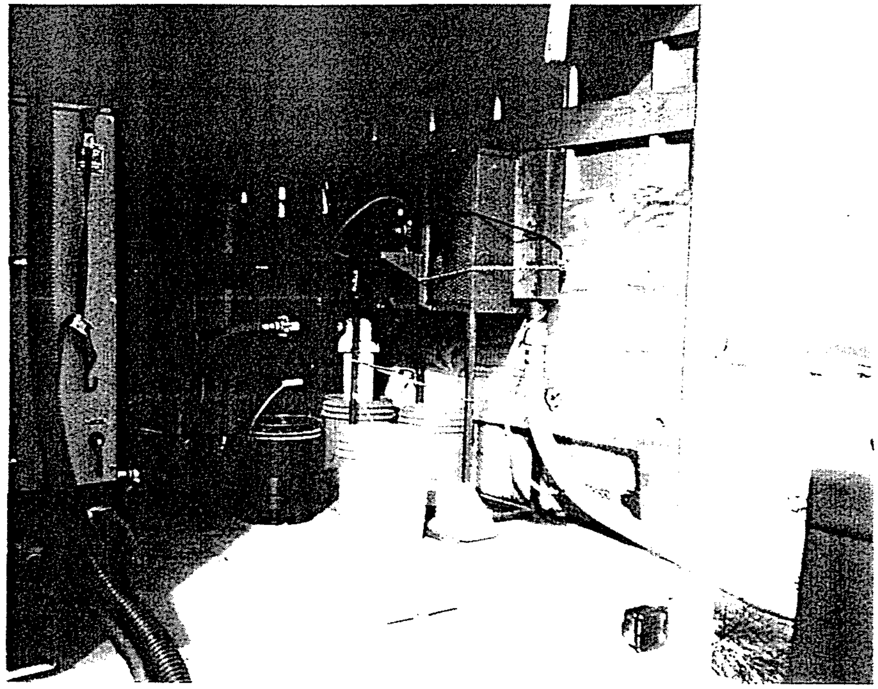


Photo 3.3 - LTC 1060Pn Abrasive Vacuum Blast Machine - Moisture Removal System

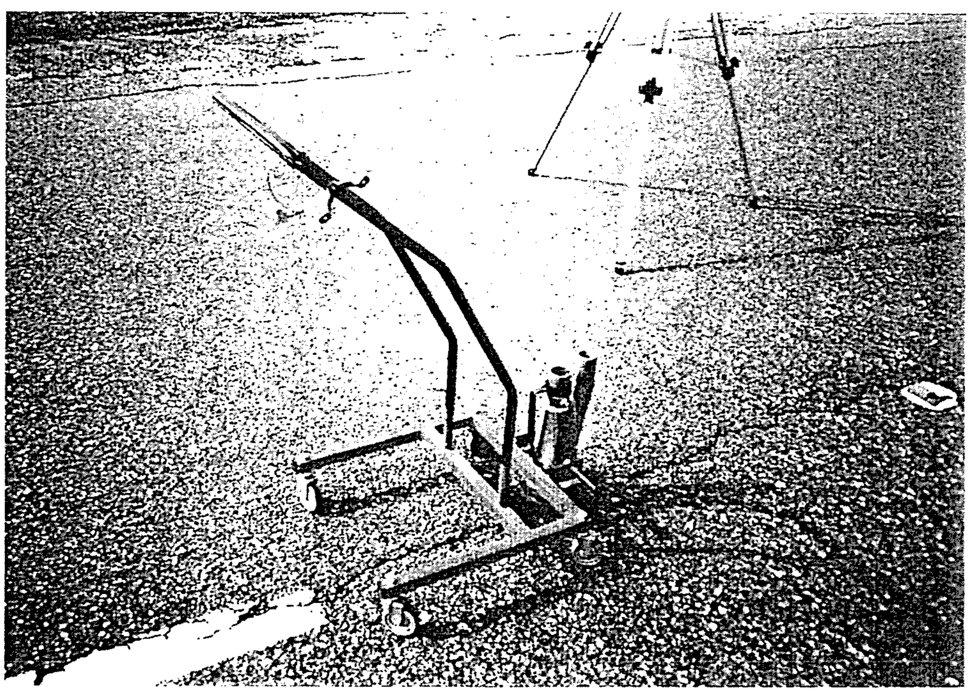


Photo 3.4 - LTC Abrasive Vacuum Blast Cart and Blast Head

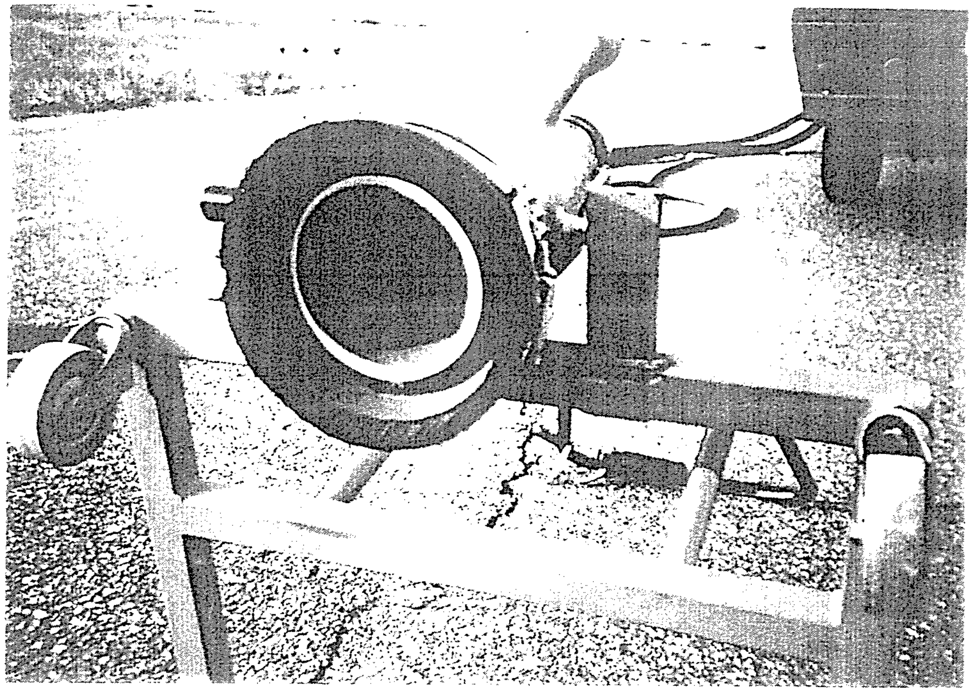


Photo 3.5 - LTC Abrasive Vacuum Blast Head

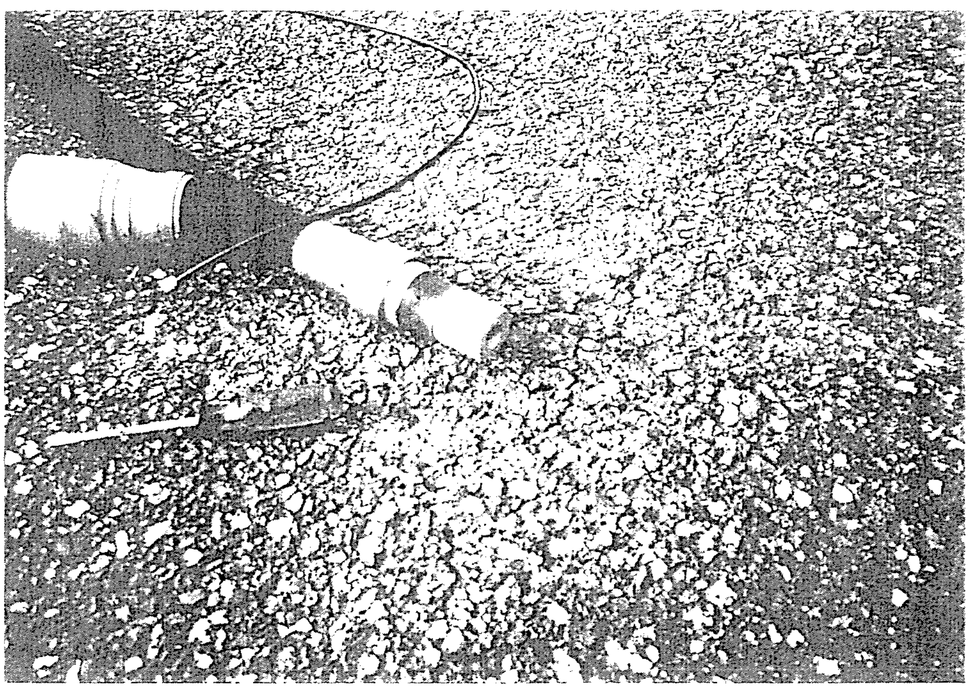


Photo 3.6 - LTC Abrasive Vacuum Blast Nozzle

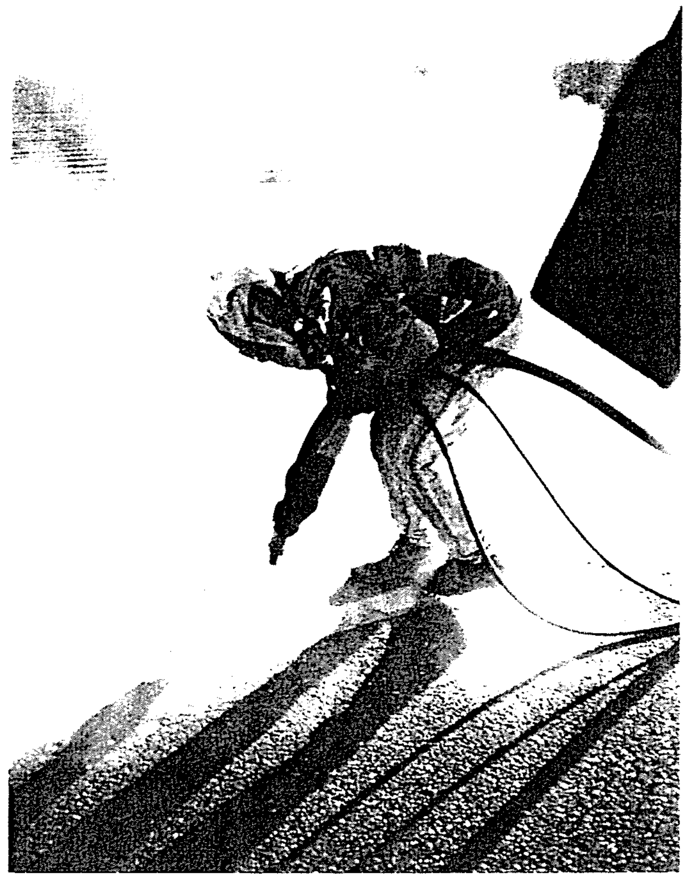


Photo 3.7 - A Typical Sandblasting Operation

3.6 - General Test Procedure

The tests for the effectiveness of the sand blasting and abrasive vacuum blasting methods for removing vegetation, loose debris, and dirt film from cracks was, for the most part, conducted simultaneously. These tests employed a single sand blast nozzle or abrasive vacuum blast nozzle which is directed over the road crack. The nozzle direction of travel was aligned with the crack. The tests were repeated for a variety of operation parameters until sufficient qualitative data is obtained. The detailed general procedure for these tests can be found in Appendix B.2.

3.7 - Observations and Conclusions

Photos 3.8 - 3.20 show "before and after" shots of road surface cracks that were cleaned using the sandblasting method. Photos 3.8 - 3.10 are one series. Photo 3.8 shows the crack with live vegetation before burning. Photo 3.9 shows the same crack after burning and Photo 3.10 shows the crack after sandblasting. Note how well the vegetation was removed from the crack. Photos 3.11 and 3.12 are another series. Photo 3.11 shows the crack, with vegetation growing in it, prior to sandblasting. Photo 3.12 shows the "after shot". Note again how well the vegetation was removed from the crack. This was done without burning the vegetation prior to blasting. Similar results can be seen in the "before and after" series of Photos 3.13 and 3.14 and Photos 3.15 and 3.16. Photos 3.17 and 3.18 show a crack with vegetation before and after burning. From a close observance of Photo 3.18 it can be seen that the burning operation did not entirely destroy the root structure of the vegetation. This was typical of most of the burning operations as the burner was just a small, handheld, propane type and was capable of producing a more intense flame. The burning process was found to be of little practical use as an aid to vegetation removal. Photo 3.19 shows an additional shot of a crack area after sandblasting. Photo 3.20 shows the effects of the sandblast jet as it is concentrated on a road surface. The flat road surface actually had no grooves in it prior to blasting. The sandblast jet was actually capable of grooving the pavement. A larger sand size and slower nozzle speed (with respect to the road surface) were used to achieve these results.

Photos 3.21 - 3.34 show "before and after" shots of road surface cracks that were cleaned using the abrasive vacuum blasting method. The results as shown in these photos are not as impressive as those for the sandblasting method. The reasons for this are explained in the paragraphs below. Photos 3.21 and 3.22 show before and after shots of one crack area in which no vegetation was growing. The results in this case were very good as can be noted by the removal of the crayon marks in Photo 3.22. The series of Photos 3.23 and 3.24 and Photos 3.25 and 3.26 show similar results. Photo 3.27 shows a wide shot of a representative crack with vegetation growing in it. Photo 3.28 shows a portion of the same crack after vacuum blasting. The series of Photos 3.29 and 3.30 and Photos 3.31 and 3.32 show before and after shots of crack areas with small amounts of vegetation and relatively large amounts of quite solid debris. The after shots confirm that nearly all of the vegetation was removed from the crack. However, it proved to be very difficult to remove the solid debris. This problem could probably have been eliminated or reduced substantially if the vacuum blast machine was working properly and modifications to the blast head could have been made according to the suggestions stated above. These two cracks could have been easily cleaned with the sandblast unit. Finally, Photos 3.33 and 3.34 show the capabilities of the vacuum blast unit for removing paint stripes from road surfaces. As can be seen from the photos, the operation was very successful although somewhat slow.

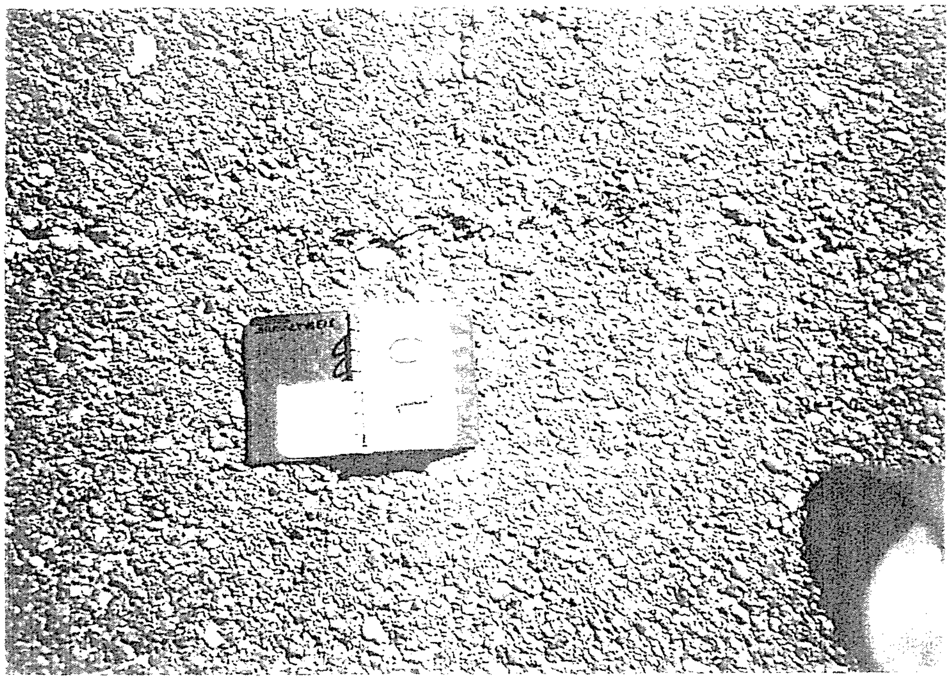


Photo 3.8 - "Before" - Vegetation, Loose Debris, and Dirt Film Removal Using Sandblast Method

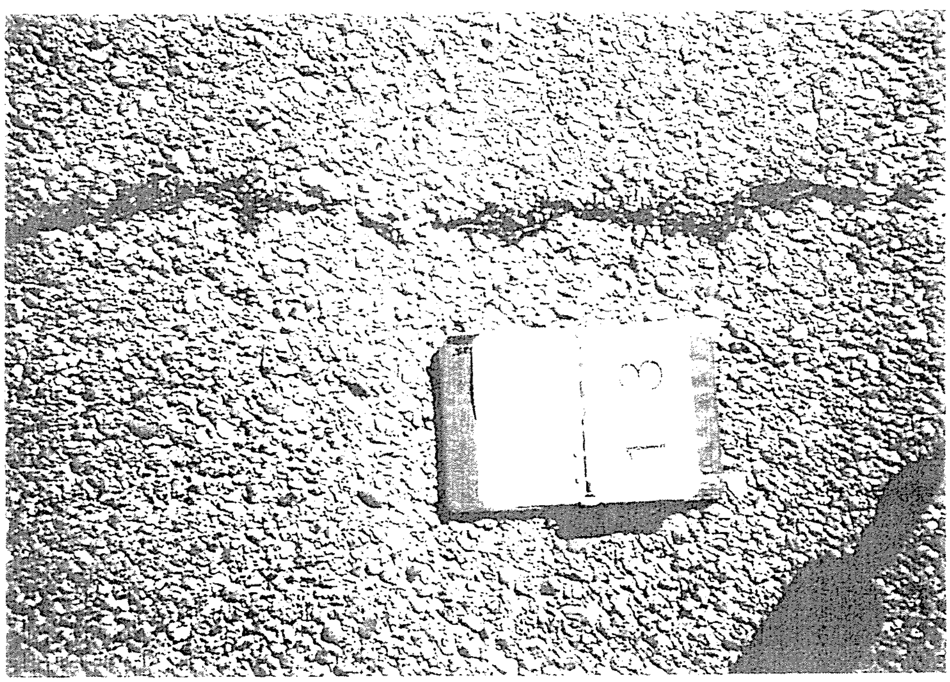


Photo 3.9 - Crack of Photo 3.8 After Vegetation Burning

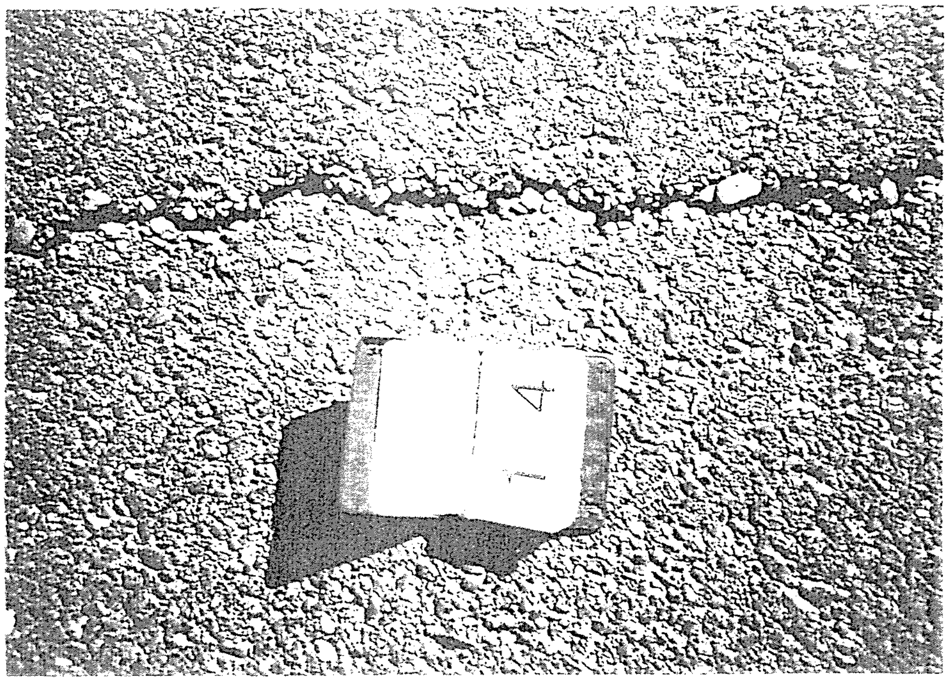


Photo 3.10 - Crack of Photo 3.9 After Sandblasting

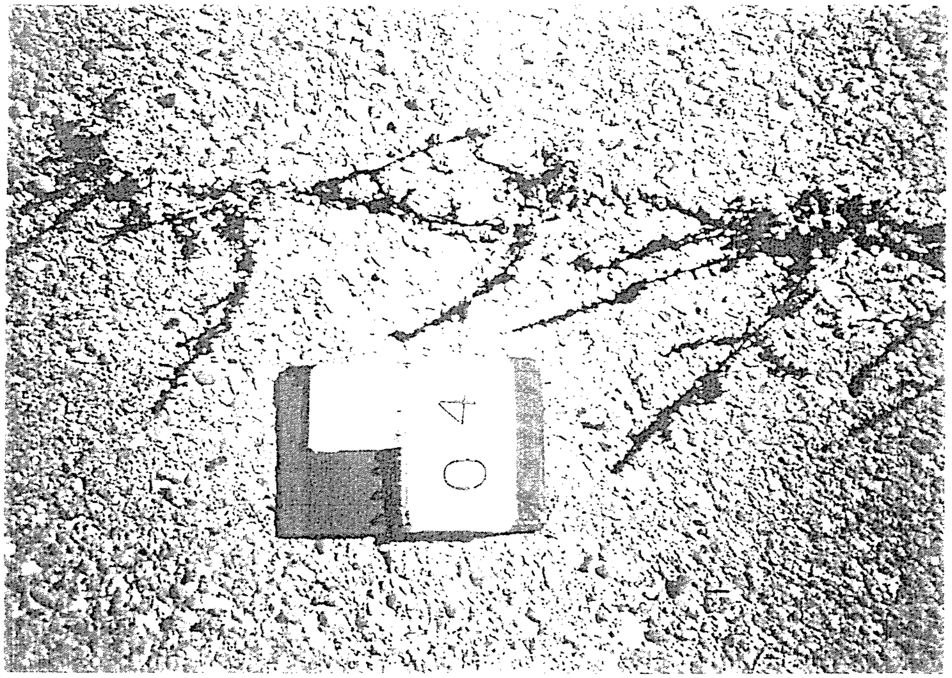


Photo 3.11 - "Before" - Vegetation, Loose Debris, and Dirt Film Removal Using Sandblast Method

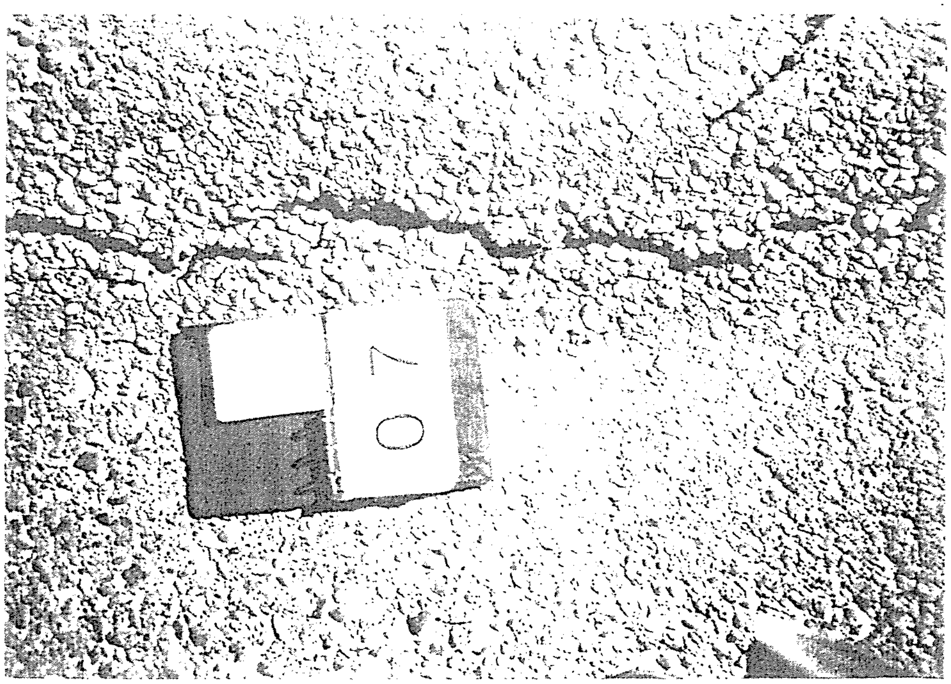


Photo 3.12 - Crack of Photo 3.11 After Sandblasting

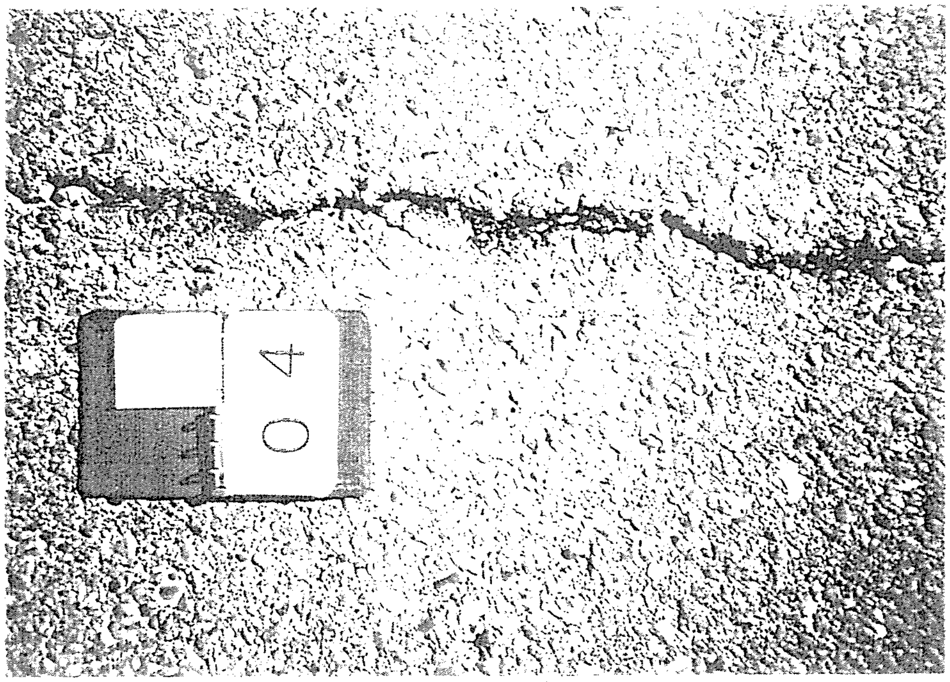


Photo 3.13 - "Before" - Vegetation, Loose Debris, and Dirt Film Removal Using Sandblast Method and "After" Vegetation Burning

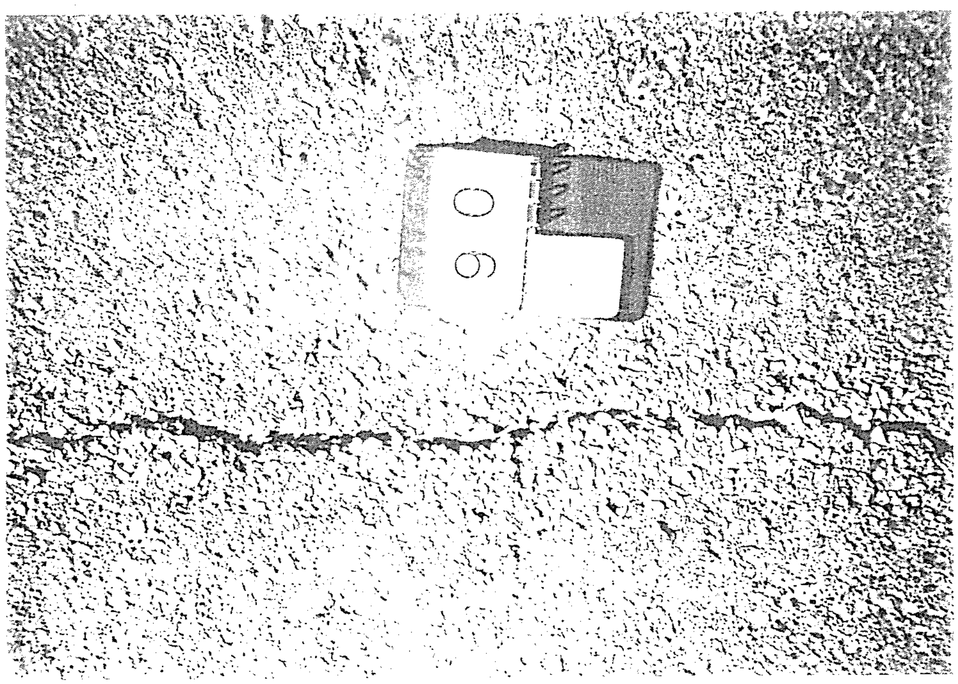


Photo 3.14 - Crack of Photo 3.13 After Sandblasting

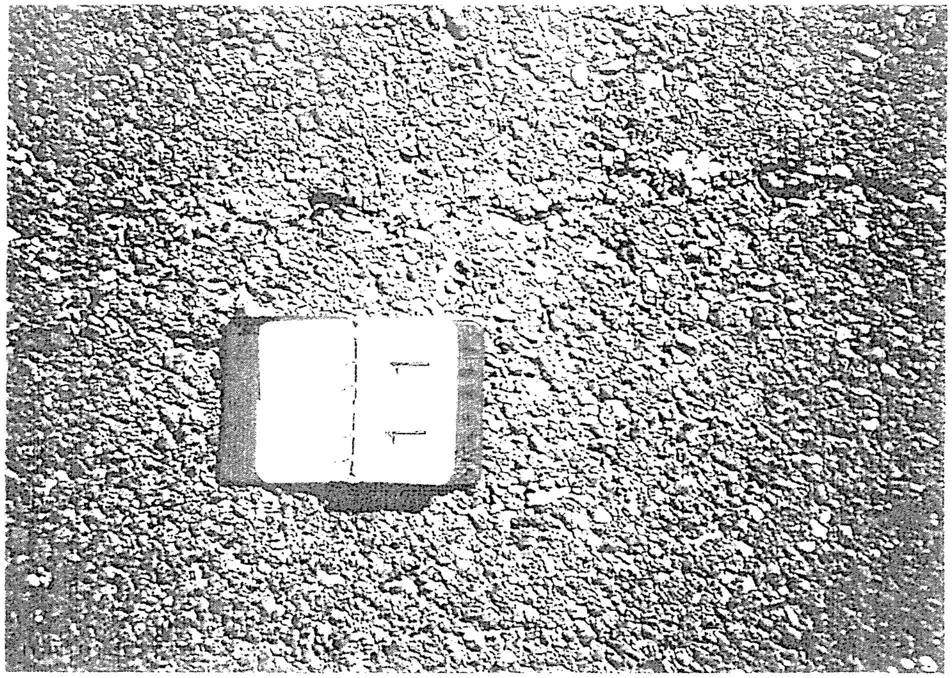


Photo 3.15 - "Before" - Vegetation, Loose Debris, and Dirt Film Removal Using Sandblast Method

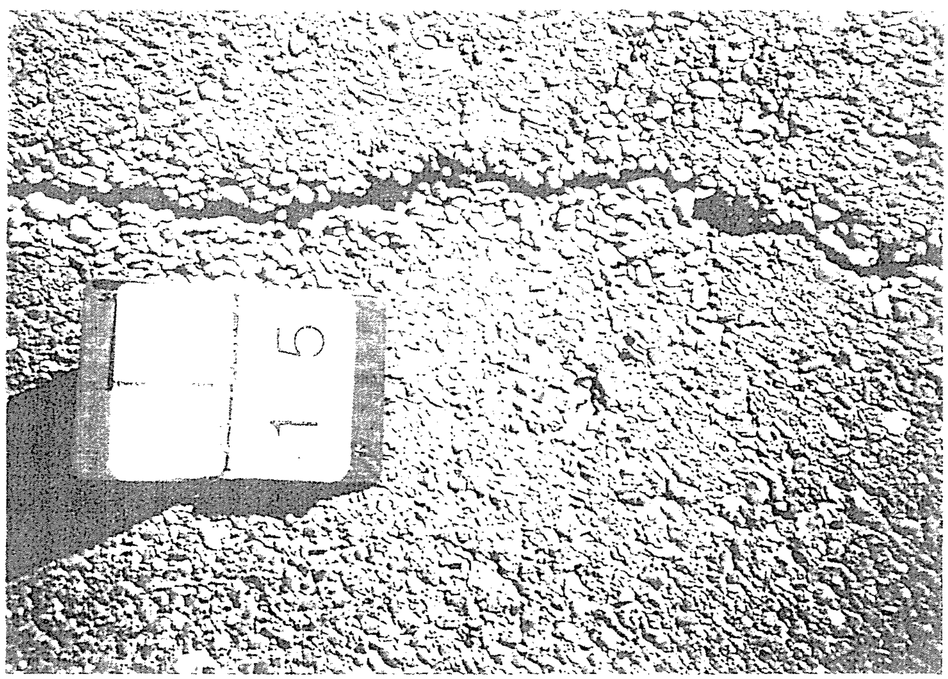


Photo 3.16 - Crack of Photo 3.15 After Sandblasting

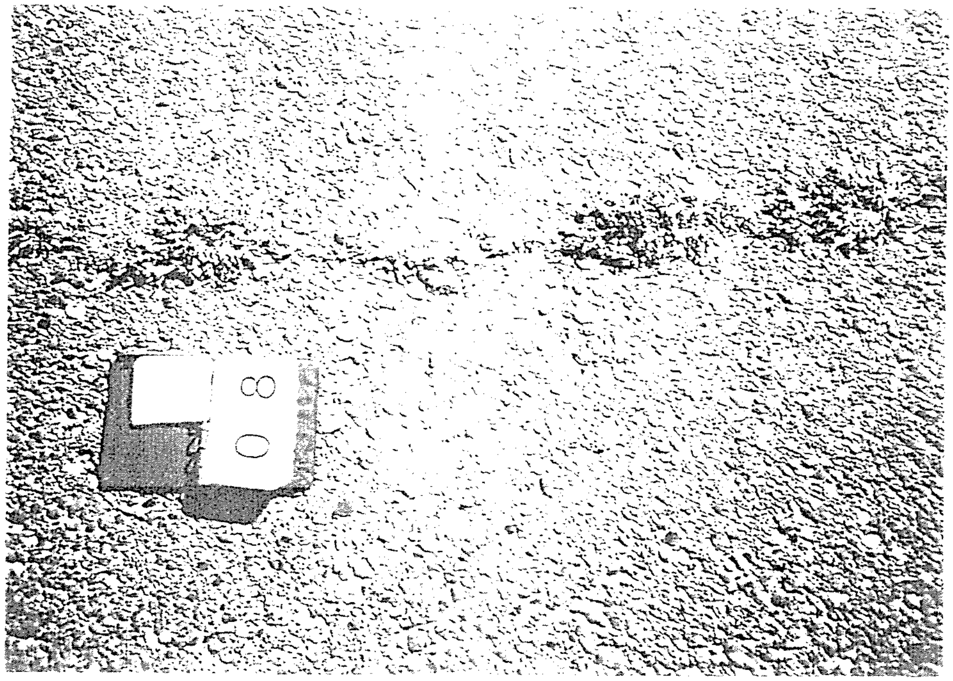


Photo 3.17 - "Before" - Vegetation Burning

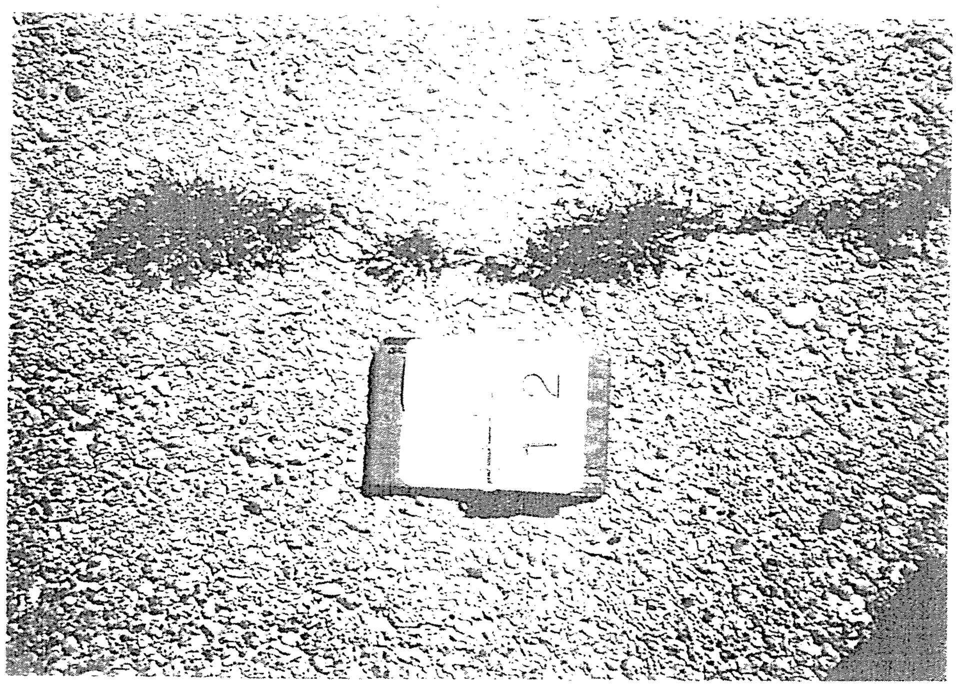


Photo 3.18 - Crack of Photo 3.17 After Burning

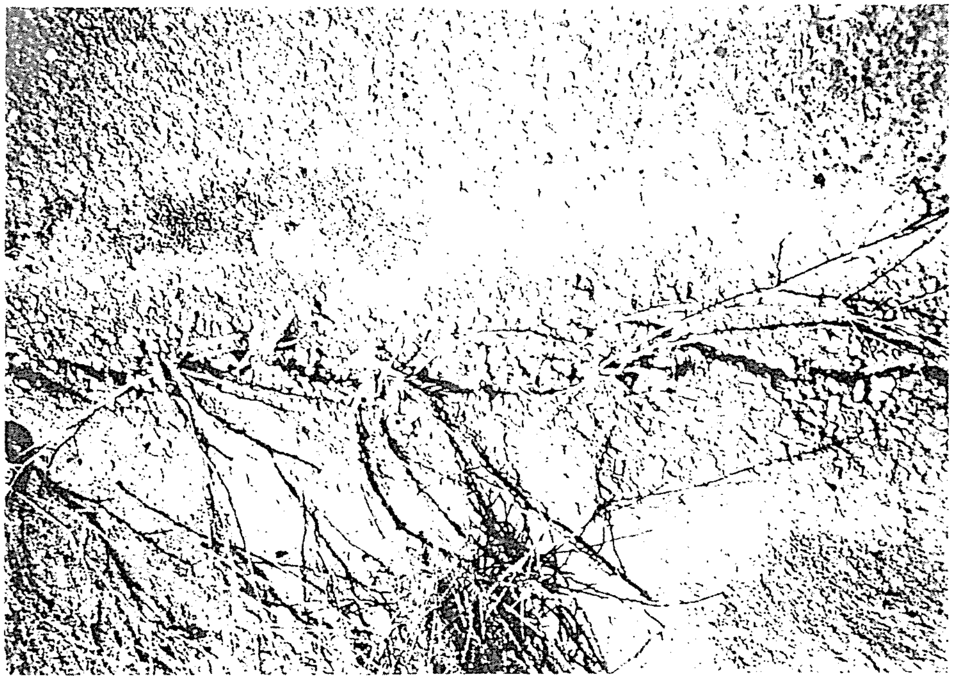


Photo 3.19 - Crack Area After Sandblasting

Photo 3.20 - Grooves Cut in Pavement Surface with Sandblaster

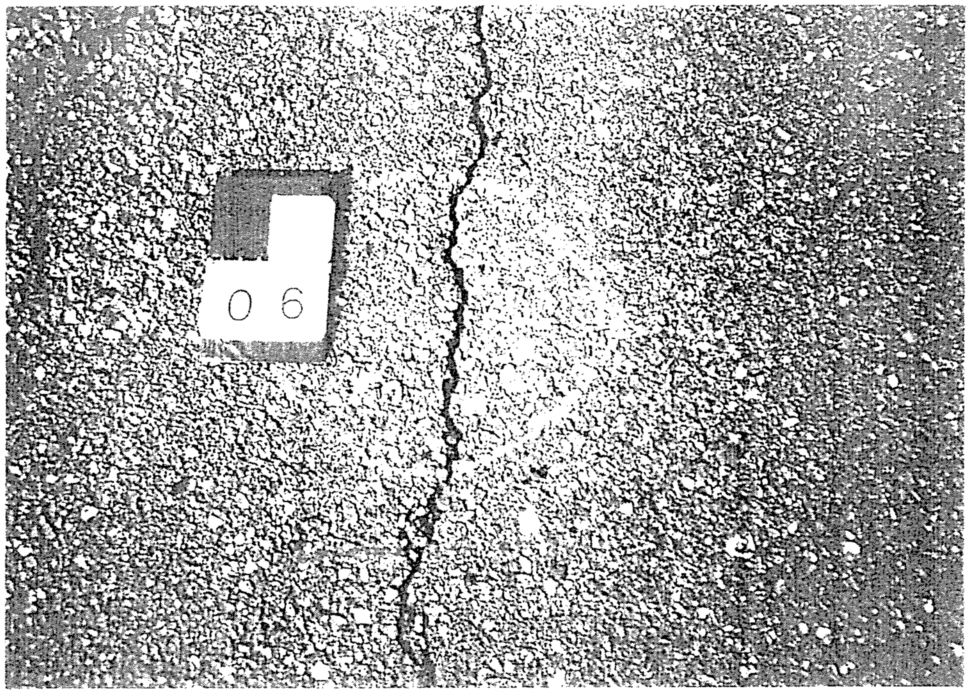


Photo 3.21 - "Before" - Loose Debris and Dirt Film Removal Using Vacuum Blast Method

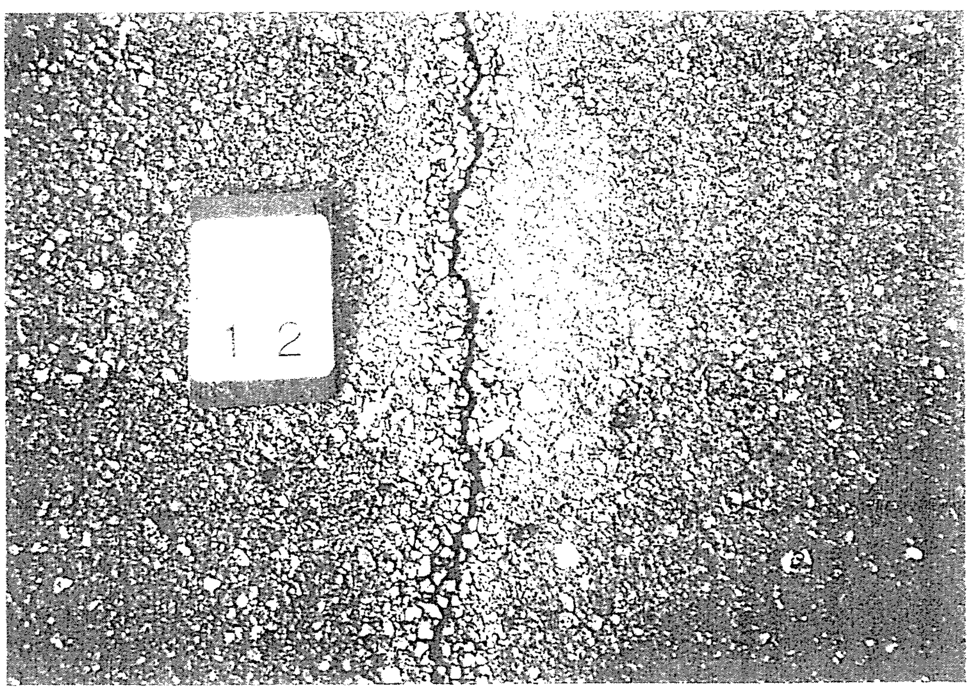


Photo 3.22 - Crack of Photo 3.21 After Vacuum Blasting

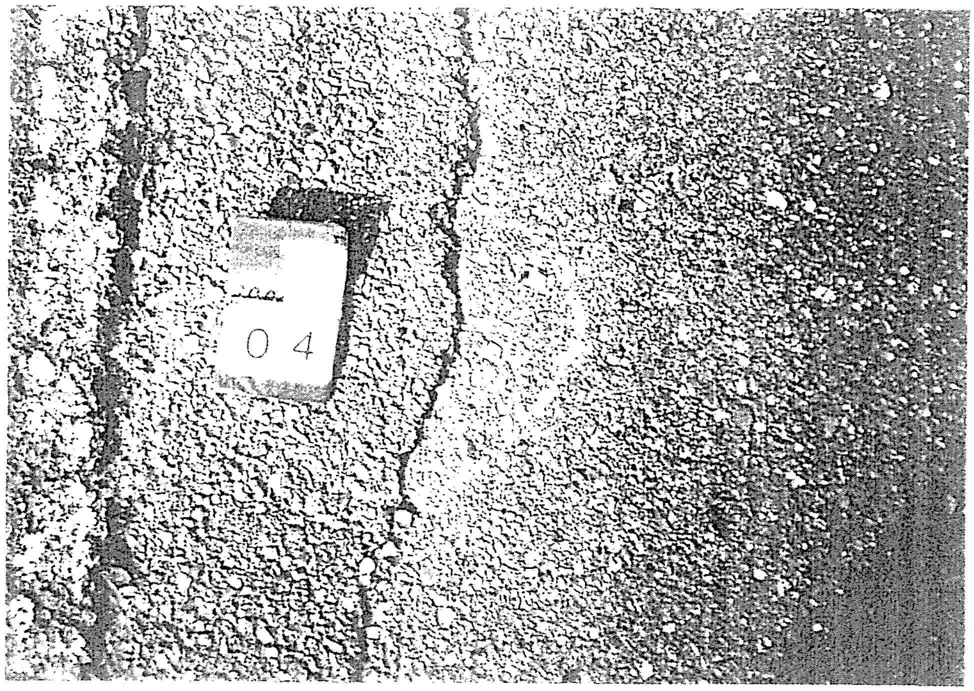


Photo 3.23 - "Before" - Loose Debris and Dirt Film Removal Using Vacuum Blast Method

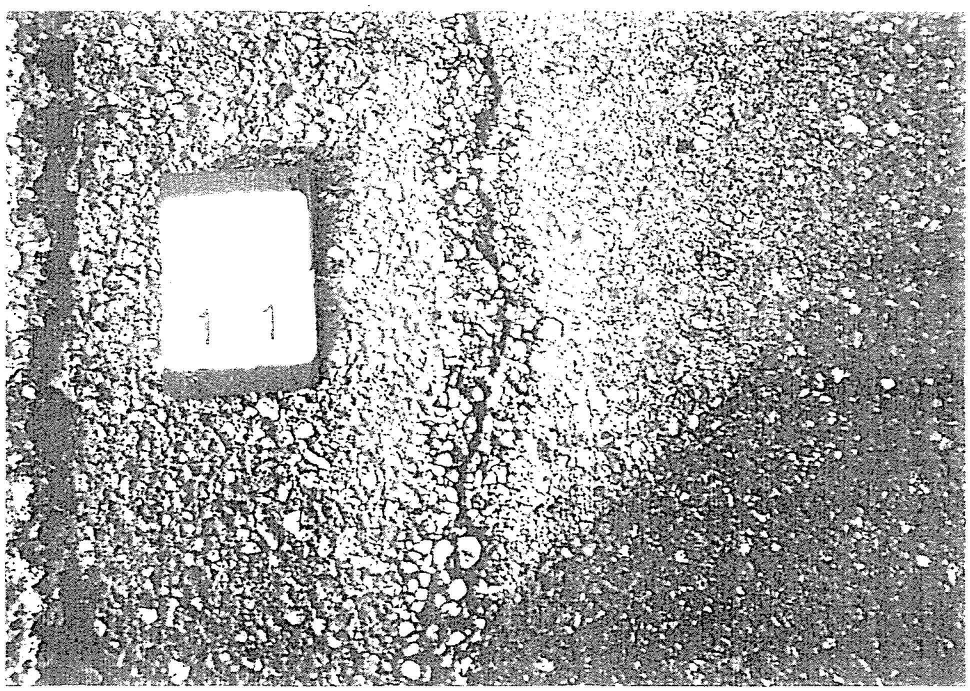


Photo 3.24 - Crack of Photo 3.23 After Vacuum Blasting

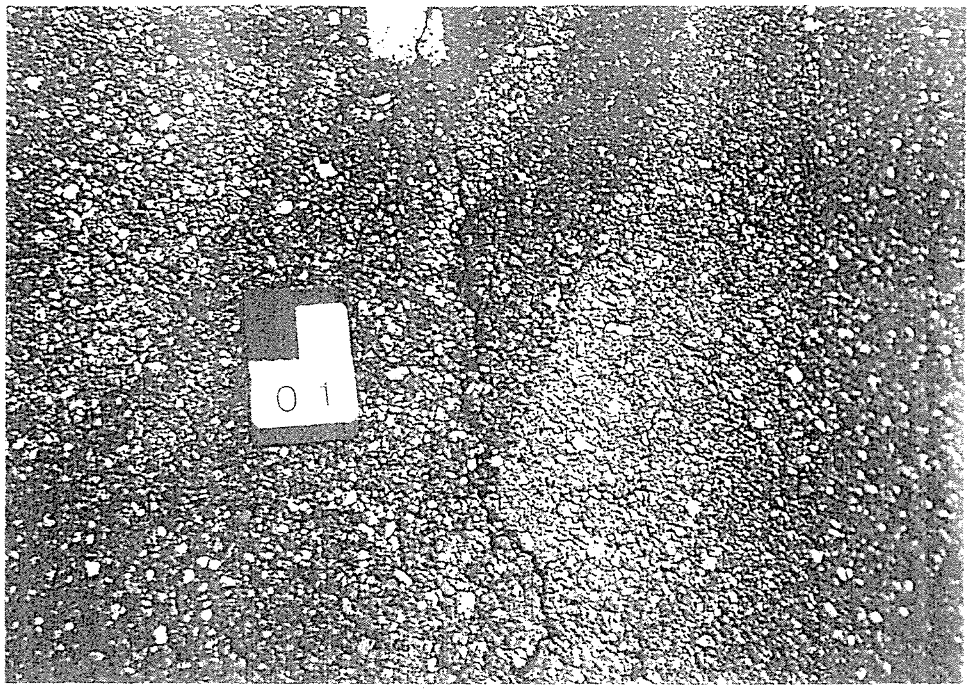


Photo 3.25 - "Before" - Loose Debris and Dirt Film Removal Using Vacuum [illegible]
Method

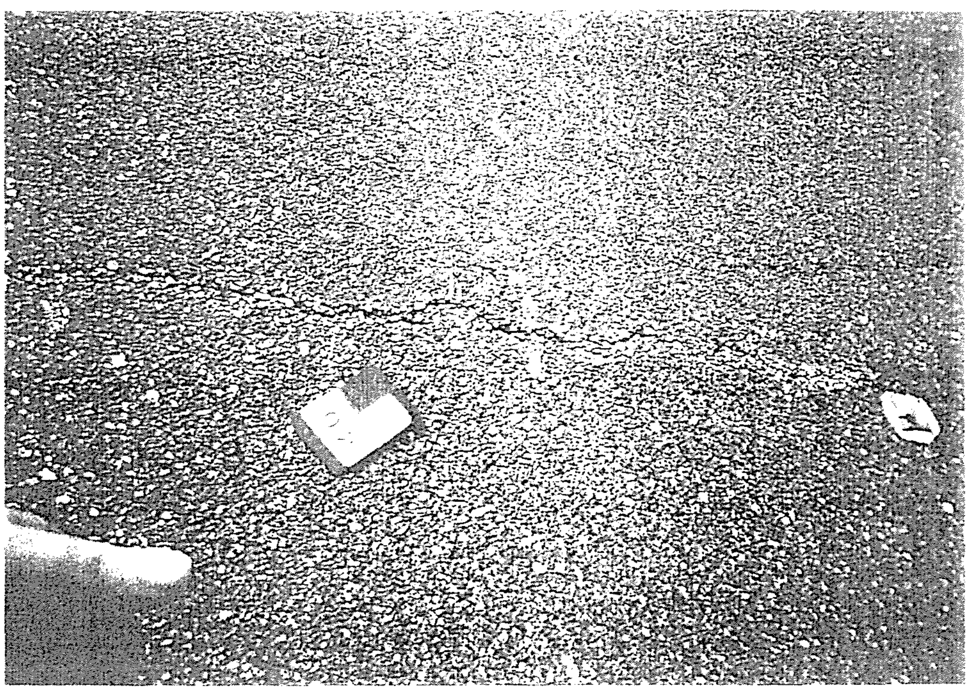


Photo 3.26 - Crack of Photo 3.25 After Vacuum Blasting

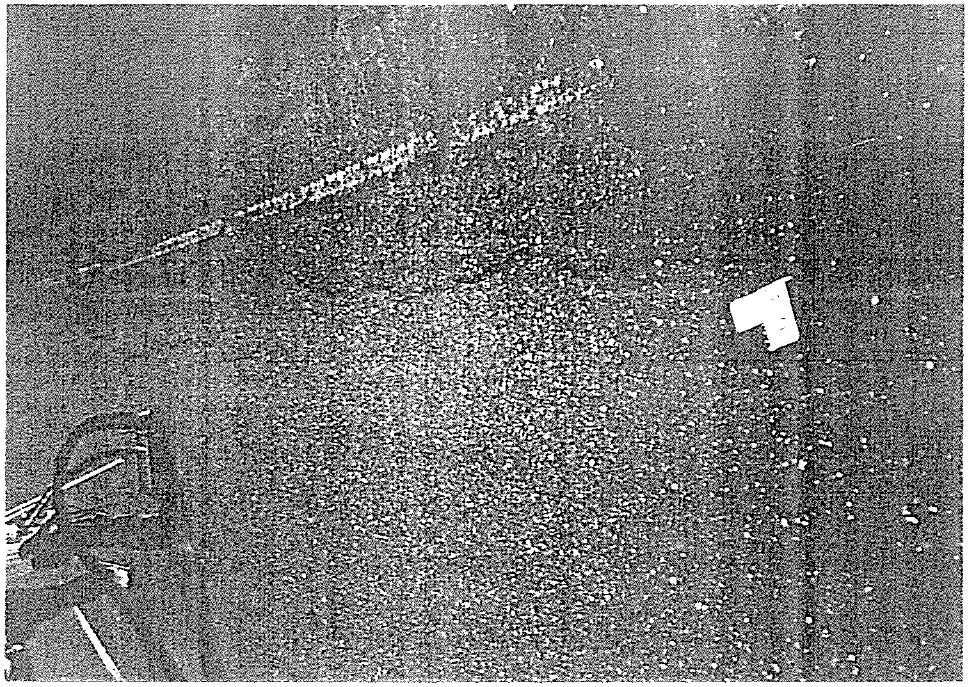


Photo 3.27 - Representative Road Crack with Vegetation Growing in It

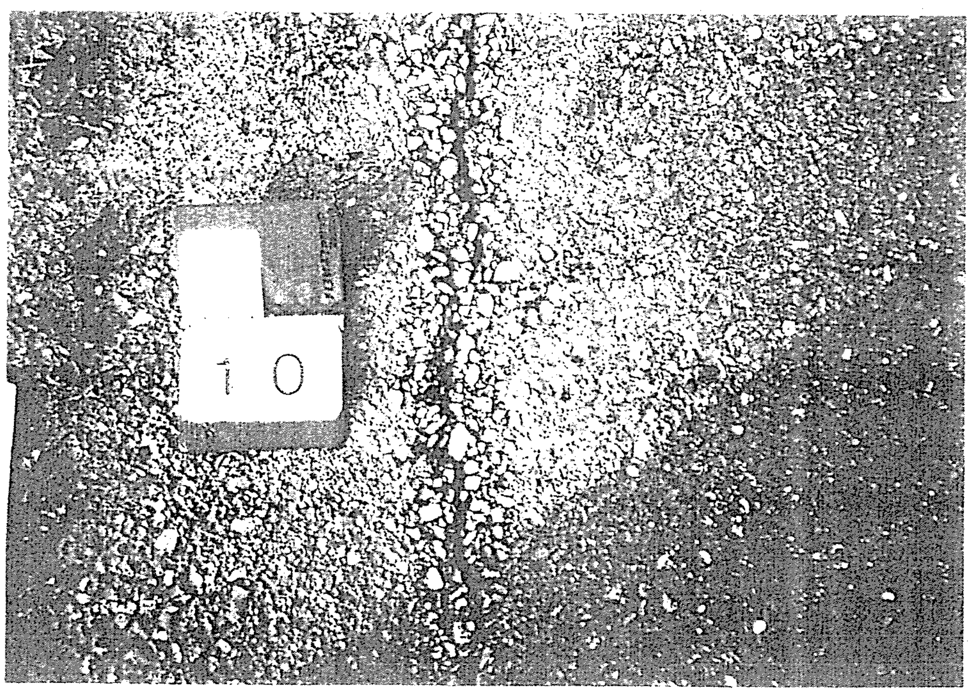


Photo 3.28 - A Portion of the Crack of Photo 3.27 After Vacuum Blasting

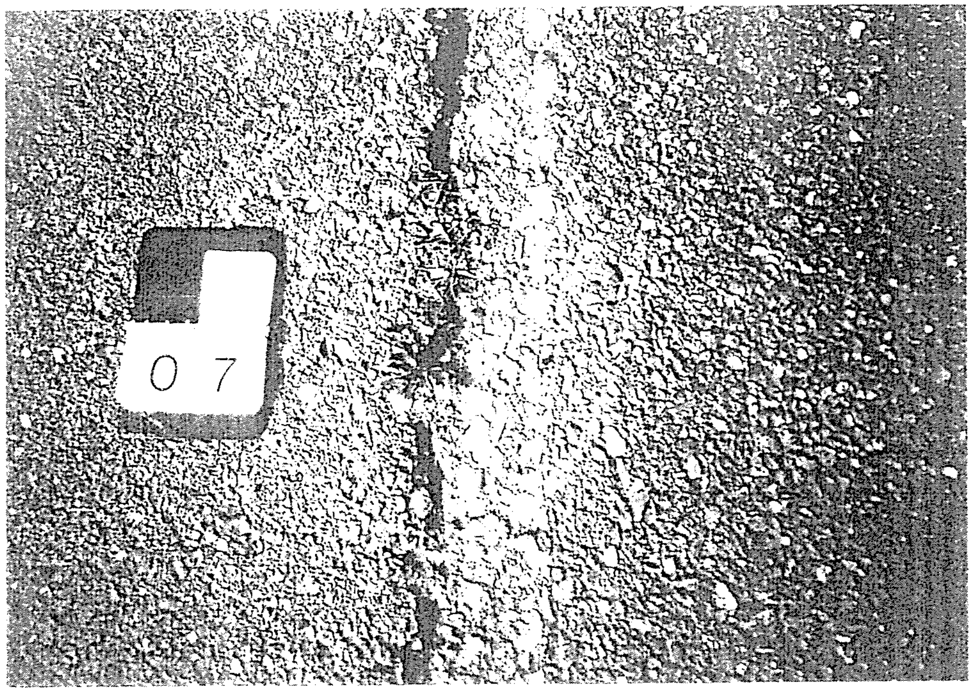


Photo 3.29 - "Before" - Vegetation, Loose and Solid Debris, and Dirt Film Removal Using Vacuum Blast Method

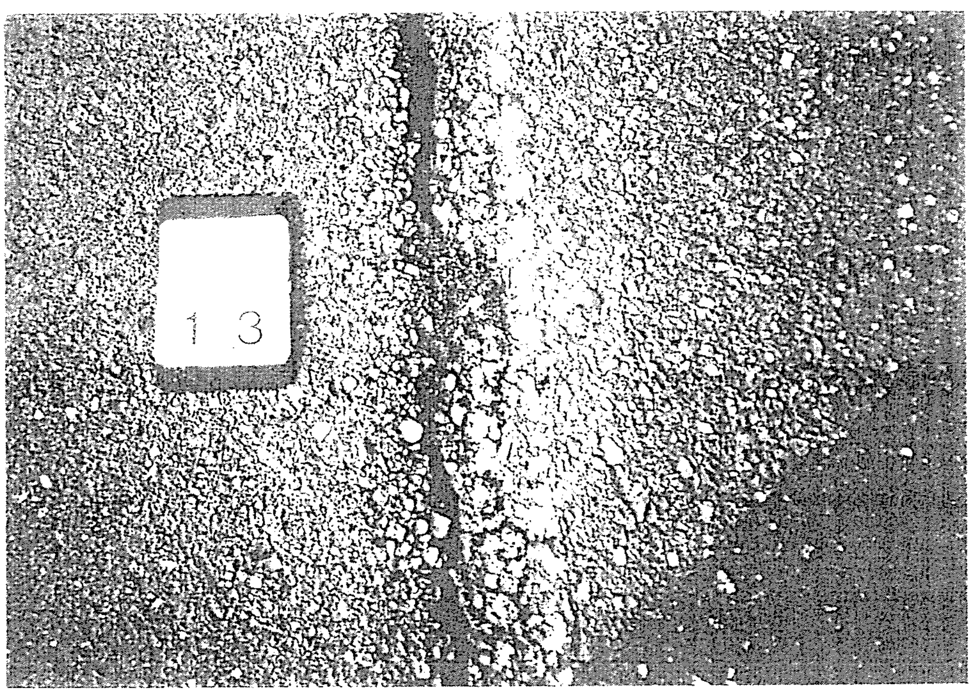


Photo 3.30 - Crack of Photo 3.29 After Vacuum Blasting

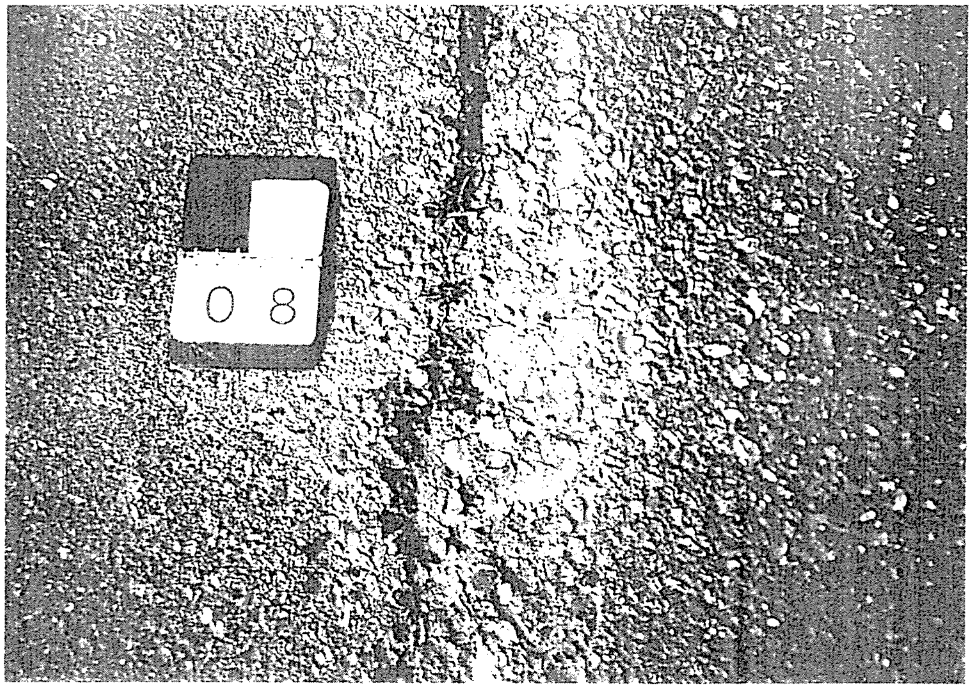


Photo 3.31 - "Before" - Vegetation, Loose and Solid Debris, and Dirt Film Removal Using Vacuum Blast Method

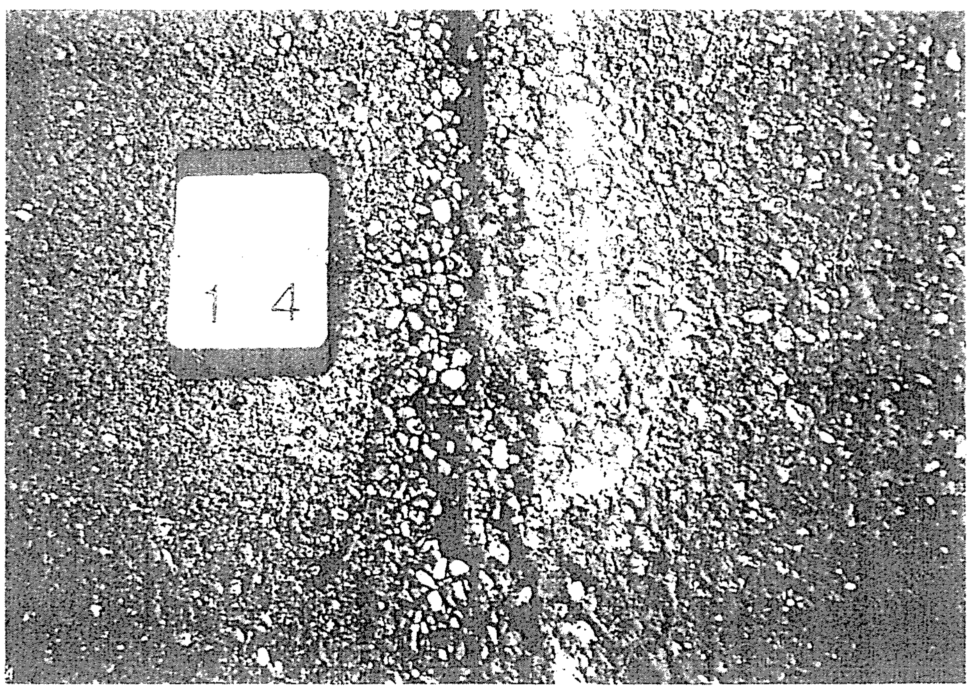


Photo 3.32 - Crack of Photo 3.31 After Vacuum Blasting

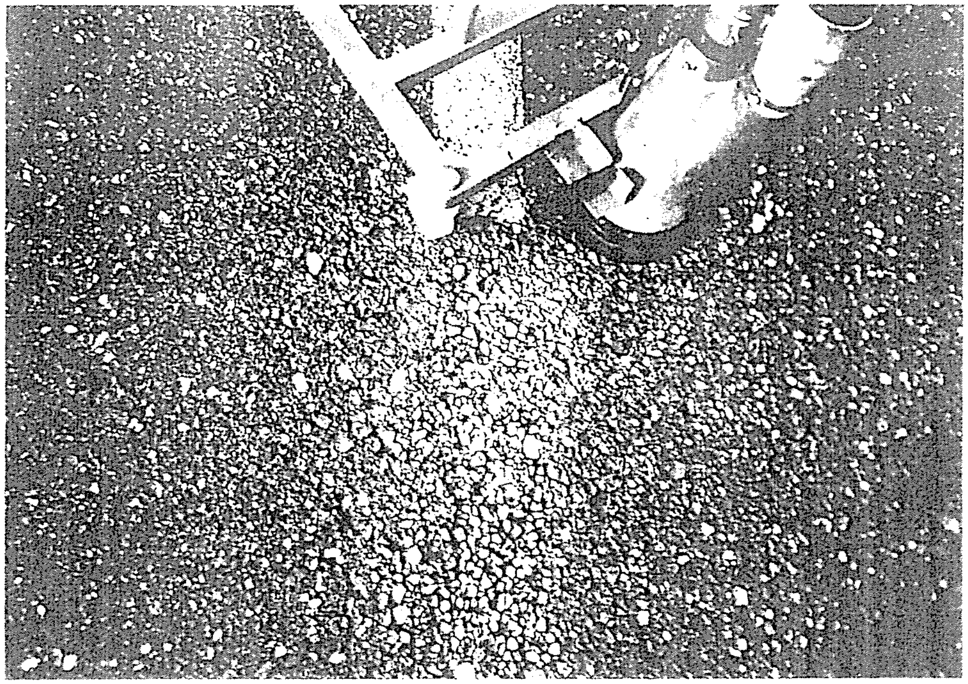


Photo 3.33 - Paint Stripe Removal Using the Vacuum Blast Method

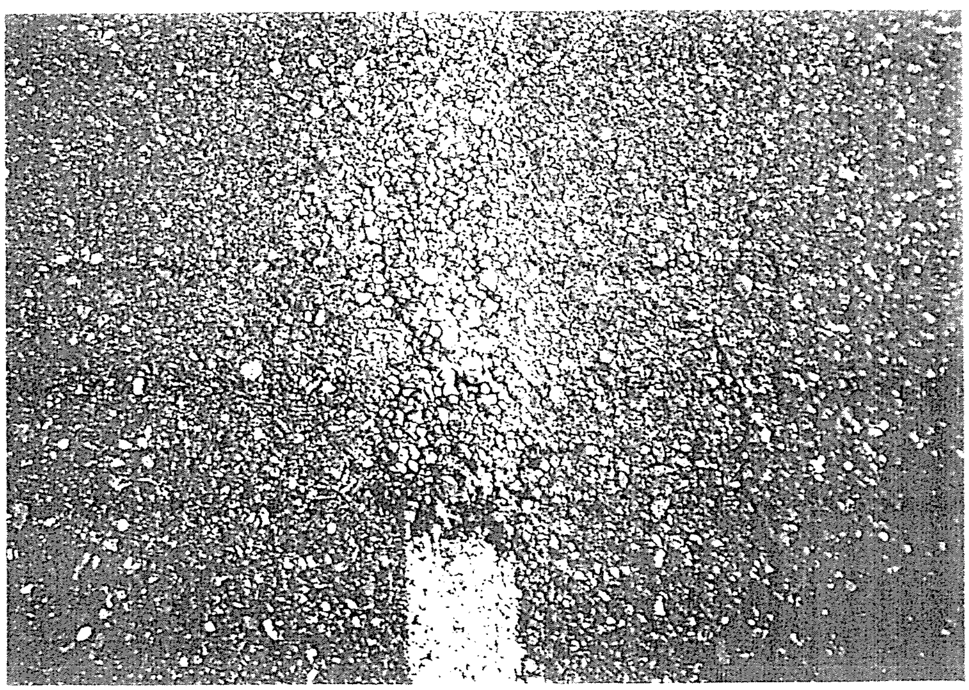


Photo 3.34 - Paint Stripe Removal Using the Vacuum Blast Method

It was concluded from this experiment that the sand blasting method is extremely effective for removing all types of vegetation, loose debris, and dirt film from road surfaces. The abrasive vacuum blasting method was found to be somewhat less effective while consuming considerably more power (on the order of 100-150 HP more - mostly for the vacuuming operation). It was also found to be considerably slower than sand blasting. However, it should be noted that the particular vacuum blasting machine that was used for this experiment was not performing up to specifications because of temporary equipment problems. The experiment continued though, because the equipment problems were not serious. In addition, it was observed that the vacuum blast head used for the experiment could probably have been more optimally designed. Design improvements could include blast nozzle adjustments for changing the nozzle orientation with respect to the road surface and the nozzle distance from the road surface. Adjustments such as these may have had a great effect on producing considerably better results when testing the sand blasting machine. Furthermore, a more effective vacuum recovery system could be devised such that power requirements could be reduced and vegetation debris could be vacuumed more efficiently (i.e. without becoming lodged in the vacuum recovery head). If these design changes were to be implemented, was concluded that the effectiveness, speed, and efficiency of the vacuum blasting operation could be considerably improved.

From a safety standpoint, the vacuum blaster was found to be much superior to the sand blaster. Primarily, this is due to the fact that the sand blaster does not contain the blast media or debris while the vacuum blaster contains both the blast media and debris. The flying debris is a safety hazard to spectators both because of the physical impact of the debris on persons and the health problems associated with the airborne dust.

The recycling capability of the abrasive vacuum blasting machine was a substantial advantage of this system over a conventional sandblast unit. By recovering the blast media and debris, the road surface and work environment was left clean. In addition, the fact that most of the blast media was reused could amount to great cost savings in terms of reduced blast media cost, reduced costs logistically to constantly supply the blast system (especially in remote locations), and reduced debris disposal costs.

CHAPTER 4

ROAD SURFACE CLEANING METHODS

4.1 - Introduction

It is concluded from the literature review (see Introduction) and feasibility studies of Chapters 2 and 3 that proper cleaning of road cracks and surfaces is essential if crack sealants are to adhere properly to the road surfaces. As such, it is necessary to determine the best road surface cleaning method for this project. This is done using the functional synthesis and brainstorming methods described previously. Step 4 of the functional synthesis process is accomplished below through the development of "cleaning method selection criteria". Each potential cleaning method is judged according to how it met the criteria. Brainstorming was useful in step 5 of the process. At that point, all possible methods of road surface and crack cleaning are listed. A listing of the more reasonable methods can be found in , Tables 4.1 - 4.3. After all of the potential cleaning methods is listed, they are each studied (step 6). The results of this study appear in Tables 4.1 - 4.3 as brief explanations of the advantages and disadvantages of each of the methods. Following the study of each cleaning method, the analysis is complete. The "best" cleaning method(s) is selected based on all of the previous work.

To summarize the information that was gathered and to better evaluate the various cleaning methods, the problem of road surface cleaning will be separated into three separate tasks. These include vegetation removal, loose debris removal, and dirt film removal. Each of these tasks must be completed satisfactorily for optimum seal adhesion to be achieved.

4.2 - Cleaning Method Selection Criteria

There are several method selection criteria that will be used to choose the desired cleaning method(s) for each task. These method selection criteria follow:

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 on the end of a robot end effector and should have a small mass, small physical size, and it must 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. In general, the use of readily available commercial equipment reduces equipment development time and costs, reduces machine development risks, and involves private companies in the development of the crack sealing machine.

4.3 - Techniques of Road Surface Preparation

Each of the road surface cleaning tasks are addressed in Tables 4.1 - 4.3. 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.

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 4.1 - Vegetation Removal Methods (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 VACUUM BLASTING	
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 VACUUM BLASTING	
EFFECTIVENESS - Research has shown that this method can do an exceptional job of removing vegetation from the road surface cracks. The abrasive blaster provides a high mass flow rate (as compared with an air jet), thus providing more efficient cleaning of the road surface. However, more development of this process is required before commercialization is feasible.	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 4.1 - Vegetation Removal Methods (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 4.1 - Vegetation Removal Methods (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.
	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.
	SERVICEABILITY - The unit would be relatively easy to maintain.
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 4.2 - Loose Debris Removal Methods (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 VACUUM BLASTING	
EFFECTIVENESS - Research has shown that this method can do an exceptional job of removing loose debris 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 4.2 - Loose Debris Removal Methods (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 4.2 - Loose Debris Removal Methods (page 3 of 3)

DIRT FILM REMOVAL METHODS	
ADVANTAGES	*DISADVANTAGES*
ABRASIVE VACUUM BLASTING	
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 4.3 - Dirt Film Removal Methods (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 4.3 - Dirt Film Removal Methods (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).

Table 4.3 - Dirt Film Removal Methods (page 3 of 3)

4.4 - Summary

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 of removing most loose debris from the road surface and cracks if controlled properly. 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 an HCA lance is by far 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 air 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 earlier, at speeds greater than 5 mph and with positional inaccuracies greater than 1/2", 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.

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 the SHRP H-107A project.

4.5 - Conclusion

It was concluded from the literature review and feasibility experiments of Chapters 2 and 3 that proper cleaning of road cracks and surfaces is essential if crack sealants are to adhere properly to the road surfaces. The development of this chapter used the functional synthesis and brainstorming methods to generate ideas for possible cleaning methods, develop selection criteria, evaluate each method carefully, compare each potential method to all the other methods, and finally select the best method(s) for cleaning cracks and road surfaces.

Although it was concluded that abrasive vacuum blasting has the potential of producing the best results, considerable development would be required to make it commercially feasible for the crack sealing machine prototype. It was decided among the project team that a centrifugal blower/vacuum system will do a satisfactory job of removing most loose debris from the road surface and cracks if controlled properly. This system will be employed on the prototype crack sealing machine. Should this system prove to be ineffective, a compressed air jet(s) can be easily implemented. These methods will not be effective in removing *all* loose debris or any live vegetation or dirt film. However, they can be easily implemented within the time frame and budget constraints of this project, they present the least development effort, and should be accepted by the majority of users. Furthermore, the use of the air blower method will be sufficient to demonstrate the main objectives of this project. Additionally, the prototype will be designed in such a way that more effective cleaning methods (e.g. abrasive vacuum blasting) can be incorporated in the future.

CHAPTER 5

A COMPARISON OF POSITIONING SYSTEM CONFIGURATIONS

5.1 - Introduction

There are two basic types of positioning system configurations that may be appropriate for positioning the applicator assemblies over the crack to be sealed. These include the "array" strategy ("array" configuration) and the "crack following" strategy ("crack following" configuration). The array configuration would employ a large number of applicator assemblies across the lane width of the machine. Each applicator assembly would service a strip of roadway approximately two inches wide (in the direction of travel of the machine). A particular applicator assembly would be activated whenever a section of a crack passed under it. The crack following configuration would employ only a small number of applicator assemblies. Each applicator assembly would be mounted as an end effector on a robot positioner. The positioner would be capable of moving the end effector laterally in either one or two dimensions (depending on the particular design chosen). A particular applicator assembly would actually follow a given crack, performing all tasks in a continuous type of operation. Both of these basic machine configurations have many advantages and disadvantages. After describing each configuration in more detail, the advantages and disadvantages of each configuration will be discussed and the best configuration will be chosen.

5.2 - The "Array" Positioning System Configuration

5.2.1 - Basic Description

A large number (approximately 80) of applicator assemblies would be mounted and equal intervals across the lane width of the machine. These applicator assemblies would be rigidly fixed to the machine frame. They would not translate or rotate. Each applicator assembly would service a strip of roadway approximately two inches wide (in the direction of travel of the machine). The operation of the assemblies would be controlled simply by a series of on/off switches. The components of the assembly would be turned on as the assembly passes over a crack in the road surface and then turned off after that portion of the crack has been sealed.

5.2.2 - Comparison of Advantages and Disadvantages

The advantages and disadvantages of the array configuration are provided in Table 5.1.

THE "ARRAY" POSITIONING SYSTEM CONFIGURATION	
ADVANTAGES	*DISADVANTAGES*
IN GENERAL	
A relatively small number of moving parts is required.	This system produces a relatively poorer quality seal and it is difficult to control the seal configuration.
A relatively smaller parts inventory selection is required.	Abrasive blasting may be difficult.
The applicator assembly is rigidly fixed to the machine frame.	Routing is extremely difficult, if not impossible. Routing may need to be done with auxiliary equipment.
Coordinate positioning of applicator assembly is not necessary.	The bandaid configuration is difficult to achieve.
Machine expansion is not difficult.	Heating (of the crack) is difficult to localize.
Faster sealant dispensing could be achieved.	Large numbers of nozzles and associated parts are required.
Sensors and control system would be relatively simple.	
Computing requirements are reduced (no need to transform to applicator coordinates).	
CRACK DETECTION	
More noise does not significantly affect results.	
Less resolution is required.	
Less processing is required.	
Significantly simpler algorithms are required.	
CONTROL SYSTEM	
The system is relatively simpler (uses simple on/off switch control).	
Each pixel of vision could control nozzles to prepare and seal a "pixel sized" area.	
CRACK PREPARATION	
Remove vegetation from the cracks	
	It may be more difficult if a localized removal method is needed.
Clean cracks and local area	
Nozzles could be controlled by simple on/off switches.	Cleaning of crack and local area is substantially less thorough.
A relatively small number of moving parts is required.	Air jets alone will not remove "dirt film."
A relatively smaller parts inventory selection is required.	Abrasive blasting is more difficult.
The applicator assembly is rigidly fixed to the machine frame.	Large "peak" flow rates may be required (depending on the design).
Coordinate positioning of applicator assembly is not necessary.	
Route cracks	
None.	Routing is extremely difficult, if not impossible. An auxiliary device may be required.
Heat cracks and local area	
Relatively few moving parts are required.	A single radiative heater method is inefficient and expensive.
	A radiative heater "array" (several heaters) is impractical and inefficient due to warm-up and cool-down of heaters.
	A torch array method requires many parts.

Table 5.1 - The Array Positioning System Configuration (page 1 of 2)

THE "ARRAY" POSITIONING SYSTEM CONFIGURATION (continued)	
ADVANTAGES	DISADVANTAGES
SEALANT APPLICATION	
Fast operation is possible.	A bandaid configuration is difficult to achieve.
	The flow of sealant through the nozzles is discontinuous (crack following configuration features continuous flow).
	Large "peak" flow rates may be required (depending on the design).
	It is more difficult to monitor the proper amount of sealant.
	The sealant flow rate may need to be varied.
SEAL FINISHING	
None.	The bandaid configuration is difficult to achieve.

Table 5.1 - The Array Positioning System Configuration (page 2 of 2)

5.3 - The "Crack Following" Positioning System Configuration

5.3.1 - Basic Description

A small number (approximately 1-6) of applicator assemblies would be mounted as end effectors on a robot positioner. The end effectors would not be rigidly fixed to the machine frame (as with the array configuration). These end effectors would be capable of moving large distances (up to approximately 14 feet) in one or two dimensions across the road surface as well as rotate 360 degrees. This design would allow each applicator assembly to sufficiently translate and rotate to track any crack in the road surface. An particular applicator assembly would be activated as a crack moves into its workspace and deactivated as the crack moves out of the workspace.

5.3.2 - Comparison of Advantages and Disadvantages

The advantages and disadvantages of the crack following configuration are provided in Table 5.2.

THE "CRACK FOLLOWING" POSITIONING SYSTEM CONFIGURATION	
ADVANTAGES	*DISADVANTAGES*
IN GENERAL	
A variety of crack seal configurations is possible.	The overall machine is considerably more complex.
Routing is possible.	A relatively large parts inventory selection is required.
Abrasive blasting is relatively straight forward to implement.	The applicator assembly is attached to a moveable end effector.
The road heating system is easier to implement.	The sensors and control system are relatively complex.
It is relatively easy to achieve a bandaid seal configuration.	Machine expansion is more difficult.
Only small numbers of nozzles and associated parts are required.	The applicator positioning system is considerably larger.
Operation of nozzles and heaters is continuous during sealing operation.	Higher computing requirements are required to transform to applicator coordinates.
CRACK DETECTION	
	Less noise tolerance is permitted.
	Higher resolution is necessary.
	More processing is required.
CONTROL SYSTEM	
None.	The system is more complex.
	Applicator assembly crack allocation is necessary.
	Applicator assembly collision avoidance algorithms are necessary.
	Path planning of the applicator assemblies is necessary.
	Control algorithms for manipulating applicator assembly end effectors are necessary.
CRACK PREPARATION	
Remove vegetation from the cracks	
It is easier to implement localized methods.	
Clean cracks and local area	
The crack cleaning potential is superior.	Nozzle motion (end effector) must be controlled by complex algorithms.
Virtually any cleaning method (i.e. air, abrasive blasting, water jet, brushes) can be employed.	A relatively large number of moving parts are required.
There is a constant material flow rate through the nozzles.	A relatively larger parts inventory selection is required.
Only small numbers of nozzles are required.	The applicator assembly is not rigidly fixed to the machine frame.
Route cracks	
Routing can be more easily performed.	
Heat cracks and local area	
There is continuous operation of the heaters (considerably more efficient).	Heaters must be attached to movable end effectors.
Only one heater per applicator assembly is necessary.	

Table 5.2 - The Crack Following Positioning System Configuration (page 1 of 2)

THE "CRACK FOLLOWING" POSITIONING SYSTEM CONFIGURATION (continued)	
ADVANTAGES	*DISADVANTAGES*
SEALANT APPLICATION	
There is continuous sealant flow through the nozzles.	
It is simpler to monitor the amount of sealant.	
SEAL FINISHING	
A bandaid configuration can be relatively easily achieved.	
This method involves a simpler squeegee configuration.	

Table 5.2 - The Crack Following Positioning System Configuration (page 2 of 2)

5.4 - Conclusion

Based on the inherent advantages and disadvantages of both the array and the crack following configurations, it was decided among the project team that the crack following configuration best meets the requirements of this project. This configuration is considerably more complex than the array configuration in terms of mechanical design, computing requirements, sensing and control, and in nearly every other aspect of the design. However, the crack following configuration allows for the capability to rout the cracks and clean them more effectively. Furthermore, variation of the seal configuration is possible and the crack heating system can be implemented more easily and efficiently. The array configuration is considerably simpler in terms of development and operation. However, this configuration presents too many major potential design limitations and difficulties and thus it would involve much greater risk in terms of project success. The crack following configuration will provide the best seal quality with the best chance for overall success of the project.

CHAPTER 6

"CONCEPT DESIGNS" FOR THE CRACK SEALING MACHINE POSITIONING SYSTEM

6.1 - Introduction

The decision has been made to proceed with the development of a "crack following" crack sealing machine configuration. The next step is to develop concept designs for the overall design of the positioning system.

The functional synthesis and brainstorming methods are used again in this chapter to select a basic concept design for the positioning system. The problem is defined (step 4) by developing a list of "basic design criteria" for the positioning system concept designs. Brainstorming is used to generate numerous design ideas (step 5), some very practical and some very impractical. Five of the more practical ideas are described below. Each of the designs is then evaluated (step 6) and summarized in Table 6.1 by listing the advantages, disadvantages, and significant design features of each design. The analysis being complete, selection of the "best" positioning system concept design is carried out using all of the information generated in the functional synthesis process.

6.2 - Basic Design Criteria

The basic design criteria for the positioning system are summarized to follow.

1) CAPACITY AND CAPABILITIES

- The positioning system shall have the ability to perform more than one operation (e.g. routing, cleaning, heating, and sealing) on a crack concurrently.
- The positioning system shall be capable of maneuvering one or more end effectors (applicator assemblies). An end effector shall be capable of routing, cleaning, heating, and sealing a road surface either singly or in combination with another end effector.
- It is desired that the positioning system provide the capability to seal one lane width (approximately 13 feet) of road surface at a speed of 2 miles per hour.
- It is desired that the positioning system allow for a seal with a "band-aid" type (or near band-aid type) configuration.
- It is desired that the positioning system be flexible enough in that it will possible to modify the positioning system so that improved road surface cleaning methods (such as abrasive vacuum blasting) can be employed at a later date.

2) STABILITY AND RUGGEDNESS

- The positioning system shall be rugged and stable. It shall be capable of properly maintaining the position of the crack sensors, applicator assemblies and peripherals while being subjected to physical disturbances (i.e. road bumps and curves, vibration, and speed fluctuations, etc.).

3) COMMERCIALLY AVAILABLE EQUIPMENT

- It is desired that the positioning system be comprised of as many commercially available components as possible. In general, the use of readily available commercial equipment reduces equipment development time and costs, reduces machine development risks, and involves private companies in the development of the crack sealing machine.

4) MODULAR CONSTRUCTION

- The machine shall be of a modular construction so that applicator assemblies and other components can be added or removed from the machine as necessary.

5) CONFIGURATION CONVERSION (Between Road Travel and Crack Sealing Configurations)

- It is desired that the positioning system have the capability of converting from the "road travel" configuration to the "crack sealing" configuration (and vice versa) with a minimum amount of time and effort.

6) EQUIPMENT MAINTENANCE AND RELIABILITY

- It is desired for the positioning system 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) COST

- It is desired that the chosen system employ a minimum number of total parts and a maximum number of identical parts. Development costs, fixed costs, and operational costs are generally reduced in this situation. A modular machine construction aids in this effort.
- It is desired that commercially available parts and materials be utilized whenever possible and practical. This will reduce overall machine development costs by relying on commercially proven designs and avoiding duplication of effort in the development and design process.

6.3 - Comparisons of Concept Designs

Five basic concept designs have been developed which attempt to meet the design goals of the project. They are listed to follow.

- The Swing-Hitch Cartesian Design (Fig. 6.1).
- The Modular Transverse Cartesian Design (Fig. 6.2).
- The Truck-Mounted Wing-Fold Cartesian Design (Fig. 6.3).
- The Truck-Mounted Swing-Frame Cartesian Design (Fig. 6.4).
- The Truck-Mounted Manipulator Arm Design (Fig. 6.5).

Additional concept designs were developed in the course of this project. However, since they were perceived by the project team as being obviously inferior (based on the design criteria) to the designs presented in this thesis, they will not be further discussed.

One of the major deficiencies of using a standard robotic manipulator arm for the crack sealing task is that of controlling the stability of the manipulator arm. Stability of a manipulator arm can be much more difficult than controlling the stability of a Cartesian based, gantry style manipulator. The reason for this is that the gantry style manipulator is supported at both ends of the slide mechanism for the end effector and the standard manipulator arm is supported at only one end of the arm. Thus, the gantry style manipulator is inherently much more stable and rugged than the standard manipulator arm design. Because of the inherently better stability and ruggedness, the gantry style manipulator would usually be more capable of properly maintaining the position of the crack sensors, applicator assemblies and peripherals while being subjected to physical disturbances (i.e. road bumps and curves, vibration, and speed fluctuations, etc.). This observation explains why several workable designs have been developed based on a Cartesian based, gantry style concept while only one workable design was developed based on the manipulator arm concept.

A close inspection of the truck-mounted manipulator arm design (Fig. 6.5) will confirm that the inherent problem of manipulator stability and ruggedness has been avoided, for the most part, in this particular design concept. One design characteristic that normally contributes to the instability and ruggedness of the manipulator is the length of the manipulator arm. As the length of the arm increases, the end effector becomes more difficult to control and is usually less rugged. In the design presented in Fig. 6.5, this problem is reduced dramatically by introducing a linear slide mechanism across the back of the support truck. The linear slide mechanism allows the manipulator arm to be much shorter while still servicing approximately the same work space. If a linear slide were not employed in this situation, the manipulator arm would have to be much longer in order to reach either side of the road lane. This problem could also be solved by attaching several manipulator arms at various locations across the back of the truck. Each arm would then service only a portion of the work space serviced by a single, longer manipulator arm. This idea is technically feasible. However, The employment of several manipulator arms to take the place of a single, longer manipulator arm would be very cost prohibitive in the case of a prototype crack sealing machine such as is being developed in this case.

Another design characteristic that normally contributes to the instability and ruggedness of the standard manipulator arm is that it is supported only at one end. Since manipulator arm is not usually supported near the end effector, the standard design is much more prone to problems associated with lack of stability and ruggedness. As can be seen in the design of Fig. 6.5, these problems have been alleviated to a large extent by supporting the end effector (in the vertical direction) on a wheeled carriage which rests on the road surface. By providing rigid support at the manipulator arm base and rolling support near the end effector, the manipulator becomes much more stable and controllable and is much less prone to problems arising from such things as road bumps and curves, vibration, and speed fluctuations.

A complete list of the advantages and disadvantages of each of the design concepts is provided in Table 6.1.

POSITIONING SYSTEM CONCEPT DESIGN COMPARISONS		
ADVANTAGES	*DISADVANTAGES*	SIGNIFICANT DESIGN FEATURES
SWING-HITCH CARTESIAN DESIGN (see Figure 6.1)		
CAPACITY AND CAPABILITIES - This system probably could be designed to sufficiently meet the design criteria.	COMMERCIALLY AVAILABLE EQUIPMENT - This system would require considerably more custom manufacturing than the proposed manipulator arm design.	Applicator assemblies move linearly in horizontal plane with limited motion in vertical plane. Applicator assemblies rotate 360 degrees about vertical axis.
CONFIGURATION CONVERSION - This system could easily convert between the high speed road travel configuration and the crack sealing configuration.	EQUIPMENT MAINTENANCE AND RELIABILITY - This design is more mechanically complicated and involves more custom manufacturing than the manipulator arm design. This design may require more maintenance and may be somewhat less reliable than the manipulator arm design.	Positioning system quickly converts from transport configuration to sealing configuration
MODULAR CONSTRUCTION - This system could sufficiently meet the design criteria.		Positioning system could be designed to expand in a modular fashion.
STABILITY AND RUGGEDNESS - This system could meet the design criteria.		Positioning system frame width during transport is under 8 feet.
COST - This system could probably be developed within the project budget.		Positioning system frame is a "stand-alone" trailer which is pulled by the support truck.
MODULAR TRANSVERSE CARTESIAN DESIGN (see Figure 6.2)		
CAPACITY AND CAPABILITIES - This system probably could be designed to sufficiently meet the design criteria.	COMMERCIALLY AVAILABLE EQUIPMENT - This system would require considerably more custom manufacturing than the proposed manipulator arm design.	Applicator assemblies move linearly in horizontal plane with limited motion in vertical plane. Applicator assemblies rotate 360 degrees about vertical axis.
CONFIGURATION CONVERSION - This system could easily convert between the high speed road travel configuration and the crack sealing configuration.	EQUIPMENT MAINTENANCE AND RELIABILITY - This design is more mechanically complicated and involves more custom manufacturing than the manipulator arm design. This design may require more maintenance and may be somewhat less reliable than the manipulator arm design.	Positioning system quickly converts from transport configuration to sealing configuration
MODULAR CONSTRUCTION - This system could sufficiently meet the design criteria.		Positioning system can be expanded in a modular fashion.
STABILITY AND RUGGEDNESS - This system could meet the design criteria.		Positioning system frame width during transport is under 8 feet.
COST - This system could probably be developed within the project budget.		Positioning system frame is a "stand-alone" trailer which is pulled by the support truck.

Table 6.1 - Positioning System Concept Design Comparisons (page 1 of 3)

POSITIONING SYSTEM CONCEPT DESIGN COMPARISONS
(continued)

ADVANTAGES	*DISADVANTAGES*	SIGNIFICANT DESIGN FEATURES
TRUCK-MOUNTED WING-FOLD CARTESIAN DESIGN (see Figure 6.3)		
STABILITY AND RUGGEDNESS - This system could meet the design criteria.	CAPACITY AND CAPABILITIES - Maneuverability of applicator assemblies may be difficult since the positioning system frame folds in two places (for transport). This creates some serious design difficulties and complications.	Applicator assemblies move linearly in horizontal plane with limited motion in vertical plane. Applicator assemblies rotate 360 degrees about vertical axis.
CONFIGURATION CONVERSION - This system could easily convert between the high speed road travel configuration and the crack sealing configuration.	COMMERCIALLY AVAILABLE EQUIPMENT - This system would require considerably more custom manufacturing than the proposed manipulator arm design.	Positioning system folds up around back of support truck bed during transport
COST - This system could probably be developed within the project budget.	MODULAR CONSTRUCTION - It could be difficult to expand this positioning system (beyond 4-6 applicator assemblies) if the need arises.	Positioning system cannot be easily expanded (beyond 4-6 applicator assemblies) in a modular fashion.
	EQUIPMENT MAINTENANCE AND RELIABILITY - This design is more mechanically complicated and involves more custom manufacturing than the manipulator arm design. This design may require more maintenance and may be somewhat less reliable than the manipulator arm design.	Positioning system frame width during transport is under 8 feet.
		Positioning system frame is integrated into the support truck frame.
TRUCK-MOUNTED SWING-FRAME CARTESIAN DESIGN (see Figure 6.4)		
CAPACITY AND CAPABILITIES - This system probably could be designed to sufficiently meet the design criteria.	COMMERCIALLY AVAILABLE EQUIPMENT - This system would require considerably more custom manufacturing than the proposed manipulator arm design.	Applicator assemblies move linearly in horizontal plane with limited motion in vertical plane. Applicator assemblies rotate 360 degrees about vertical axis.
STABILITY AND RUGGEDNESS - This system could meet the design criteria.	MODULAR CONSTRUCTION - It could be difficult to expand this positioning system (beyond 4-6 applicator assemblies) if the need arises.	Positioning system folds up vertically and is positioned along the side of the support truck during transport. Frame supports its own weight during transport.
CONFIGURATION CONVERSION - This system could easily convert between the high speed road travel configuration and the crack sealing configuration.	EQUIPMENT MAINTENANCE AND RELIABILITY - This design is more mechanically complicated and involves more custom manufacturing than the manipulator arm design. This design may require more maintenance and may be somewhat less reliable than the manipulator arm design.	Positioning system cannot be easily expanded (beyond 4-6 applicator assemblies) in a modular fashion.
COST - This system could probably be developed within the project budget.		Positioning system frame width + truck width during transport is under 8 feet.
		Positioning system frame is integrated into the support truck frame.

Table 6.1 - Positioning System Concept Design Comparisons (page 2 of 3)

POSITIONING SYSTEM CONCEPT DESIGN COMPARISONS (continued)		
ADVANTAGES	*DISADVANTAGES*	SIGNIFICANT DESIGN FEATURES
TRUCK-MOUNTED MANIPULATOR ARM DESIGN (see Figure 6.5)		
CAPACITY AND CAPABILITIES - This system probably could be designed to sufficiently meet the design criteria.		Applicator assemblies (end effectors) move freely in horizontal plane (during sealing operation). End effector is supported (and floats) vertically by resting on carriage wheels which roll on the pavement surface. End effectors rotate 360 degrees about vertical axis (with respect to road surface).
STABILITY AND RUGGEDNESS - This system very likely could meet the design criteria.		Manipulator arms move horizontally on linear slides across the back of the truck. This feature allows arms to be shorter and still service the required work space.
COMMERCIALLY AVAILABLE EQUIPMENT - This system would require less custom manufacturing than the proposed Cartesian type, gantry style positioning systems.		One manipulator performs routing operations. The other manipulator performs cleaning and sealing operations.
MODULAR CONSTRUCTION - This system could sufficiently meet the design criteria.		Positioning system folds up along back of truck during transport.
CONFIGURATION CONVERSION - This system could easily convert between the high speed road travel configuration and the crack sealing configuration.		Positioning system could be easily expanded modularly by adding a supporting frame (for additional manipulators) behind the truck.
EQUIPMENT MAINTENANCE AND RELIABILITY - This design is mechanically simpler than any of the proposed Cartesian type, gantry style systems. All known maintenance and reliability problems can be overcome satisfactorily using existing technology. This system can meet the design criteria.		Positioning system frame width during transport is under 8 feet.
COST - This system could probably be developed within the project budget.		Positioning system frame is integrated into the support truck frame.

Table 6.1 - Positioning System Concept Design Comparisons (page 3 of 3)

6.4 - Conclusion

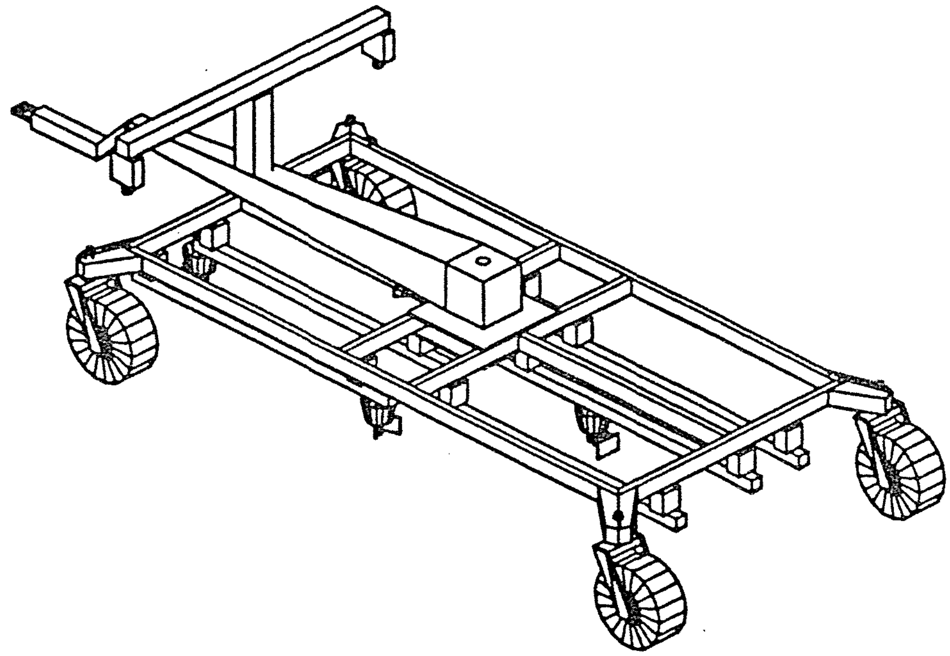
Based on the design criteria, ideas, discussion gathered using the functional synthesis and brainstorming methods, it was decided among the project team that the Truck-Mounted Manipulator Arm Design (Fig. 6.5) best meets the requirements of this project. This design concept should meet all of the basic design criteria and it should present the best chance for overall success of the project.

The end effectors (applicator assemblies) are supported vertically by resting on the road surface. This significantly reduces the joint stresses on the manipulator arms and allows for more precise control of the end effectors. Additionally, since the manipulator arms are mounted on linear slides across the back of the truck, the work space of the end effectors is expanded while reducing the length and mass of the arms. This provides for faster and more controlled manipulation of the end effector. The end effectors should have full range of motion both laterally and rotationally (about a vertical axis).

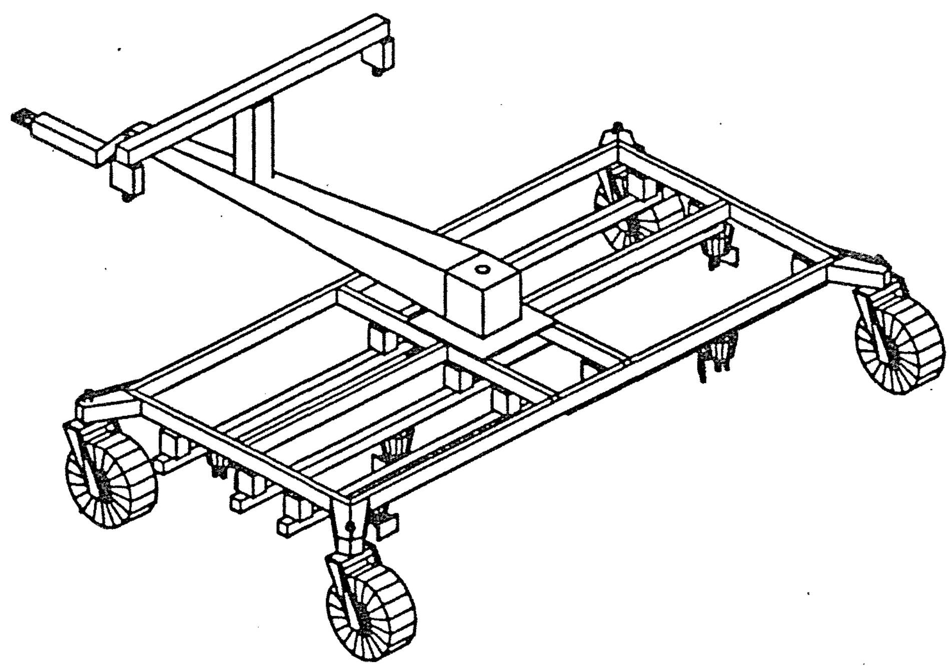
This design is compact in that the entire machine is contained on one vehicle. The positioning system (manipulator arms) will fold up quickly and neatly along the back of the truck (when converting from sealing mode to high speed transport mode) permitting the vehicle to be within the legal width limit for normal road travel.

Since this system uses considerable amounts of commercially available equipment and doesn't require an elaborate framework for attachment of the manipulator arms (in the case of one or two arms), it should require less custom manufacturing than the other proposed designs. In addition, it will be mechanically simpler and should consequently be easier to maintain. Modularity of the positioning system can also be achieved by providing a framework at the rear of the truck to which additional manipulator arms could be attached.

The particular combination of attributes that this truck-mounted manipulator arm design possess should result in a very versatile, controllable, and efficient machine.



Transport Configuration



Crack Sealing Configuration

Figure 6.1 - Swing-Hitch Cartesian Design

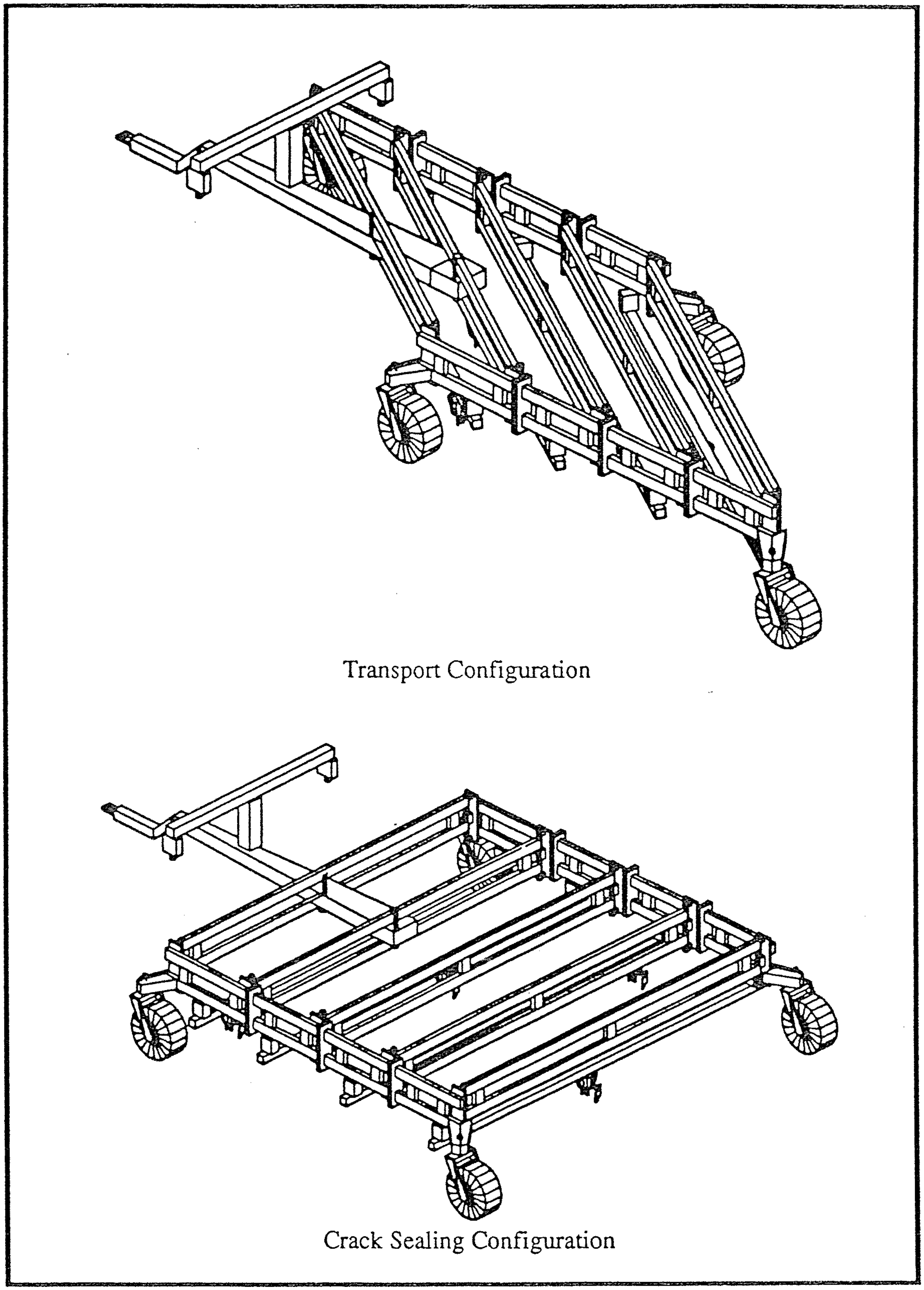
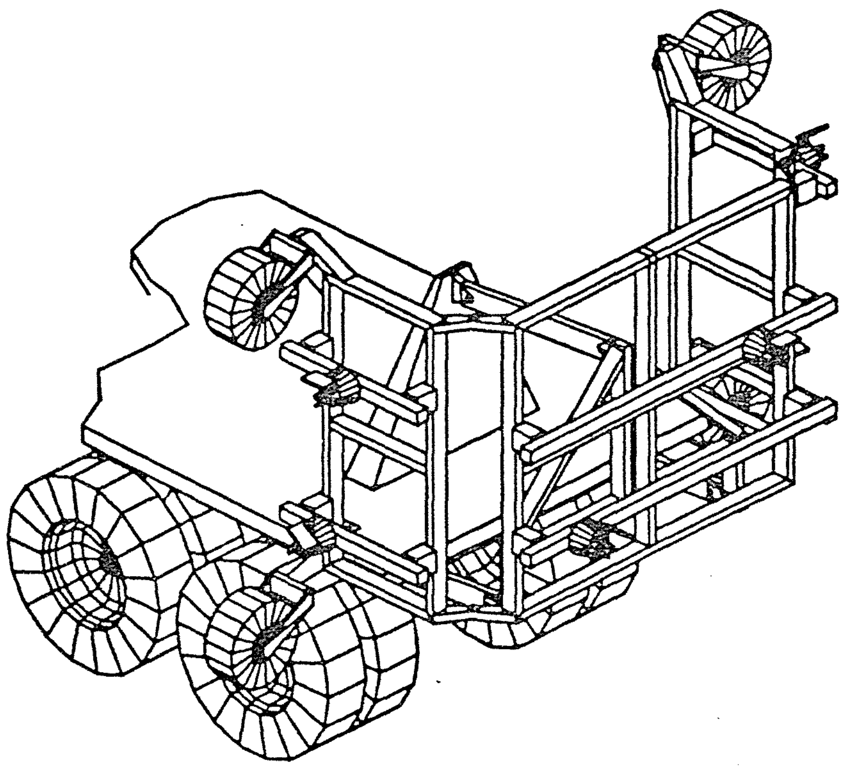
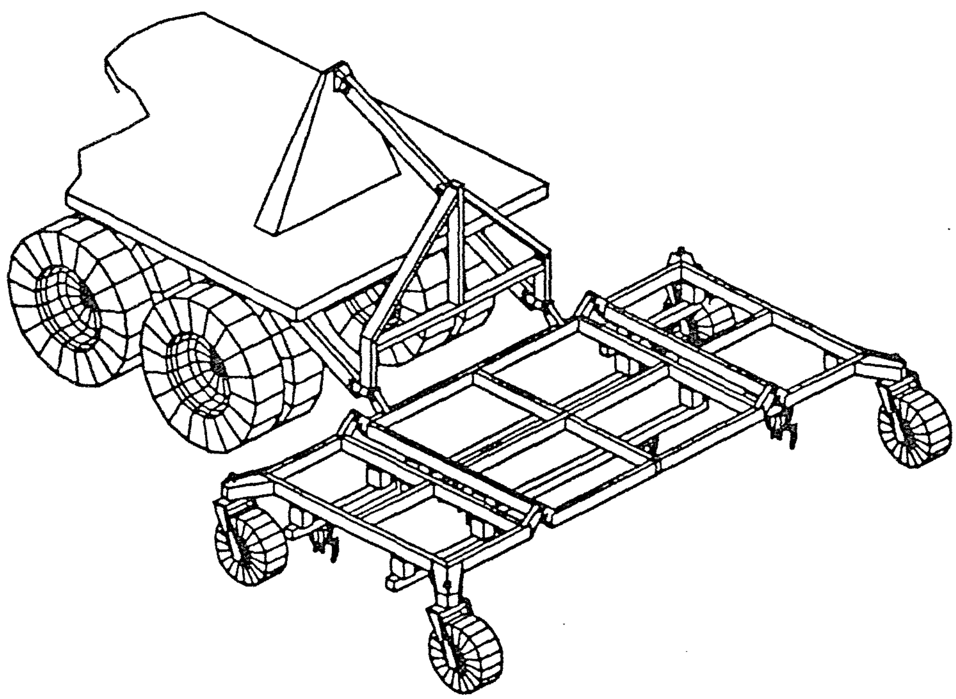


Figure 6.2 - Modular Transverse Cartesian Design



Transport Configuration



Crack Sealing Configuration

Figure 6.3 - Truck-Mounted Wing-Fold Cartesian Design

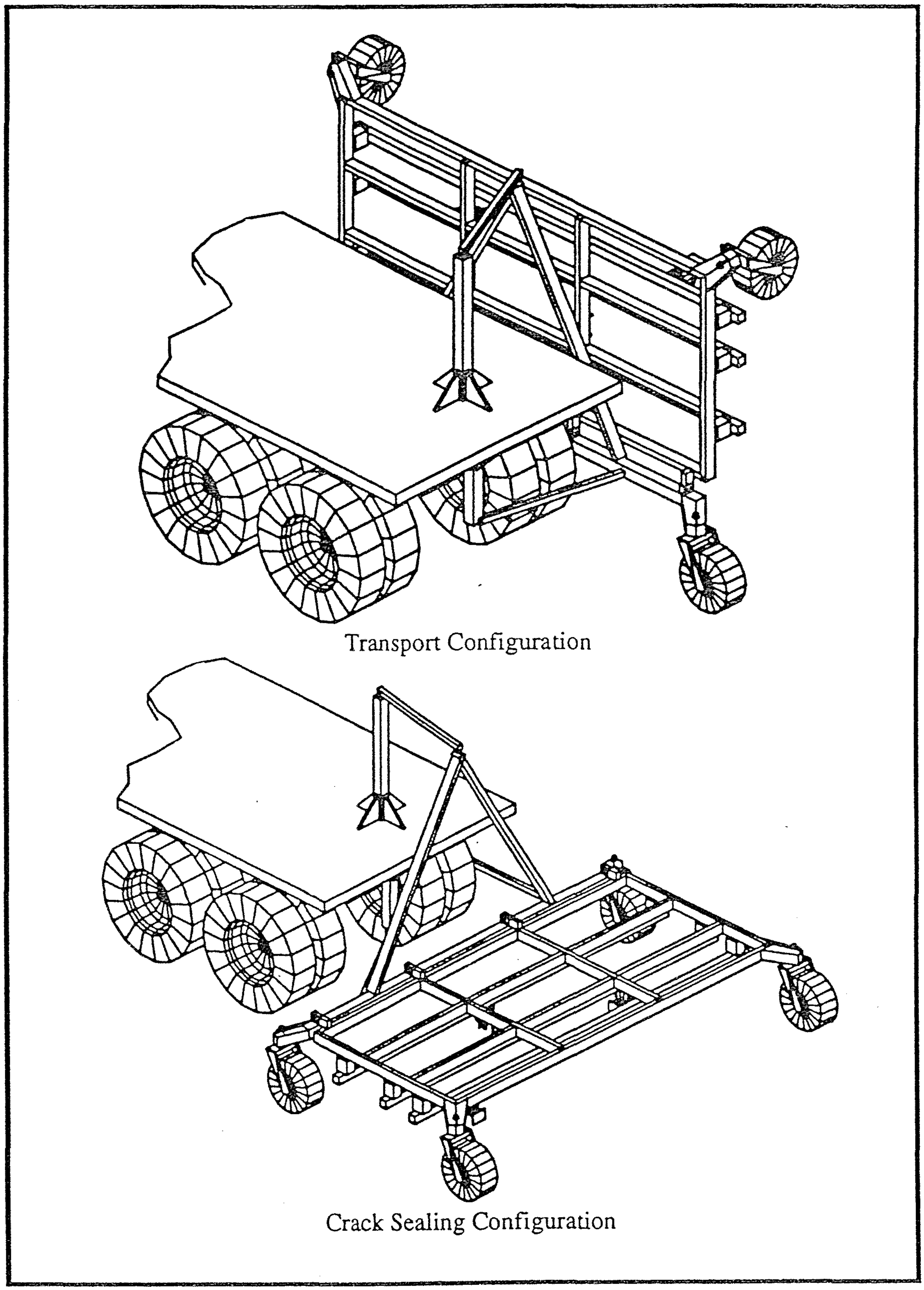
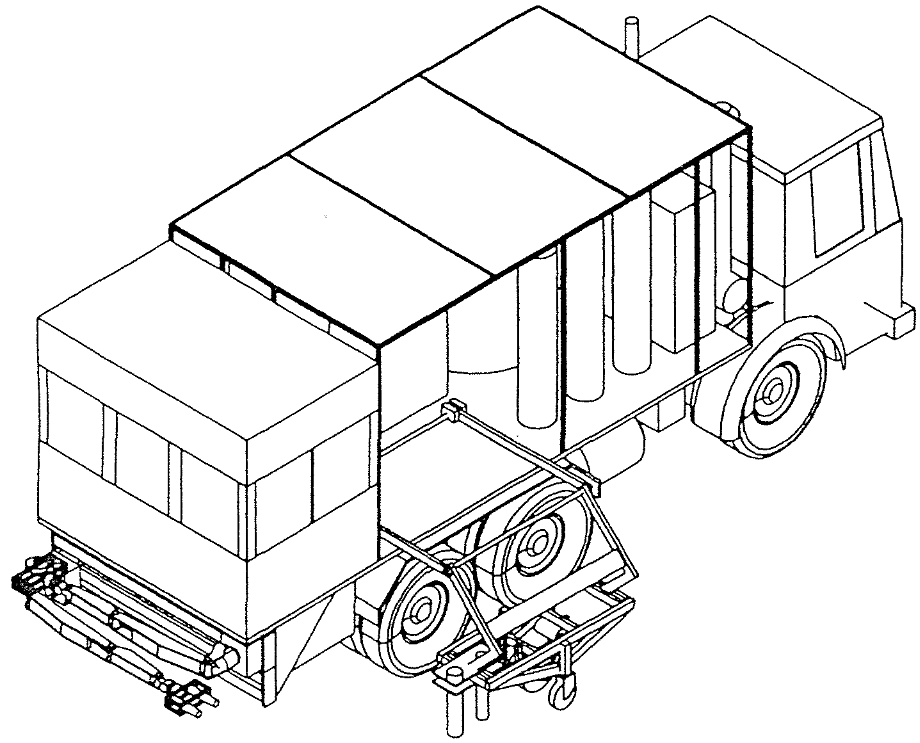
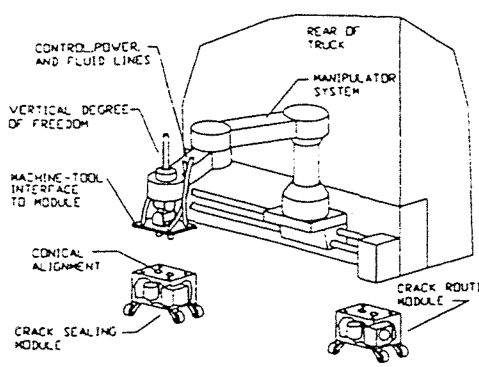


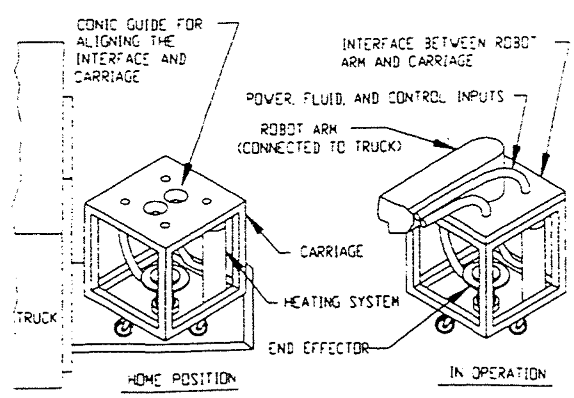
Figure 6.4 - Truck-Mounted Swing-Frame Cartesian Design



Integrated Machine Concept
(General Sealing Components Stowed - Longitudinal Sealing Components Operational)



Detail of Manipulator Arm
on Rear of Truck



Detail of End Effector
and Tool Guide

Figure 6.5 - Truck-Mounted Manipulator Arm Design

CHAPTER 7

MAJOR CONCLUSIONS AND RECOMMENDATIONS

7.1 - Cleaning Method Selection

First of all, it was necessary to determine the best and most practical method(s) for cleaning the road surface and cracks. A literature review was conducted on this subject and considerable information was gathered on seven basic potential cleaning methods. However, the published literature was not adequate to form educated assessments of the compressed air jet method, the sandblast method, or the abrasive vacuum blast method. Because of this it was necessary to conduct additional feasibility experiments for these three cleaning methods.

The compressed air jet experiment was necessary to gain a better understanding of the effectiveness of and the conditions for using compressed air jets to clean road surfaces. The data of this experiment was achieved through a series of laboratory tests and field tests. Data was obtained to develop technical specifications for the implementation of compressed air jets nozzles on the prototype automated crack sealing machine. This data was used to compare the compressed air jet cleaning method to the other cleaning methods. In addition, the data will be used to develop technical specifications pertaining to such machine subsystems as the positioning system, applicator assemblies, global vision system, local sensing system, and air compressor requirements if this cleaning method is needed in the future.

A list of major conclusions drawn from this experiment follows:

- It is not possible to remove a significant amount of "dirt film" from the sides of the cracks with an air jet. Therefore, if dirt film removal necessary, another cleaning method is required.
- The air jet was unsuccessful in removing weeds from cracks unless the plant roots were dead. Therefore, if vegetation removal is necessary, another method is required.
- Observing the results of cleaning actual road surface cracks, it is concluded that a compressed air jet should satisfactorily remove all sizes of *loose* debris from cracks at speeds of approximately 0 - 5 mph. 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. this information will be useful for determining the overall speed of the applicator assemblies with respect to the road surface.
- Nozzle eccentricities greater than approximately 1/2" clean the crack relatively poorly as compared with eccentricities less than approximately 1/2". This phenomenon may be a function of the crack width. Therefore, it may be useful to perform additional tests on cracks of smaller width to determine if a 1/2" nozzle eccentricity is acceptable for cleaning all sizes of road cracks. This information will be useful for developing specifications for the positioning system and applicator assemblies as well as requirements for the vision system and local sensing system.
- For optimum air jet performance, it is preferable for the nozzle direction of travel to be aligned with the crack direction of travel (i.e. crack approach angle = 0 degrees). Therefore, it is recommended that the air jet direction of travel be continuously aligned with the crack direction of travel during the cleaning procedure. This finding indicates that an

"array" type crack sealing machine would probably not be a viable design since this design would require that the crack approach angle vary from 0-90 degrees.

- Air pressures of approximately 65-80 PSI and air flow rates of approximately 60-90 CFM seem to be adequate for cleaning most road cracks.

The sandblast and abrasive vacuum blast experiments were necessary to gain a better qualitative understanding of the effectiveness of using these methods to clean road surfaces. The sandblast method was found to be extremely effective for removing all types of vegetation, loose debris, and dirt film from road surfaces. The abrasive vacuum blast method was found to be somewhat less effective while consuming considerable more power (mostly for the vacuuming operation). It was also found to be considerably slower than sandblasting. In addition, it was observed that the vacuum blast head used for the experiment could probably have been more optimally designed. Design improvements could include blast nozzle adjustments for changing the nozzle orientation with respect to the road surface and the nozzle distance from the road surface. Adjustments such as these may have had a great effect on producing considerably better results when testing the sand blasting machine. Furthermore, a more effective vacuum recovery system could be devised such that power requirements would be reduced and vegetation debris could be vacuumed more efficiently (i.e. without becoming lodged in the vacuum recovery head). If these design changes were to be implemented, it is concluded that the effectiveness, speed, and efficiency of the vacuum blasting operation could be considerably improved.

From a safety standpoint, the vacuum blaster was found to be much superior to the sand blaster. Primarily, this is due to the fact that the sand blaster does not contain the blast media or debris while the vacuum blaster contains both the blast media and debris.

The flying debris is a safety hazard to spectators both because of the physical impact of the debris on persons and the health problems associated with the airborne dust.

The recycling capability of the abrasive vacuum blasting machine is a substantial advantage of this system over a conventional sandblast unit. By recovering the blast media and debris, the road surface and work environment is left clean. In addition, the fact that most of the blast media can be reused amounts to great cost savings in terms of reduced blast media cost, reduced costs logistically to constantly supply the blast system (especially in remote locations), and reduced debris disposal costs.

From the review of published literature and additional feasibility experiments that were conducted, it was concluded that abrasive vacuum blasting has the potential of producing the best results. However, considerable development would be required to make this method commercially feasible for the crack sealing machine prototype. It was decided among the project team that a centrifugal blower/vacuum system will do a satisfactory job of removing most loose debris from the road surface and cracks if controlled properly. It is recommended that this system be employed on the prototype crack sealing machine. Should this system prove to be ineffective, a compressed air jet(s) could be easily implemented. These methods will not be effective in removing *all* loose debris or any live vegetation or dirt film. However, they can be easily implemented within the time frame and budget constraints of this project, they present the least development effort, and should be accepted by the majority of users. Furthermore, the use of the air blower method will be sufficient to demonstrate the main objectives of this project. Additionally, it is recommended that the prototype machine be designed in such a way that more effective cleaning methods (e.g. abrasive vacuum blasting) can be incorporated in the future.

7.2 - Positioning System configuration Selection

The next major objective of this project was to determine the best positioning system configuration to accommodate the crack detection, cleaning, preparation, and sealing operations. Based on the inherent advantages and disadvantages of both the array and the crack following configurations, it was decided among the project team that the crack following configuration best meets the requirements of this project. This configuration is considerably more complex than the array configuration in terms of mechanical design, computing requirements, sensing and control, and in nearly every other aspect of the design. However, the crack following configuration allows for the capability to rout the cracks and clean them more effectively. Furthermore, variation of the seal configuration is possible and the crack heating system can be implemented more easily and efficiently. The array configuration is considerably simpler in terms of development and operation. However, this configuration presents too many major potential design limitations and difficulties and thus it would involve much greater risk in terms of project success. The crack following configuration will provide the best seal quality with the best chance for overall success of the project. Therefore, it is recommended that the prototype positioning system be designed as some type of crack following configuration.

7.3 - Positioning System Concept Design Selection

The last objective of this project was to determine the positioning system concept design, based on the chosen positioning system configuration, that will best perform the entire crack sealing operation. Based on the design criteria, ideas, discussion gathered using the functional synthesis and brainstorming methods, it was decided among the project team that the Truck-Mounted Manipulator Arm Design (Fig. 6.5) best meets the conceptual design requirements for the positioning system. This design concept should meet all of the basic design criteria and have the present the best chance for overall success of the project.

The end effectors (applicator assemblies) are supported vertically by resting on the road surface. This significantly reduces the joint stresses on the manipulator arms and allows for more precise control of the end effectors. Additionally, since the manipulator arms are mounted on linear slides across the back of the truck, the work space of the end effectors is expanded while reducing the length and mass of the arms. This provides for faster and more controlled manipulation of the end effector. The end effectors should have full range of motion both laterally and rotationally (about a vertical axis).

This design is compact in that the entire machine is contained on one vehicle. The positioning system (manipulator arms) will fold up quickly and neatly along the back of the truck (when converting from sealing mode to high speed transport mode) permitting the vehicle to be within the legal width limit for normal road travel.

Since this system uses considerable amounts of commercially available equipment and doesn't require an elaborate framework for attachment of the manipulator arms (in the case of one or two arms), it should require less custom manufacturing than the other proposed designs. In addition, it will be mechanically simpler and should consequently be easier to maintain. Modularity of the positioning system can also be achieved by providing a framework at the rear of the truck to which additional manipulator arms could be attached.

The particular combination of attributes that this truck-mounted manipulator arm design possess should result in a very versatile, controllable, and efficient machine. Therefore, it is the final recommendation of this report that the prototype crack following positioning system be designed around the basic concept of a Truck-Mounted Manipulator Arm Design such as is shown in Fig. 6.5.

APPENDIX A

ROADWAY CRACK DEBRIS REMOVAL

USING A HIGH PRESSURE AIR JET

A.1 - Equipment And Materials Required

The following is a detailed list of equipment and materials necessary to conduct this experiment:

- variable velocity testing machine (VVTM) "whirlybird machine" (for producing relative velocity between the air jet and the pavement specimen)
- air compressor (Sullair, 185 CFM compressor, John Deere Engine serial # CD 4239 D 761767, 4239 DF, unit #D4 BB 761767 was used.)
- air hose (3, 3/4" x 50' hoses were used.)
- "live" swivel (for connection between the stationary 3/4" air hose (attached to the compressor) and the rotating air hose (on the VVTM))
- air nozzle ("ACB SupAir Knife", model X-1, 125 CFM)
- nozzle orientation adjustment bracket (for adjusting nozzle eccentricity, nozzle angle of incidence, and nozzle approach angle)
- test specimen table, saw horses, and nozzle guide (for supporting the test specimen and guiding the air nozzle)
- representative (cracked) pavement specimen (10" diameter pavement core samples were used.)
- representative debris material (refer to Section 2.5 - Debris Material)
- "SupAir Knife" air flow meter

- video camera (with remote control so camera can be turned on/off while operator is outside of the VVTM protective fence) (with relatively fast shutter speed for slow motion shots)
- camera tripod
- 35mm camera
- light, if necessary (for illuminating the local test specimen area during video taping and photographing)
- whisk broom and/or low pressure air nozzle and hose (for removing unwanted debris material from the test specimen and the surrounding table)
- other necessary tools for adjusting the equipment

A.2 - Experiment Setup

An illustration of the experiment setup is shown in Chapter 2, Fig. 2.3. The actual test setup is depicted in Chapter 2, Photos 2.1 - 2.4. A detailed procedure for setting up the basic experiment follows:

1. Mount nozzle orientation adjustment bracket and nozzle on VVTM rotor tip.
2. Mount air nozzle counter weight on opposite rotor tip.
3. Set up air compressor.
4. Secure "live" swivel to top of VVTM center shaft.
5. Connect one end of a 50' air hose to the air nozzle at the rotor tip and the other end to the "live" swivel at the VVTM center shaft. Then secure sir hose to VVTM using tape or "quick tie" straps.

6. Connect the remaining two, 50' air hoses together. Attach one end of the hose to the air compressor. Use suitable means to extend the other end of the hose over the VVTM machine to the VVTM center shaft (A nearby tree was used in this experiment.). Attach the extended hose to the "live" swivel located at the VVTM center shaft.
7. Construct test specimen stand and air nozzle guide and locate in correct position at the nozzle tip.
8. Set up video camera on tripod and locate in position so as to get a good view of the surface and crack of the test specimen.
9. Set up VVTM controller and connect the proper power cables to electrical power source and the VVTM.

A.3 - Part One - Air Flow Rate Calibration Test

The purpose of the air flow rate calibration test is to obtain sufficient data to produce performance curves of nozzle air pressure vs. air hose length and air flow rate vs. air hose length for the air compressor and hose used in these experiments. Four nozzle sizes (N1, N2, N3, and N4) were used for the test. An Illustration of the nozzle shapes and overall dimensions are shown in Chapter 2, Fig. 2.4. Five air hose lengths (hose length = 0, 50', 100', 150', and 200') were used for the test. For hose length = 0, the flow meter was attached directly to the output valve on the air compressor. The compressor was then loaded to full capacity and air pressure and air flow rate were recorded. A similar procedure was followed for all combinations of nozzles and hose lengths. A summary of the test data is shown below in Table A.1. A plot of air pressure vs. hose length, for each of the nozzles, is shown in Chapter 2, Fig. 2.5. A plot of air flow rate vs. hose length, for each of the nozzles, is shown in Chapter 2, Fig. 2.6.

COMPRESSOR AIR PRESSURE AND AIR FLOW RATE TEST FOR NOZZLES N1, N2, N3, AND N4 FOR HOSE LENGTHS 0 - 200 FEET				
COMPRESSOR OUTPUT PRESSURE = 100 PSI AIR FLOW RATE VARIES LINEARLY WITH CHANGES IN COMPRESSOR OUTPUT PRESSURE AIR COMPRESSOR SPECIFICATION - "SULLAIR" 185Q (185 CFM) AIR HOSE SPECIFICATION - "HORIZON BY GOODYEAR", 3/4" DIA., 250 PSI W.P. 14092				
HOSE LENGTH = 0 FEET				
	Nozzle N1	Nozzle N2	Nozzle N3	Nozzle N4
Nozzle Pressure (PSI)	90	90	84	74
Nozzle Air Flow Rate (CFM)	52	106	150	180
HOSE LENGTH = 50 FEET				
	Nozzle N1	Nozzle N2	Nozzle N3	Nozzle N4
Nozzle Pressure (PSI)	92	84	72	62
Nozzle Air Flow Rate (CFM)	53	99	133	154
HOSE LENGTH = 100 FEET				
	Nozzle N1	Nozzle N2	Nozzle N3	Nozzle N4
Nozzle Pressure (PSI	90	79	65	54
Nozzle Air Flow Rate (CFM)	53	93	120	137
HOSE LENGTH = 150 FEET				
	Nozzle N1	Nozzle N2	Nozzle N3	Nozzle N4
Nozzle Pressure (PSI	90	74	60	48
Nozzle Air Flow Rate (CFM)	52	90	112	130
HOSE LENGTH = 200 FEET				
	Nozzle N1	Nozzle N2	Nozzle N3	Nozzle N4
Nozzle Pressure (PSI	88	70	55	42
Nozzle Air Flow Rate (CFM)	50	85	105	116

Table A.1 - Compressor Air Pressure and Air Flow Rate Test Data

A.4 - Part Two - Nozzle Eccentricity Test

Basic Test Description

This test simulated the use of an air jet for cleaning cracks in which the nozzle direction of travel was the same as the crack direction of travel (i.e. crack approach angle = 0 degrees). Data was obtained for many combinations of nozzle approach angles, angles of incidence, eccentricities, speeds, and air pressures. This data is especially applicable to the development of a machine for sealing "longitudinal" road surface cracks. Refer to Chapter 2, Photos 2.5 - 2.10 for typical results of this test. Orientation parameters for the air nozzle are provided in Chapter 2, Fig. 2.1. A detailed general procedure for this test is provided below.

NOTE: The debris material for all tests consisted of thoroughly mixed, equal volume amounts of small, medium, and large debris. During preliminary tests, it was observed that the amount of each size of debris material removed by the air jet was not significantly dependant on the size of the debris material (for the particular sizes of small, medium, and large debris selected for this experiment). Therefore, in all subsequent tests, no attempt was made to separate the debris into its respective sizes (following a particular test) for the purpose of recording the respective amounts of small, medium, and large debris removed by the air jet during that test.

NOTE: Several preliminary tests were conducted to determine the effect of debris moisture content on the ability to remove debris from cracks (No data is available for these tests.). During these tests, it was observed that there were not measurable differences in the ability of the air jet to remove debris from the test crack. This observation could in part be due to the fact that only "sand" debris was used for this experiment. Because of this, the debris did not "cake together" as it probably would have if a dirt and sand debris mixture was used. In the interest of time, a debris mixture of dirt and sand was not investigated.

General Test Procedure

1. Rotate crack test specimen to crack approach angle = 0 degrees.
2. Set nozzle approach angle and nozzle angle of incidence to the specified settings.
3. Adjust nozzle eccentricity to correct setting.
4. Adjust nozzle air pressure to correct setting.
5. Fill crack test specimen with debris in accordance with crack filling procedure.
6. Turn on video camera.
7. Start air nozzle motion (start VVTM).
8. When air nozzle reaches correct speed, turn on air to air nozzle.
9. Pass air nozzle over test specimen.
10. Immediately following step 9, turn off air to nozzle.
11. Stop air nozzle motion (stop VVTM).
12. Turn off video camera.
13. Measure and record depth of debris removed from crack in test specimen.
14. Take photograph of test specimen for future reference.
15. Repeat steps 5-14 for all nozzle speeds.
16. Repeat steps 4-15 for all nozzle air pressures.
17. Repeat steps 3-16 for all nozzle eccentricities.
18. Repeat steps 2-17 for all nozzle approach angles and nozzle angles of incidence.

A.4.1 - Part Two (A) - Nozzle Approach Angle Variations

In an effort to reduce that amount of data to be taken, a small test was conducted to determine whether variations in nozzle approach angle had a significant effect on the amount of debris removed from the crack. Nozzle settings for this test were as follows.

- crack approach angle = 0 degrees
- nozzle angle of incidence = 0 degrees
- nozzle eccentricity = 0 inches
- nozzle speed = 25 mph

Data was then obtained for all combinations of nozzle approach angles (0, 15, and 30 degrees) and nozzle air pressures (45, 65, and 80 psi). For a summary of the data obtained, refer to Table A.2. For a plot of depth of debris removed from the crack vs. nozzle approach angle, for each nozzle pressure, refer to Chapter 2, Fig. 2.7.

NOZZLE ECCENTRICITY TEST TEST DATA		
Crack Approach Angle = 0 Nozzle Angle of Incidence = 0 Nozzle Eccentricity = 0 inches Nozzle Speed = 25 MPH		
NOZZLE SETTINGS		TEST RESULTS
Nozzle Approach Angle (degrees)	Nozzle Air Pressure (PSI)	Depth of Debris Removed form Crack (inches)
0	45	0.35
0	65	0.54
0	80	0.51
15	45	0.33
15	65	0.46
15	80	0.65
30	45	0.26
30	65	0.50
30	80	0.62

Table A.2 - Nozzle Eccentricity Test Data (Nozzle Speed = 25 MPH)

A.4.2 - Part Two (B) - Subsequent Nozzle Eccentricity Tests

Nozzle settings for this test were as follows.

- crack approach angle = 0 degrees
- nozzle approach angle = 0 degrees
- nozzle angle of incidence = 0 degrees
- nozzle pressure = 80 psi

Data was obtained for all combinations of nozzle eccentricities (0, 1/2", 1", and 1 1/2") and nozzle speeds (2, 5, 10, 15, 20, and 25 mph). For a summary of the data obtained, refer to Table A.3. For a plot of depth of debris removed from the crack vs. nozzle speed, for each nozzle eccentricity, refer to Chapter 2, Fig. 2.8. Chapter 2, Photos 2.5 - 2.10 show the results of tests at nozzle eccentricity variations of 1/2", 1", and 1 1/2" and at speeds of 5 and 10 mph.

NOZZLE ECCENTRICITY TEST TEST DATA		
Crack Approach Angle = 0 Nozzle Angle of Incidence = 0 Nozzle Approach Angle = 0 Nozzle Air Pressure = 80 PSI		
NOZZLE SETTINGS		TEST RESULTS
Nozzle Eccentricity (inches)	Nozzle Speed (MPH)	Depth of Debris Removed From Crack (inches)
0	2	1.20 (clean)
0	5	1.20 (clean)
0	10	.85
0	15	.60
0	20	.56
0	25	.51
0.5	2	1.20 (clean)
0.5	5	1.05
0.5	10	.75
0.5	15	.64
0.5	20	.60
0.5	25	.47
1.0	2	.95
1.0	5	.63
1.0	10	.34
1.0	15	.28
1.0	20	.22
1.0	25	.19
1.5	2	.78
1.5	5	.51
1.5	10	.26
1.5	15	.26
1.5	20	.20
1.5	25	.16

Table A.3 - Nozzle Eccentricity Test Data (Nozzle Air Pressure = 80 PSI)

A.5 - Part Three - General Crack Test

Basic Test Description and Purpose

With the crack approach angle set at 90 degrees, many tests are run for various combinations of nozzle approach angles, incidence angles, speeds, and air pressures. The purpose of this test is to evaluate the feasibility of an "array" type crack sealing machine. More generally, the purpose of this test is to evaluate the performance of an air jet in cases where the jet must cross the crack at a 90 degree angle (i.e. crack approach angle = 90 degrees). Refer to Chapter 2, Fig. 2.1. for an illustration of the air nozzle orientation parameters for the general crack test. Refer to Chapter 2, Photo 2.11 for a typical result of this test. A detailed general procedure for this test is provided below.

General Test Procedure

1. Rotate crack test specimen to crack approach angle = 90 degrees.
2. Adjust nozzle eccentricity to 0 inches.
3. Set nozzle approach angle and nozzle angle of incidence to the specified settings.
4. Adjust nozzle air pressure to correct setting.
5. Fill crack test specimen with debris in accordance with crack filling procedure.
6. Turn on video camera.
7. Start air nozzle motion (start VVTM).
8. When air nozzle reaches correct speed, turn on air to air nozzle.
9. Pass air nozzle over test specimen.
10. Immediately following step 9, turn off air to nozzle.
11. Stop air nozzle motion (stop VVTM).
12. Turn off video camera.

13. Measure and record amount of debris removed from crack in test specimen.
14. Take photograph of test specimen for future reference.
15. Repeat steps 5-14 for all nozzle speeds.
16. Repeat steps 4-15 for all nozzle air pressures.
17. Repeat steps 3-16 for all nozzle approach angles and nozzle angles of incidence.

A.5.1 - Part Three (A) - Variations in Nozzle Air Pressure, Angle of Incidence, and Speed

Nozzle settings for this test were as follows.

- crack approach angle = 90 degrees
- nozzle approach angle = 0 degrees
- nozzle eccentricity - not applicable

Data was obtained for all combinations of nozzle angles of incidence (0, 15, and 30 degrees), nozzle air pressures (45, 65, and 80 psi), and nozzle speeds (2, 5, and 10 mph). For a summary of the data obtained, refer to Table A.4. For plots of debris removal for the various nozzle settings refer to Figures A.1 - A.6.

GENERAL CRACK TEST TEST DATA				
Crack Approach Angle = 90 degrees, Nozzle Approach Angle = 0				
NOZZLE SETTINGS			TEST RESULTS	
Nozzle Air Pressure (PSI)	Nozzle Angle of Incidence (degrees)	Nozzle Speed (MPH)	Depth of Debris Removed from Crack (inches)	Length of Debris Removed from Crack (inches)
45	0	2	1.02	6.00
45	0	5	0.94	5.10
45	0	10	0.59	3.65
45	15	2	* 1.20	6.50
45	15	5	1.02	5.00
45	15	10	0.61	3.29
45	30	2	1.00	5.50
45	30	5	0.90	4.30
45	30	10	0.54	3.50
65	0	2	* 1.20	7.00
65	0	5	0.98	6.00
65	0	10	0.73	3.76
65	15	2	* 1.20	5.55
65	15	5	1.05	5.13
65	15	10	0.70	3.94
65	30	2	1.18	6.00
65	30	5	0.95	5.70
65	30	10	0.55	3.84
80	0	2	1.19	6.25
80	0	5	0.91	5.80
80	0	10	0.62	4.13
80	15	2	* 1.20	5.80
80	15	5	1.02	5.16
80	15	10	0.76	3.87
80	30	2	1.16	** 5.75
80	30	5	0.99	5.50
80	30	10	0.56	4.22
NOTES: * Maximum depth possible (to bottom of crack in test specimen) ** Maximum length possible (to edge of test specimen)				

Table A.4 - General Crack Test Data (Crack Approach Angle = 90 Degrees, Nozzle Approach Angle = 0)

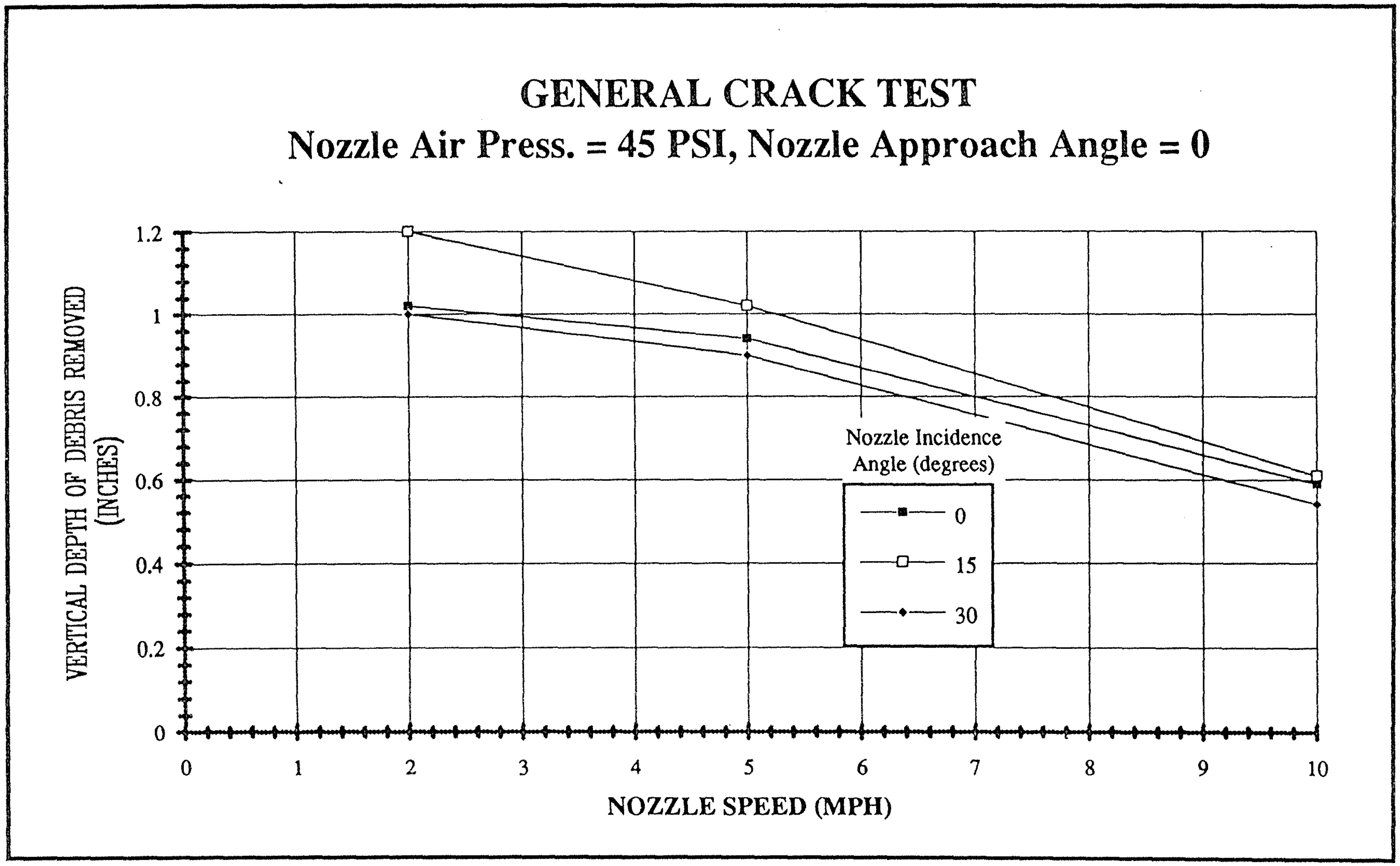


Figure A.1 - General Test - Depth of Debris Removed vs. Nozzle Speed (Nozzle Air Pressure = 45 psi)

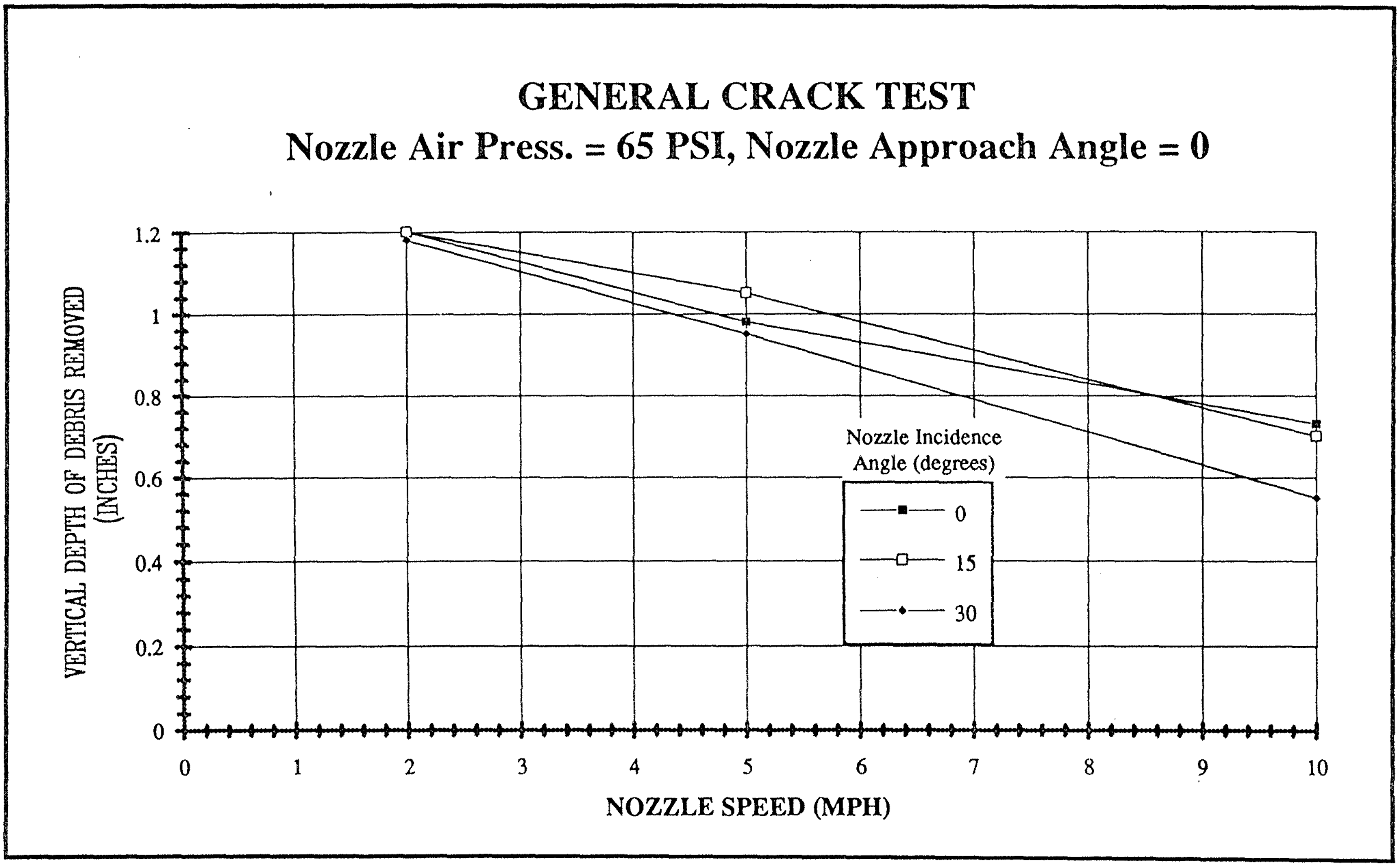


Figure A.2 - General Test - Depth of Debris Removed vs. Nozzle Speed (Nozzle Air Pressure = 65 psi)

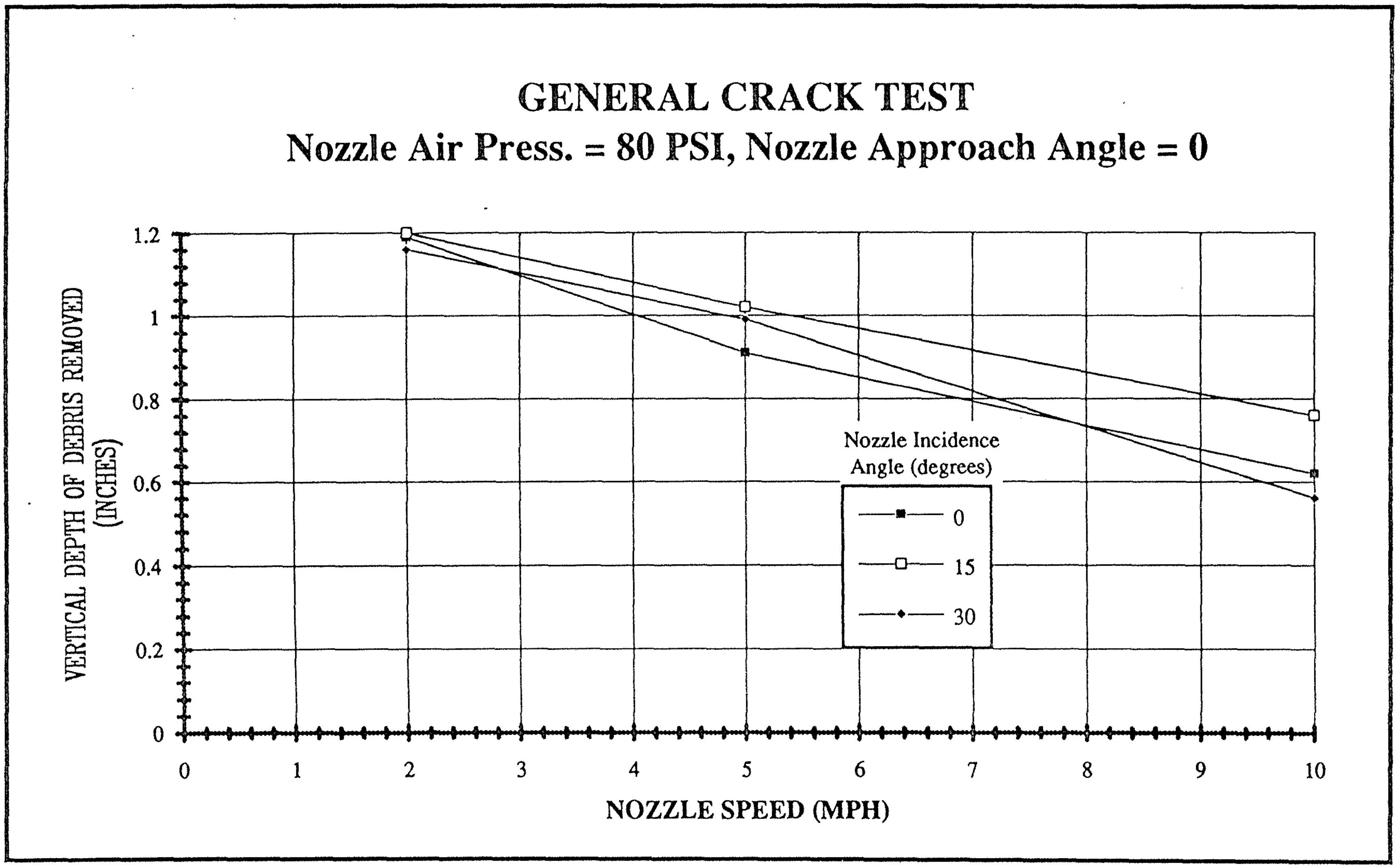


Figure A.3 - General Test - Depth of Debris Removed vs. Nozzle Speed (Nozzle Air Pressure = 80 psi)

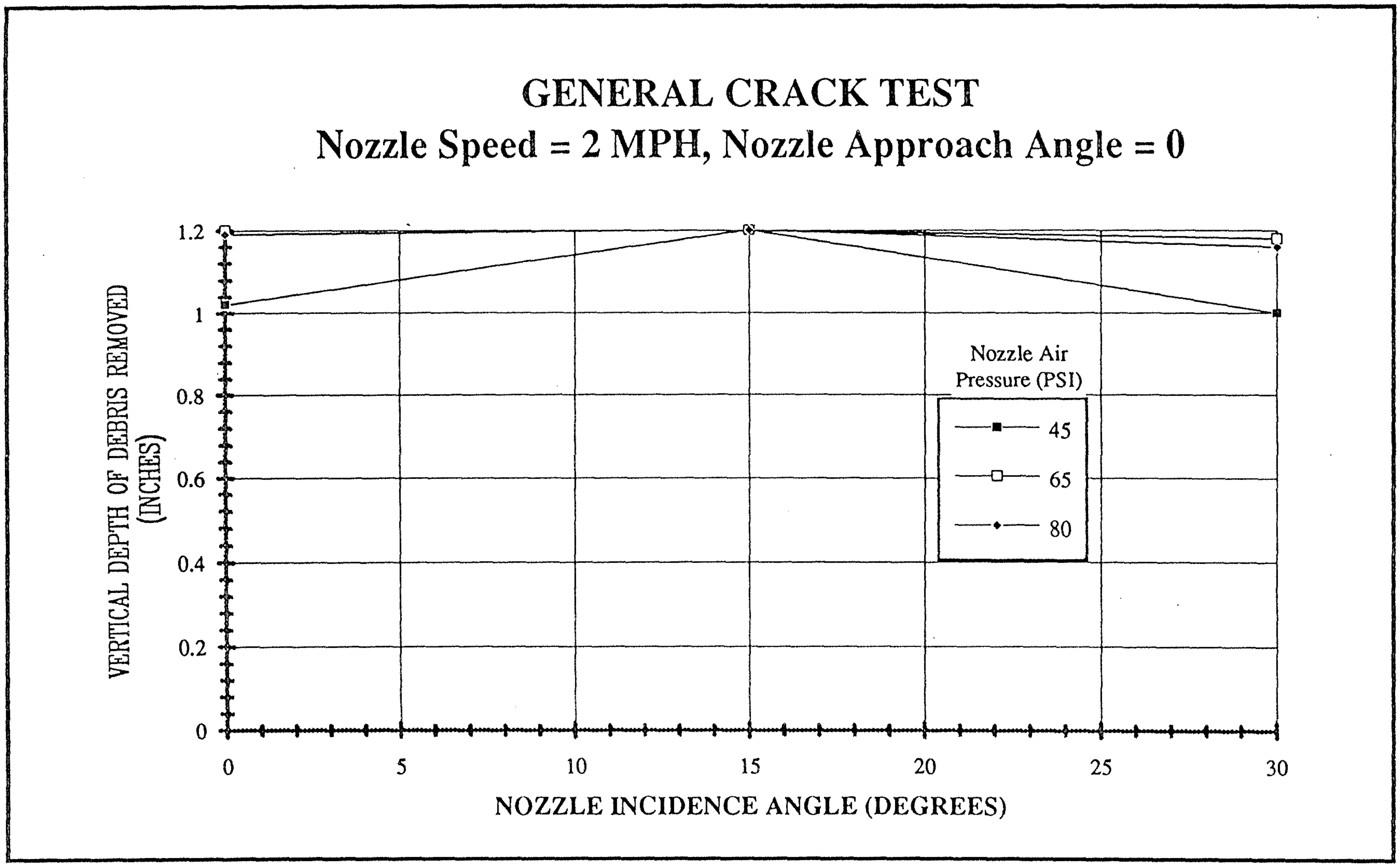


Figure A.4 - General Test - Depth of Debris Removed vs. Nozzle Incidence Angle (Nozzle Speed = 2 mph)

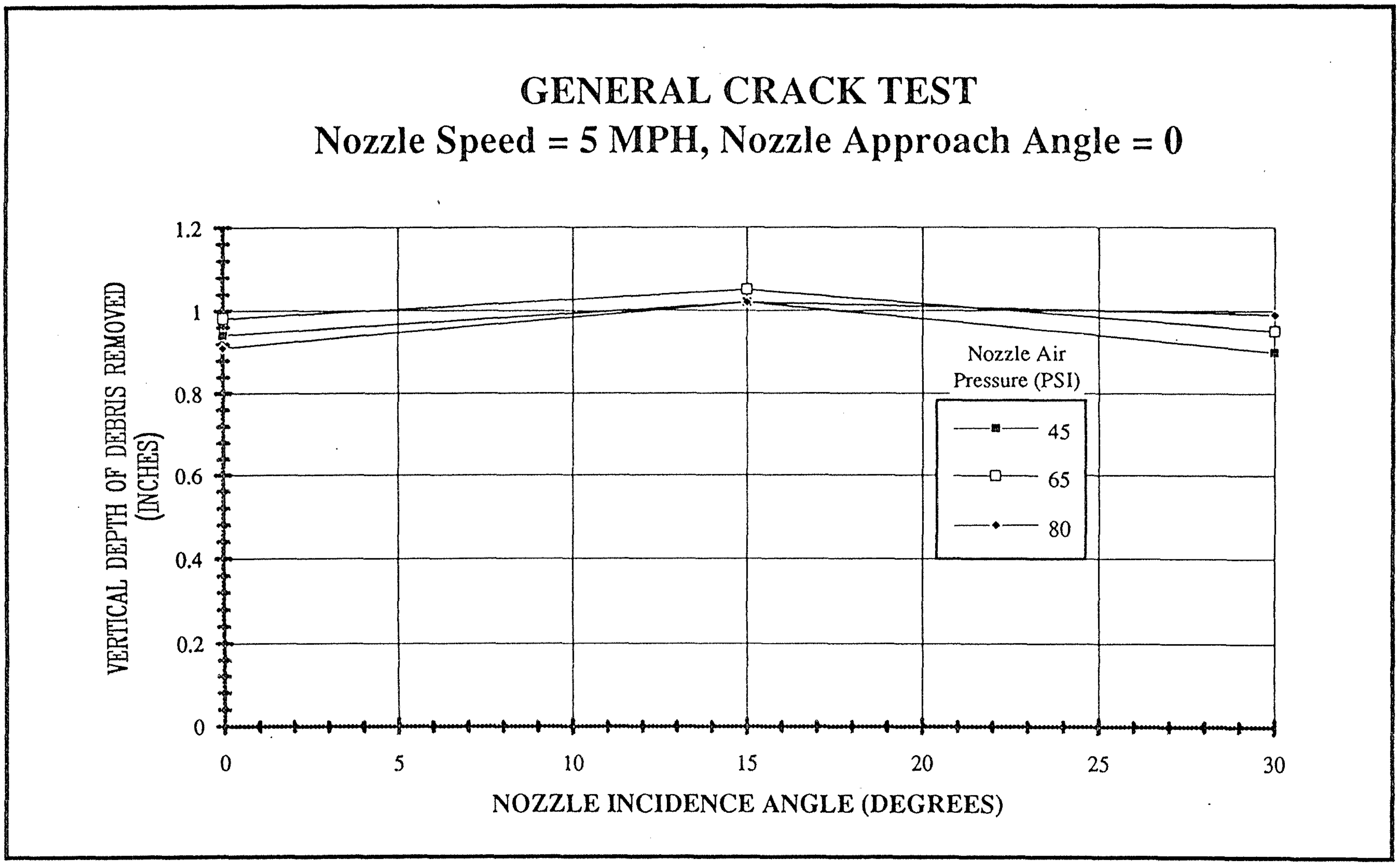


Figure A.5 - General Test - Depth of Debris Removed vs. Nozzle Incidence Angle (Nozzle Speed = 5 mph)

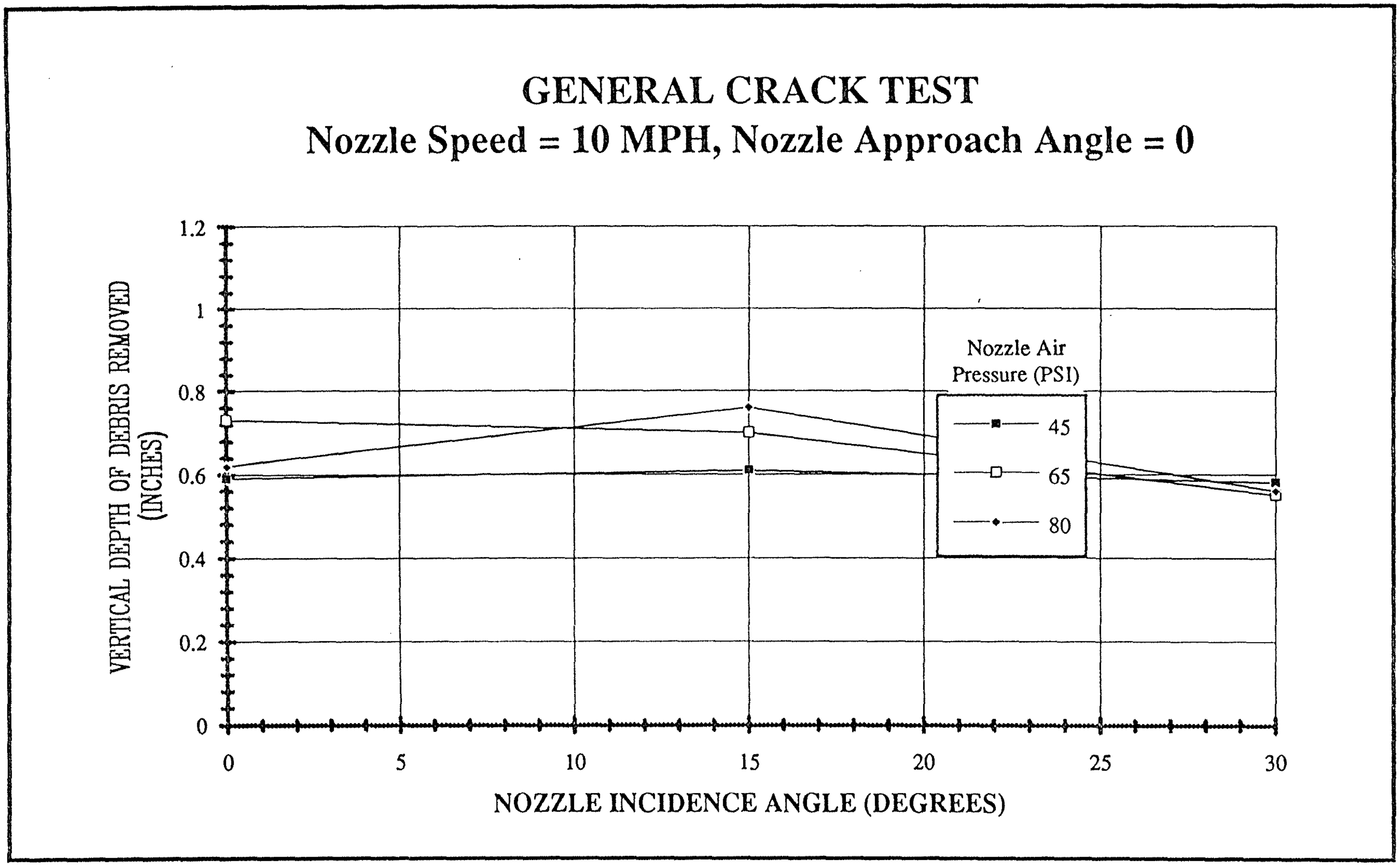


Figure A.6 - General Test - Depth of Debris Removed vs. Nozzle Incidence Angle (Nozzle Speed = 10 mph)

A.5.2 - Part Three (B) - Variations in Nozzle Approach Angle, Angle of Incidence, and Speed

Nozzle settings for this test were as follows.

- crack approach angle = 90 degrees
- nozzle air pressure = 65 psi
- nozzle eccentricity - not applicable

Data was obtained for all combinations of nozzle approach angles (0, 15, and 30 degrees), nozzle angles of incidence (0, 15, and 30 degrees), and nozzle speeds (2, 5, and 10 mph). For a summary of the data obtained, refer to Table A.5. For plots of debris removal for the various nozzle settings refer to Figures A.7 - A.12.

GENERAL CRACK TEST TEST DATA				
Crack Approach Angle = 90 degrees, Nozzle Air Pressure = 65 PSI				
NOZZLE SETTINGS			TEST RESULTS	
Nozzle Approach Angle (degrees)	Nozzle Angle of Incidence (degrees)	Nozzle Speed (MPH)	Depth of Debris Removed from Crack (inches)	Length of Debris Removed from Crack (inches)
0	0	2	* 1.20	7.00
0	0	5	0.98	6.00
0	0	10	0.73	3.76
0	15	2	* 1.20	5.55
0	15	5	1.05	5.13
0	15	10	0.70	3.94
0	30	2	1.18	6.00
0	30	5	0.95	5.70
0	30	10	0.55	3.84
15	0	2	* 0.97	5.75
15	0	5	0.97	5.48
15	0	10	0.59	3.60
15	15	2	* 1.20	5.96
15	15	5	1.03	5.20
15	15	10	0.71	4.37
15	30	2	1.17	** 5.80
15	30	5	* 1.20	** 6.25
15	30	10	0.65	3.95
30	0	2	1.09	6.50
30	0	5	0.75	5.47
30	0	10	0.53	3.48
30	15	2	* 1.20	5.90
30	15	5	1.00	5.27
30	15	10	0.68	3.99
30	30	2	0.96	**5.70
30	30	5	0.85	5.40
30	30	10	0.60	3.91
NOTES: * Maximum depth possible (to bottom of crack in test specimen) ** Maximum length possible (to edge of test specimen)				

Table A.5 - General Crack Test (Crack Approach Angle = 90 degrees, Nozzle Air Pressure = 65 PSI)

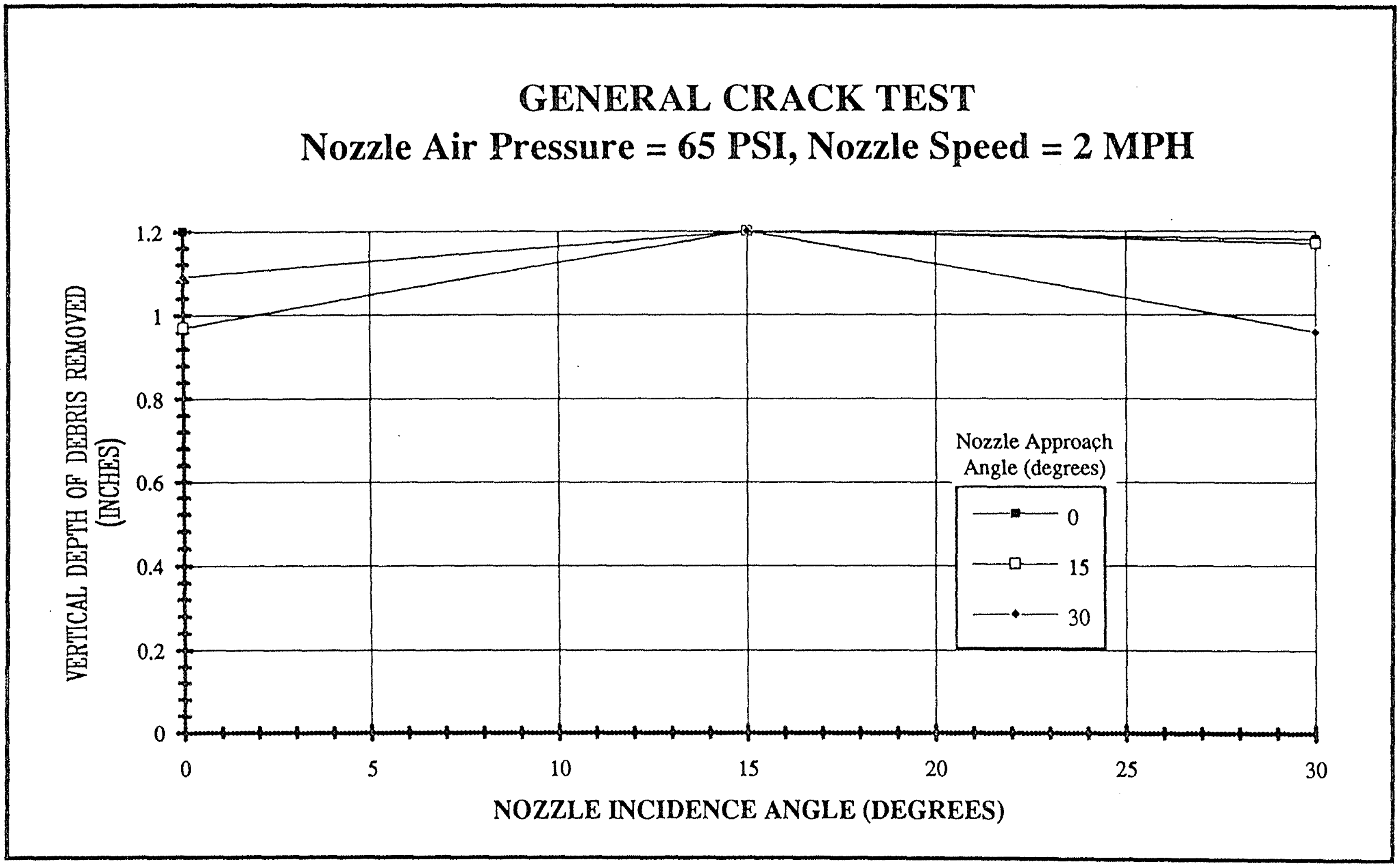


Figure A.7 - General Test - Debris Depth Removed vs. Nozzle Incidence Angle (Nozzle Air Press. = 65 psi, Nozzle Speed = 2 mph)

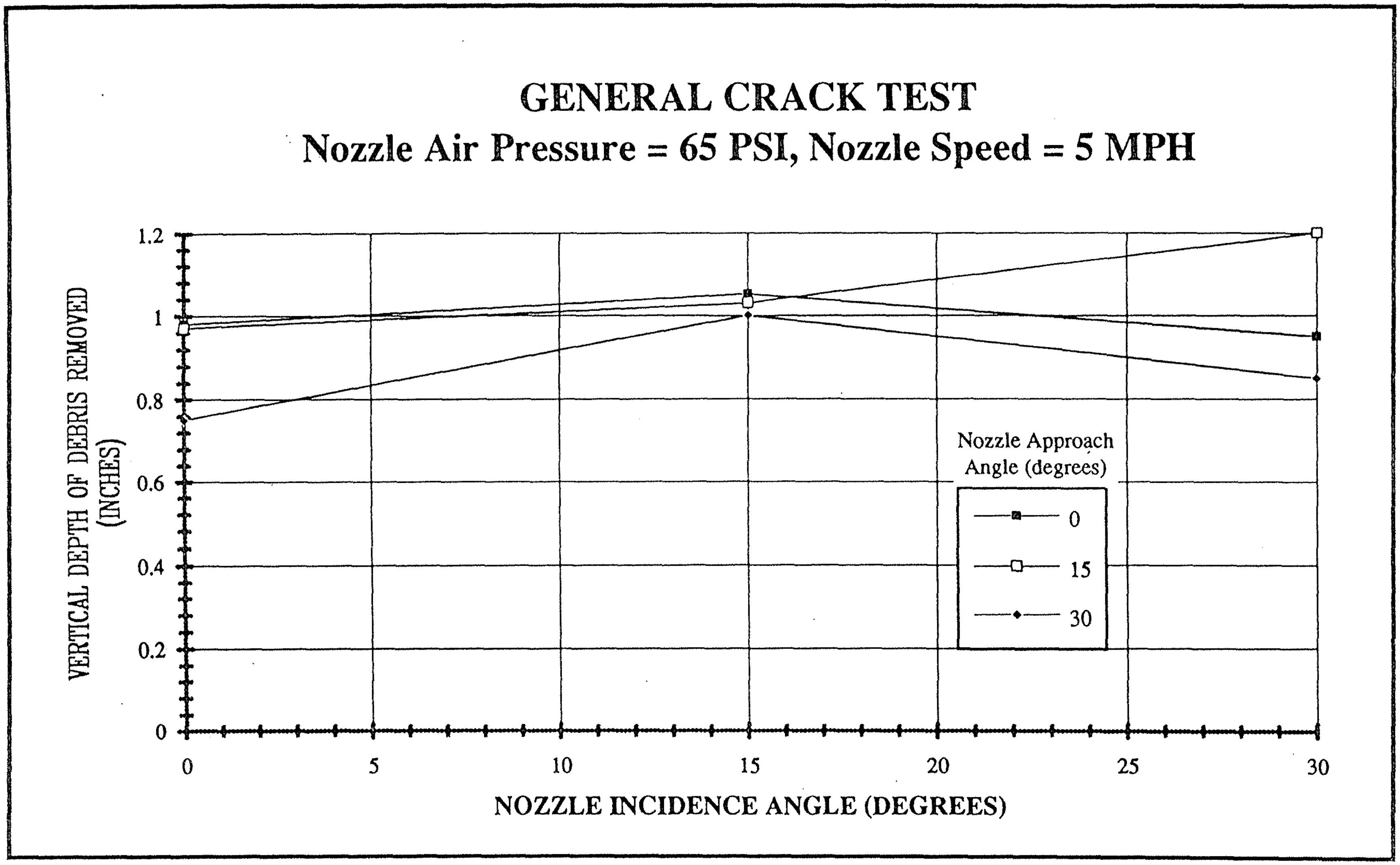


Figure A.8 - General Test - Debris Depth Removed vs. Nozzle Incidence Angle (Nozzle Air Press. = 65 psi, Nozzle Speed = 5 mph)

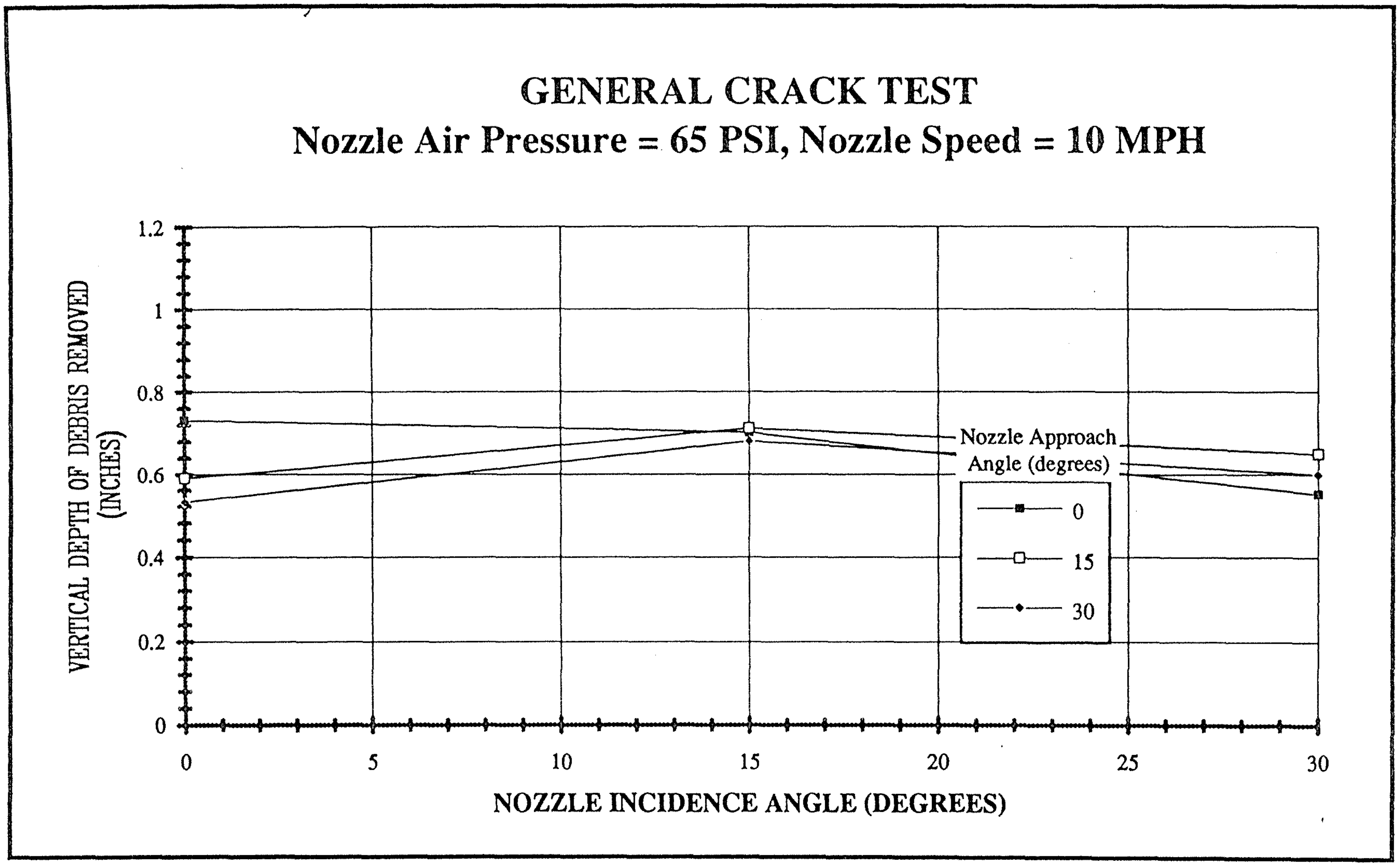


Figure A.9 - General Test - Debris Depth Removed vs. Nozzle Incidence Angle (Nozzle Air Press. = 65 psi, Nozzle Speed = 10 mph)

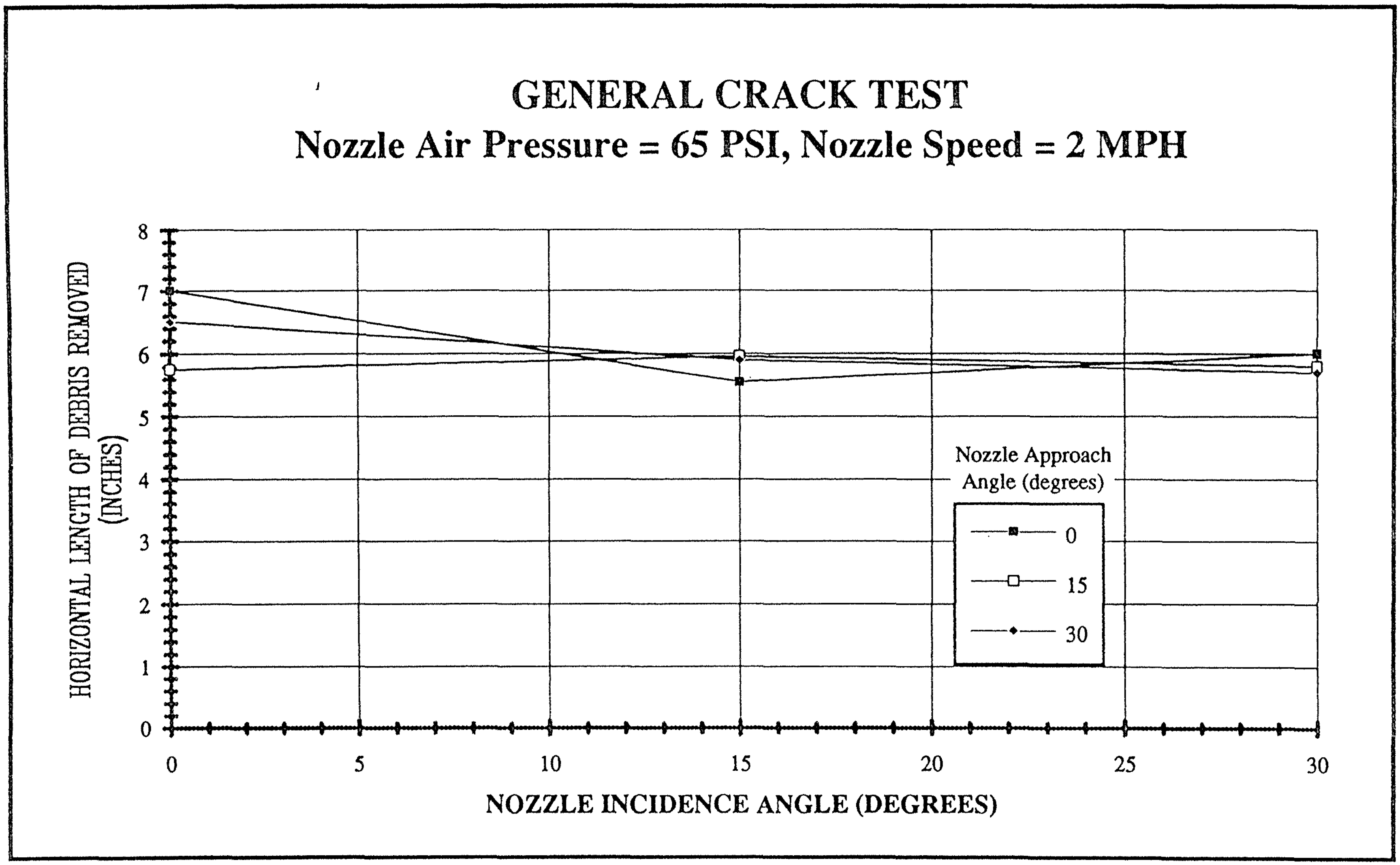


Figure A.10 - General Test - Debris Length Removed vs. Nozzle Incidence Angle (Noz. Air Press. = 65 psi, Noz. Speed = 2 mph)

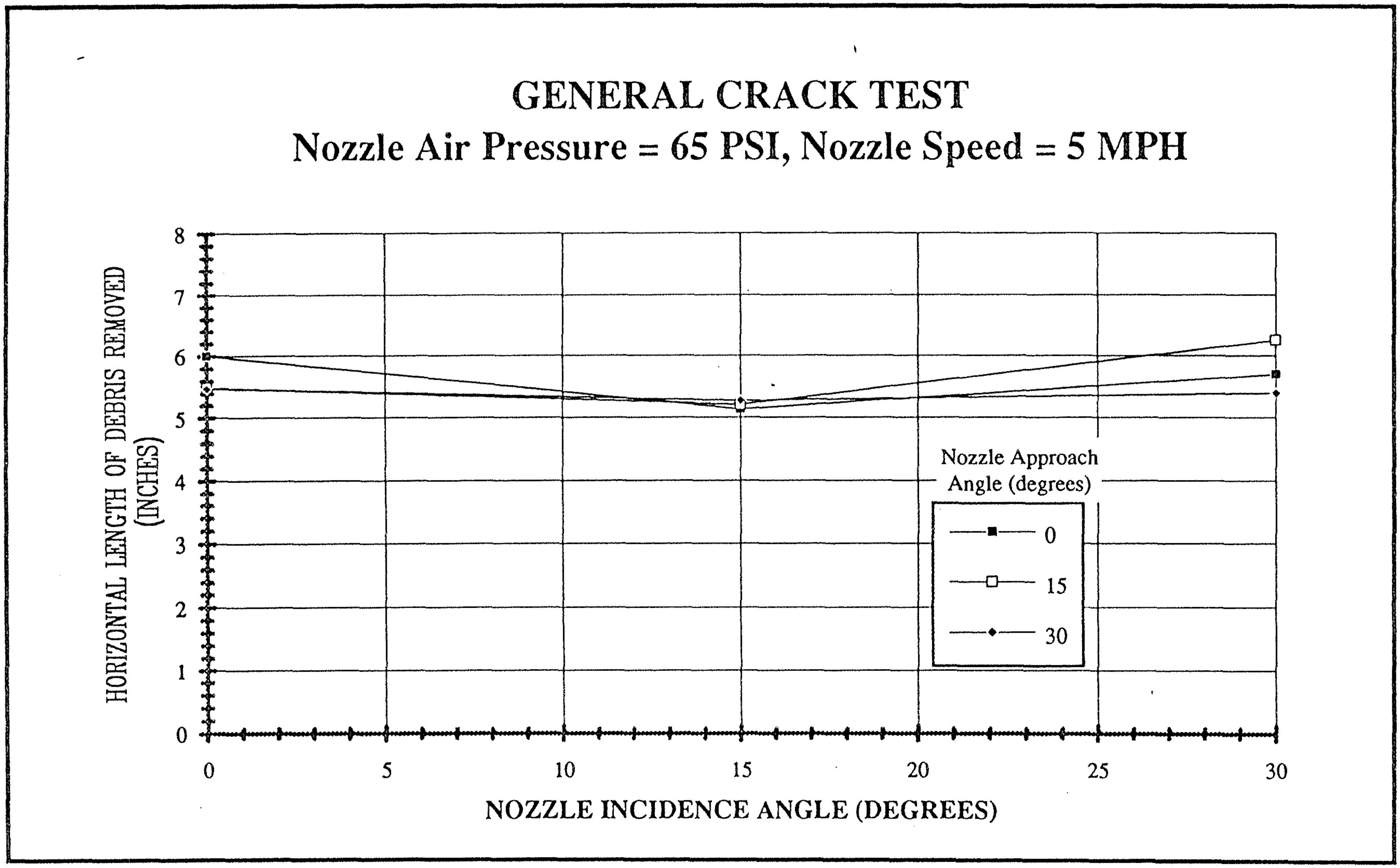


Figure A.11 - General Test - Debris Length Removed vs. Nozzle Incidence Angle (Noz. Air Press. = 65 psi, Noz. Speed = 5 mph)

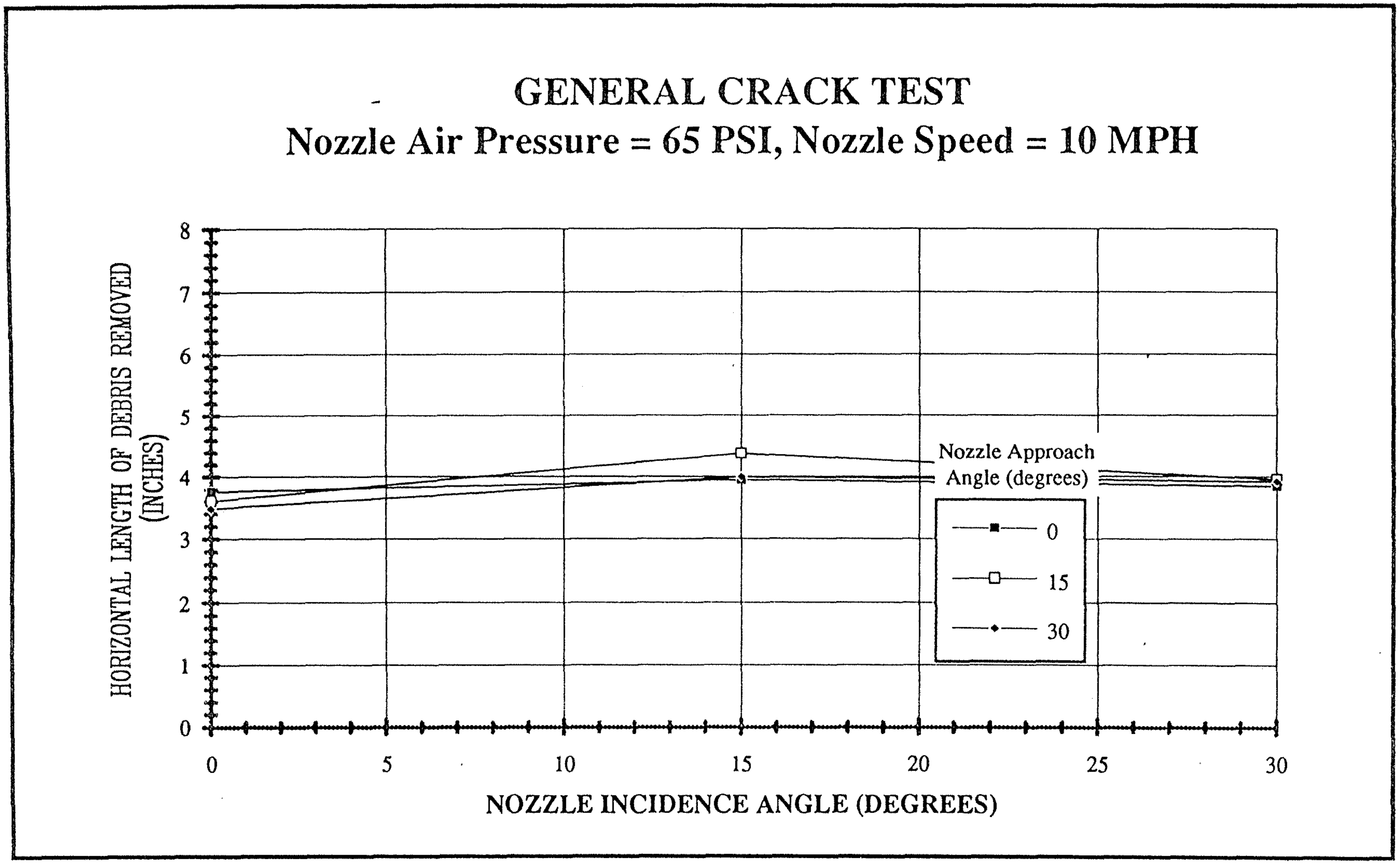


Figure A.12 - General Test - Debris Length Removed vs. Nozzle Incidence Angle (Noz. Air Press. = 65 psi, Noz. Speed = 10 mph)

APPENDIX B

ROADWAY CRACK DEBRIS REMOVAL USING THE SANDBLASTING METHOD AND THE ABRASIVE VACUUM BLASTING METHOD

B.1 - Equipment and Materials Required

A detailed list of the equipment and materials necessary to conduct the abrasive blasting experiment of Chapter 3 is provided below:

- representative, cracked roadway test areas (including areas with live vegetation growing in the cracks)
- industrial sand blasting machine (portable) - P & G (Pauli & Griffin Co.), model 16WB CAL
- industrial abrasive vacuum blasting machine (portable) - LTC (LTC International) model 1060Pn
- blast media (sand, aluminum oxide, steel shot cut wire, etc.)
- air compressor ,approximately 300 CFM (portable)
- air hose
- propane torch (small, hand-held model)
- matches
- tape measure
- heavy duty marking crayons (for marking road surface)
- number chart (for identifying photo shots)
- video camera (with relatively fast shutter speed for slow motion shots)
- camera tripod

- Plexiglass shield (if necessary) (for video camera)
- 35mm camera
- light (if necessary) (for illuminating the local test area during video taping and photographing)
- extension cord (if necessary) (for light source)
- heavy duty shoes, long pants, long sleeve shirt
- goggles (for spectators)
- ear plugs
- face hood (for abrasive blast operator)
- heavy duty gloves (e.g. welding gloves)
- fire extinguisher
- other necessary tools for adjusting the equipment

B.2 - General Test Procedure

The tests for the effectiveness of the sand blasting and abrasive vacuum blasting methods for removing vegetation, loose debris, and dirt film from cracks can, for the most part, be conducted simultaneously. These tests employ a single sand blast nozzle or abrasive vacuum blast nozzle which is directed over the road crack. The nozzle direction of travel is aligned with the crack. The tests are repeated for a variety of operation parameters until sufficient qualitative data is obtained. The detailed general procedure for the abrasive blasting experiment of Chapter 3 follows:

1. Turn on air compressor.
2. Turn on abrasive blasting machine.
3. Observe and note general operation parameters.
4. Record "before shots" of the selected crack area. Note especially;
   - the amount and condition of the vegetation present in the crack,

- the amount of loose debris present in the crack and the local surrounding area,
- and the amount of dirt film present in the crack and the local surrounding area.

5. Initiate blasting process.
6. Pass sand blaster wand over roadway crack at various crack approach angles, nozzle incidence angles, nozzle approach angles, and nozzle eccentricities.
7. Record video tape of the operation.
8. Terminate blasting process.
9. Record "after shots" of the selected crack area. Note especially;
    · the amount and condition of the vegetation removed from and remaining in the crack,
    · the amount of loose debris removed from and remaining in the crack and the local surrounding area,
    · and the amount of dirt film removed from and remaining in the crack and the local surrounding area.
10. Repeat steps 3-9 for a variety of operation parameters until sufficient qualitative data is obtained.

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