SHRP-H-659

Fabrication and Testing of An Automated Crack Sealing Machine

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Strategic Highway Research Program
National Research Council
Washington, DC 1993

SHRP–H-659
Contract H-107A

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August 1993

key words:
construction and maintenance equipment

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500/NAP/893

Acknowledgments

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

The entire SHRP staff is gratefully acknowledged for their continual support, particularly S.C. Shah, Project Manager, for his valuable direction and assistance. The SHRP-H107A Expert Task Group has spent considerable time and effort providing invaluable direction to this project and their help is gratefully acknowledged. Expert Task Group member Mr. Lee Smithson of the Iowa Department of Transportation is especially thanked for his numerous presentations promoting the project, and his unceasing and vigorous support of the overall concept of automating highway maintenance activities.

The continued support of Caltrans is gratefully acknowledged, particularly Mr. Thomas West, Mr. Tim Leahy, and Mr. Roy Bushey of the Division of New Technology, Materials and Research, Mr. John West, Chief of the Division of New Technology, Materials and Research, and Mr. Earl Shirley, former Chief of that division. The value of this project is derived directly from the active involvement of Caltrans personnel and resources.

The success of this project has come from a concerted effort of individuals from Caltrans, Bechtel, and ERES in addition to a great team of students and staff from the University of California at Davis.

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Abstract

This document reports on the development of a machine aimed at the automated sealing of cracks and joints in highway pavement. This machine is comprised of two independent machine systems: one for longitudinal cracks and joints that exist at the edge of the lane (e.g., construction joints), and the other for general (random or transverse) cracks/joints that may extend across a lane. The development effort has included a detailed feasibility analysis, development of machine concept, design and development of first and second generation machine components, and component testing, culminating in a first generation integrated automated machine. The machine is discussed in detail in this document along with market and cost analyses. The developed machinery appears commercially viable based on its potential for improving personnel safety and productivity while concurrently improving the quality and uniformity of the resultant seal.

Executive Summary

Worldwide, a tremendous amount of resources are expended annually maintaining highway pavement. Highway maintenance activities are generally labor-intensive and dangerous to both the workers and the traveling public. It is quite evident to most travelers that improved materials and procedures including the use of more advanced technologies are severely needed. This is even more pronounced in light of the significant current fiscal crises being experienced at all levels of government. Accordingly, the Strategic Highway Research Program (SHRP) has had the improvement of pavement maintenance as one of its primary goals. This area has been addressed in research projects in several key areas. These areas include a study of pavement maintenance effectiveness (SHRP H-101), maintenance measuring equipment (SHRP H-103 and H-104), improving work zone safety (SHRP H-108 and H-109), and the development of improved maintenance equipment (SHRP H-105 and H-107). Recognizing the need to additionally transfer these findings, SHRP has funded an implementation effort as well (SHRP H-110).

The research reported herein was performed under SHRP project H-107A, *Fabrication and Testing of Maintenance Equipment Used for Pavement Surface Repairs - Crack and Joint Sealing*. This study has been performed in parallel to SHRP H-107B which is aimed at the development of equipment for pothole repairs. The SHRP H-107 study was begun in December 1990 and was completed in March 1993. The ultimate goal of the SHRP H-107A project was to develop prototype automated machinery that will sense, prepare, and seal (or fill) cracks and joints on pavement. As such, the primary objectives of this project were to design machinery for the sealing and filling of joints and cracks in pavement in order to:

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

Machinery that satisfies these objectives will additionally reduce lane and highway closures and thus will play a significant role in reducing traffic congestion, an area of considerable concern in the major urban regions around the world. The cost effectiveness of such machinery comes from a combination of the increased speed and reduced manpower needs, in addition to the higher quality seal which will reduce the frequency of major highway rehabilitations. Furthermore, considerable cost savings will be realized through improved worker safety, improved safety for the traveling public, and reduced congestion related costs.

The SHRP H-107A project was initiated with a detailed feasibility study. This was done in conjunction with the development of a machine system concept and the design of first generation components. The incorporation of feasibility and first generation component design and testing allowed the project to progress at a rapid pace. The design and development of second generation components coincided with initial integration efforts. The project has culminated in a first generation, integrated, Automated Crack Sealing Machine (ACSM).

The following are critical aspects that have allowed for the rapid prototyping of the ACSM and the large potential for its use.

- The machine is comprised of two independent primary machine systems which address longitudinal and general cracks, respectively. The longitudinal crack sealing system operates off the side of the vehicle and addresses cracks and joints at the edge of the lane that run with the direction of travel ,e.g. construction joints, whereas the general crack sealing system operates off the rear of the vehicle to address cracks that run generally across the pavement, e.g. random or transverse cracks and joints.

- The ACSM has been developed in a modular manner. The component subsystems are stand alone; they can operate independently. This has allowed for rapid prototyping as well. Additionally, this implies that the end user can tailor the set of components to best meet their crack and joint sealing methods. Furthermore, the two primary systems share many identical components, which reduces the parts inventory necessary, reduces the need to train on a wide variety of components, and simplifies machine maintenance.

- The ACSM utilizes a large number of commercially available components. This has allowed for rapid machine development by eliminating the need to design many components. Secondly, commercial components provide the highest possible component reliability, and component service is also readily available.

This document reports on the prototype integrated machine developed, in addition to the final components used. The important features and the coordinated activities of the numerous components of both the integrated longitudinal and general crack sealing systems are discussed. Detailed second generation component descriptions and discussions on the principles of operation of each of the machine components and subsystems are presented. Engineering drawings of the various components and vendor specifications for much of the equipment purchased have been included. Performance specifications of the components are also discussed. Qualitative test results for the integrated prototype longitudinal machine and numerous components are given, and the corresponding machine operational performance is discussed.

Commercialization issues of the integrated machine are discussed, including focus group discussion results, machine cost projections, and cost benefit analysis, in addition to recommended machine modifications that will allow the machinery to address all types of crack and joint sealing/filling operations. A conservative analysis shows that an ACSM has the potential to recover its cost in less than three years. The longitudinal machine is commercially viable today. While the feasibility of the complete ACSM has been demonstrated, the machine would appear to have at least one more generation of development to go through before being a marketable system. However, the prototypes have demonstrated their potential for vast improvement in personnel safety and productivity while concurrently improving the quality and uniformity of the resultant seal. Finally, ideas as to how the automated machinery could be integrated into the maintenance programs of highway agencies are also discussed.

This document constitutes Volume 1 of the Final Report for SHRP H-107A. The second volume of the report, *Operator's and Maintenance Manual*, provides detailed information on the use and repair of the prototype ACSM.

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Introduction

1.1 - Study Objectives

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

The sealing and filling of cracks are tedious, labor-intensive operations. A typical operation to seal transverse cracks in AC pavement involves a crew of eight individuals which can seal between one and two lane miles per day. The associated costs are approximately $1800 per mile with 66% attributed to labor, 22% to equipment and 12% to materials. Furthermore, the procedure is not standardized and there is a large distribution in the quality of the resultant seal. In addition, the crack sealing work team is exposed to a great deal of danger from moving traffic in adjacent lanes.

The ultimate goal of the SHRP H-107A project is to develop prototype automated machinery that will sense, prepare, and seal (or fill) cracks and joints on pavement. As such, the primary objectives of this project are to design machinery for the sealing and filling of joints and cracks in pavement in order to:

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Machinery that satisfies these objectives will additionally reduce lane and highway closures and thus, will play a significant role in reducing traffic congestion, an area of considerable concern in the major urban regions around the world. The cost effectiveness of such machinery comes from a combination of the increased speed and reduced manpower needs, in addition to the higher quality seal which will reduce the frequency of major highway rehabilitations.

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

- Sense the occurrence and location of cracks in pavement.
- Adequately prepare the pavement surface for sealing/filling with the appropriate methods; for example, any operation that is deemed necessary such as removing entrapped moisture and debris, preheating the road to ensure maximum sealant adhesion, refacing of reservoirs, etc.
- Prepare the sealant/filler for application; i.e., heat and mix the material, etc.
- Dispense the sealant/filler.
- Form the sealer/filler into the desired configuration.
- Finish the sealer/filler.

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

- Reasonable in cost,
- Easy to use,
- Reliable and fast,
- Rugged,
- Safe,

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

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

In this section of this report, we will present our approach to the development of the machinery. We will first establish the intended functions of the machine in terms of the various sealing and filling operations that the machinery is expected to perform. The initial functional requirements, which drove the machine and component concepts, will be presented. We will then present the machine system architecture, followed by description of the integrated machine concept.

1.2 - Development Plan

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

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

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

1.2.1 - Assumptions

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

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

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

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

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

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

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

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

1.2.2 - Crack Sealing Approach

There has been a significant amount of research time and effort spent on identifying the appropriate means of sealing cracks; e.g., Blais, 1984; Belangie & Anderson, 1985; Chehovits & Manning, 1984; Chong & Phang, 1988; Turgeon, 1989; Smith, et al. 1991; Wolters, 1973. The following discussion applies some of the findings of the above-referenced research studies, concentrating on those portions that apply to the sealing of cracks in bituminous pavements. It should be noted that the greatest body of research on this topic has been conducted, with a few exceptions, in regions subjected to fairly harsh winters (Utah, Minnesota, Ontario, Delaware, Georgia, Montana, and Tennessee) and, in most cases, excessive moisture. Their findings must be considered as representative of conditions in which the environment has the most severe effect on pavement performance.

Causes and Development of Cracks

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

If there are too many cracks, it is both uneconomical to seal them, and unsound from an engineering standpoint. Generally speaking, too many cracks are indicative of a pavement in an advanced state of deterioration. At that point, the pavement is more likely a candidate for major rehabilitation or reconstruction. This approach eliminates from consideration a pavement with fatigue or alligator cracking, or one with serious block cracking. Even a pavement that exhibits primarily transverse cracking may be ruled out as a candidate for sealing if the cracks are too closely spaced or excessively wide. One study recommended that pavements with cracks closer than 25 ft should not be considered for crack routing and sealing because that would indicate a later stage of deterioration in which crack sealing would not be effective in prolonging pavement life (Chong and Phang, 1988).

Crack width

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

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

Studies which specifically addressed crack width as a sealing criterion were fairly consistent in their recommendations. Chong and Phang recommended that cracks between 6 and 12 mm (approximately 0.25 to 0.5 in) were candidates for routing and sealing; narrower cracks were to be left alone and wider cracks were simply to be cleaned and sealed (Chong and Phang, 1988). The Value Engineering study of crack sealing recommended that cracks wider than 0.19 to 0.25 in were to be sealed, although no upper limit was recommended (Belangie and Anderson, 1985). Utah recommended that cracks between 0.19 and 1.0 in wide were candidates for crack sealing (Blais, 1984). A review of the available literature on the topic suggested that cracks between 0.20 and 0.60 in wide be considered as suitable for sealing by the automated sealant equipment.

Crack Length

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

Random Crack Orientation

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

Reservoir Dimensions

The shape of the reservoir has a large effect on sealant performance. The shape is characterized through the ratio of the sealant depth to reservoir width, also known as the shape factor. The desired shape factor is a function of the type of sealant selected and the expected movement at the crack. A variety of approaches are used for both rubberized asphalt sealants as well as for silicone sealants. Low profile channels have received increased attention with popular dimensions being 0.4" wide by 1.6" deep (10 mm deep by 40 mm wide) and 0.2" deep by 1.5" wide (5.1 mm deep by 38.1 mm wide).

Crack Preparation

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

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

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

Reservoir Cleaning

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

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

Water blasting has seen some use, but is not really appropriate for AC pavements. While it may be useful to prepare concrete pavements, it also leaves the pavement wet, and most sealants cannot be applied until the pavement is dry.

Safety is also a major concern when using water blasting. Crack saws have seen increasing use for reservoir preparation. The technology has not been totally successfully applied to cracks because of the difficulty in following their meandering path.

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

Material Type

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

Sealing Configuration

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

1.2.3 - Summary and Plan

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

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

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

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

Later in this document, we will discuss the recommended component modifications to allow all types of crack sealing and filling operations to be performed.

1.3 - Machine System Architecture

With consideration of the range of activities required of an automated crack sealing machine, a general machine system architecture was devised. In addition to the support vehicle itself, the total machine includes seven subsystems. A block diagram of the total machine architecture including block diagrams of the individual subsystems is included in Figs. 1.1-1.8. To follow is a short description of each system.

Integration and Control Unit (ICU): The ICU acts as a clearing house for all information flow. Many of its functions are listed in the block diagram. Fundamentally, this unit includes the ability to communicate with all the systems and the ability to process the information. The ICU oversees the entire operation and coordinates the activities of the other subsystems. The information forwarded from the Vision Sensing System (VSS) will be translated into a planned path for the Applicator and Peripherals System (APS) components (crack/joint preparation equipment, etc.).

Thus, the ICU will include the necessary algorithms to plan a crack/joint sealing path.[1] If multiple end-effectors are employed, the ICU will need to first allocate cracks to the individual applicators and will do so in a manner to maximize speed and avoid interference. This system keeps account of the actual position of the total machine and its components by interacting with sensors on the Robot Positioning System (RPS). It additionally monitors the APS to ensure adequate volume and temperature of sealant/filler, air, etc. Following the planning of the appropriate path(s), the ICU controls the motion of the applicator(s) with the interaction of the Local Sensing System (LSS) and it additionally controls the individual applicator functions.

System Display Unit (SDU): The SDU provides for any interactions with the machinery operator. It provides information on the machinery status, and it allows for the operator's inputs to the ICU. It is unrealistic to expect that an integrated machine of this type will work with no operator involvement; i.e., it is not an autonomous machine. As such, this system offers the operator a convenient means for interacting with the machine.

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

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

Local Sensing System (LSS): The LSS is a laser range finder based system, and it is used to both verify the presence of cracks identified by the VSS and to participate in the APS path. The LSS includes both the actual sensor and the support processor. The LSS has the potential to provide information on crack depth and width in addition to extremely accurate positional information.

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1 The path planning function is actually performed by the Path Planning Module. Since this module is housed within the ICU, we do not distinguish it as a separate system for machine architecture purposes. Later in this document, however, it will be discussed independently of the ICU.

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

Vehicle Orientation and Control (VOC): The VOC provides vehicle motion measurements to the ICU and VSS. The VOC includes all necessary hardware to measure vehicle speed and orientation. In future commercial machinery, we anticipate that the VOC will additionally be required to control motion of the support vehicle, and as such, the VOC will have the necessary sensors and actuators to perform this task.

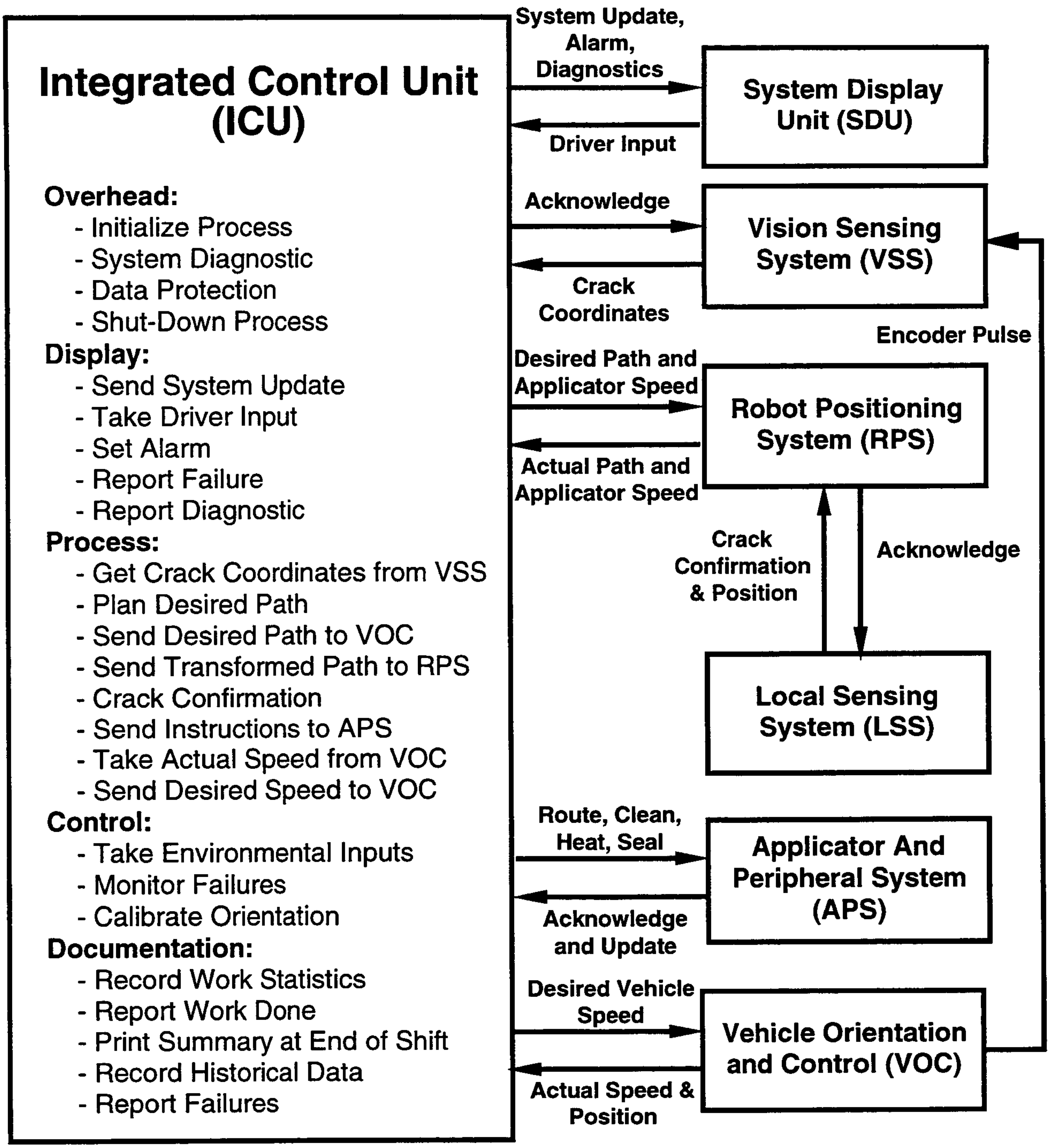


Figure 1.1 - Crack Machine System Architecture.

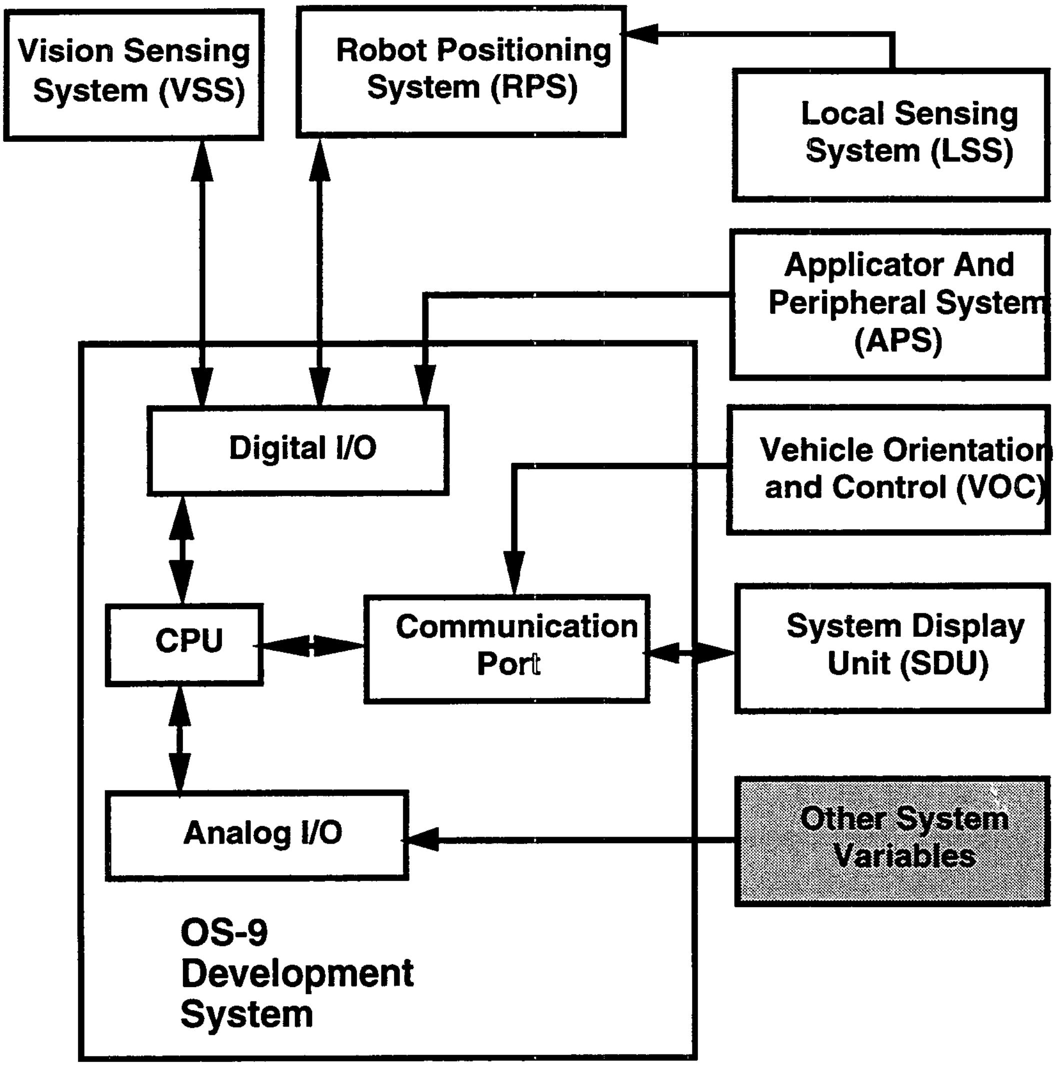


Figure 1.2 - Integration and Control Unit Block Diagram.

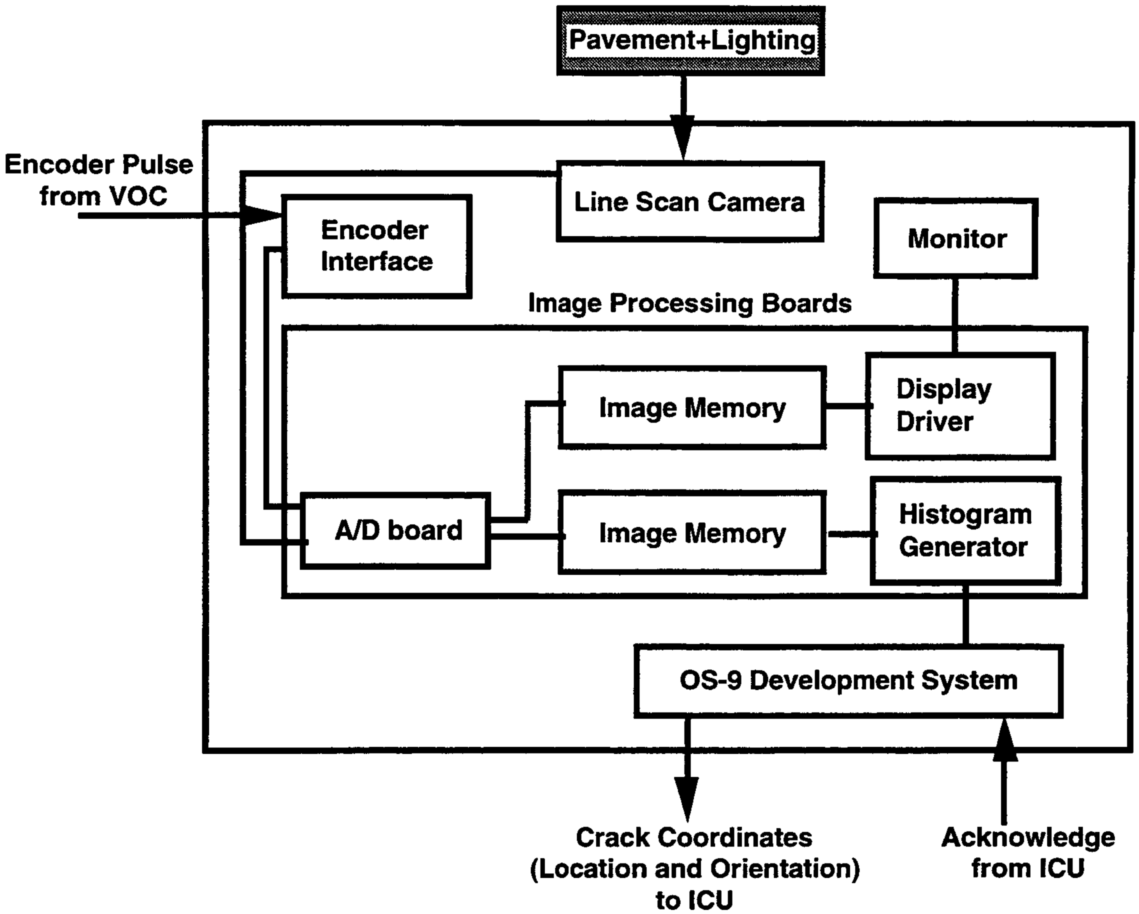


Figure 1.3 - Vision Sensing System Block Diagram.

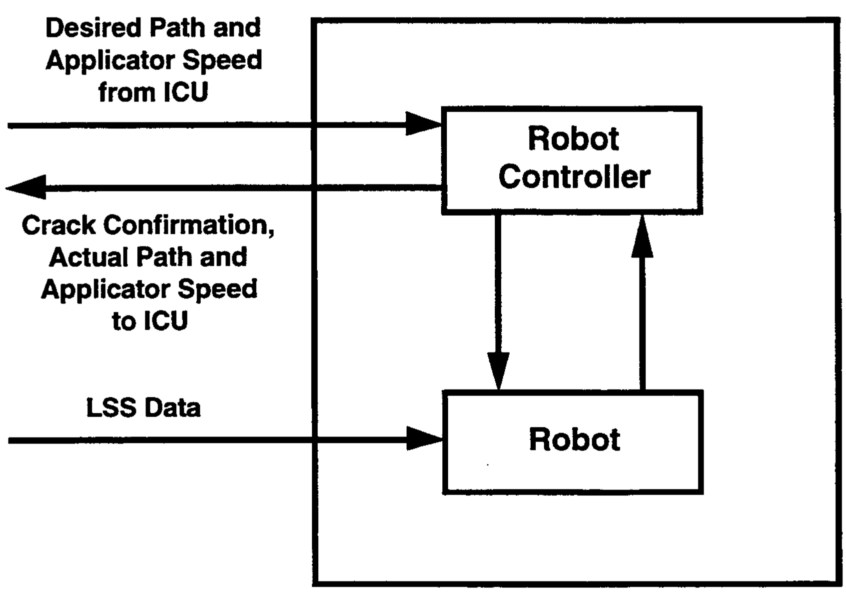


Figure 1.4 - Robot Positioning System Block Diagram.

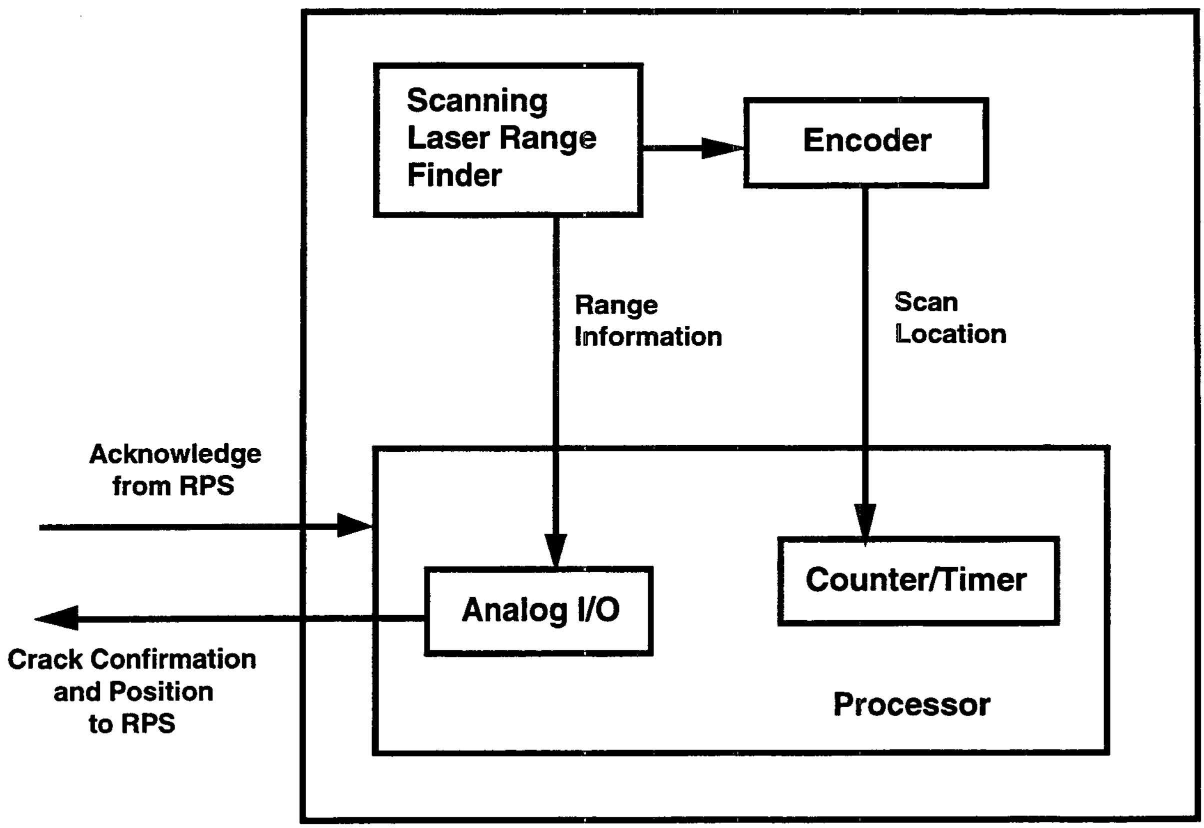


Figure 1.5 - Local Sensing System Block Diagram.

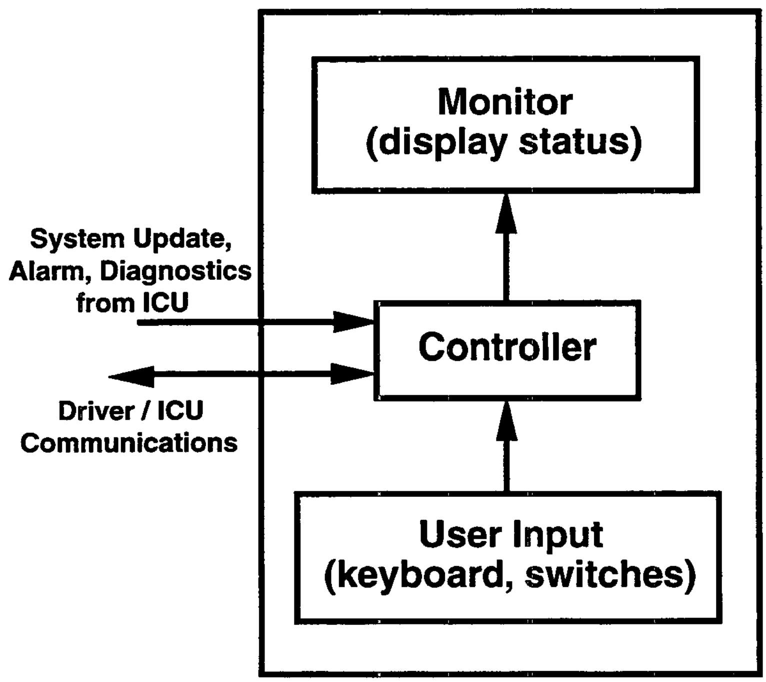


Figure 1.6 - System Display Unit Block Diagram.

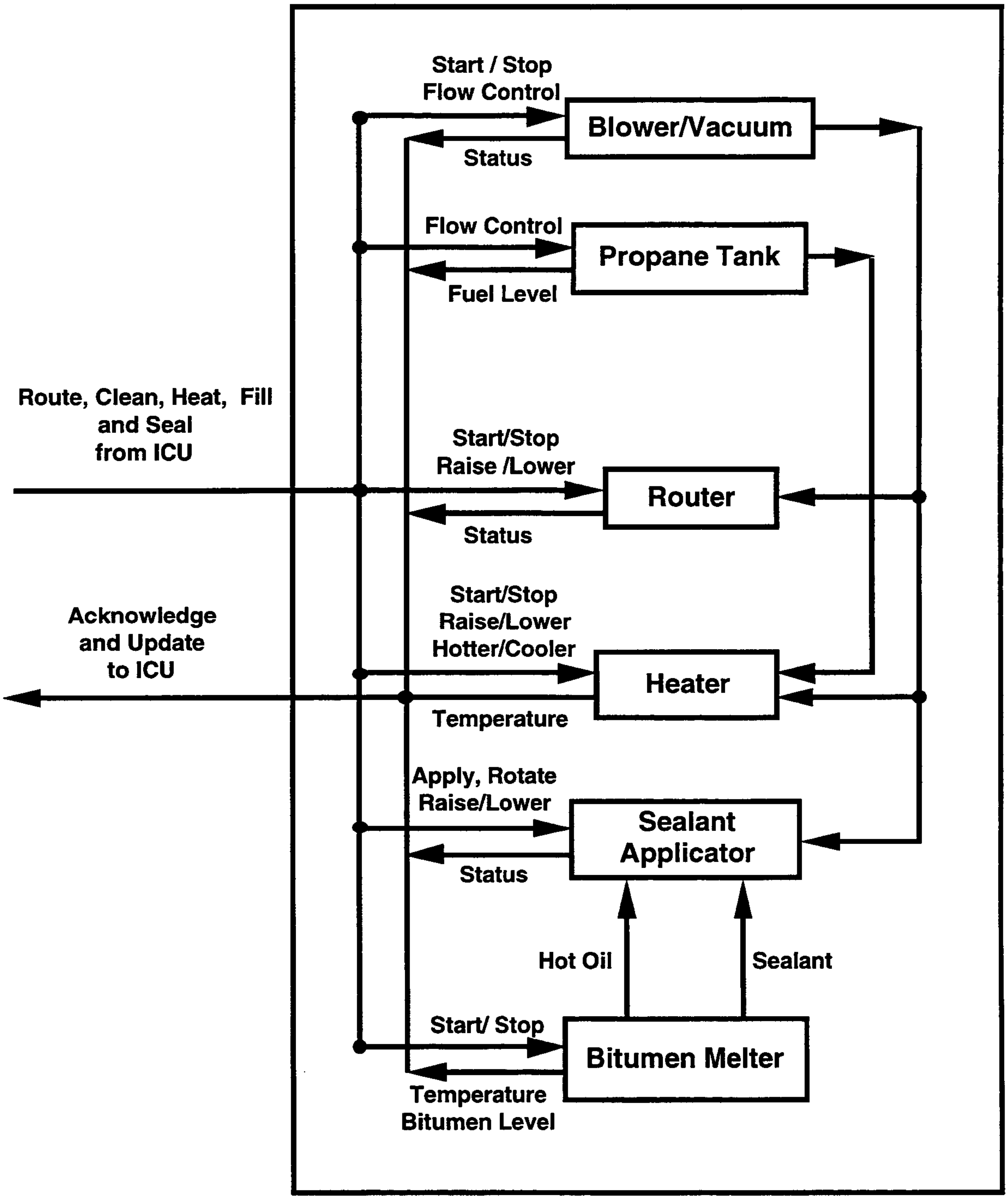


Figure 1.7 - Applicator And Peripherals System Block Diagram.

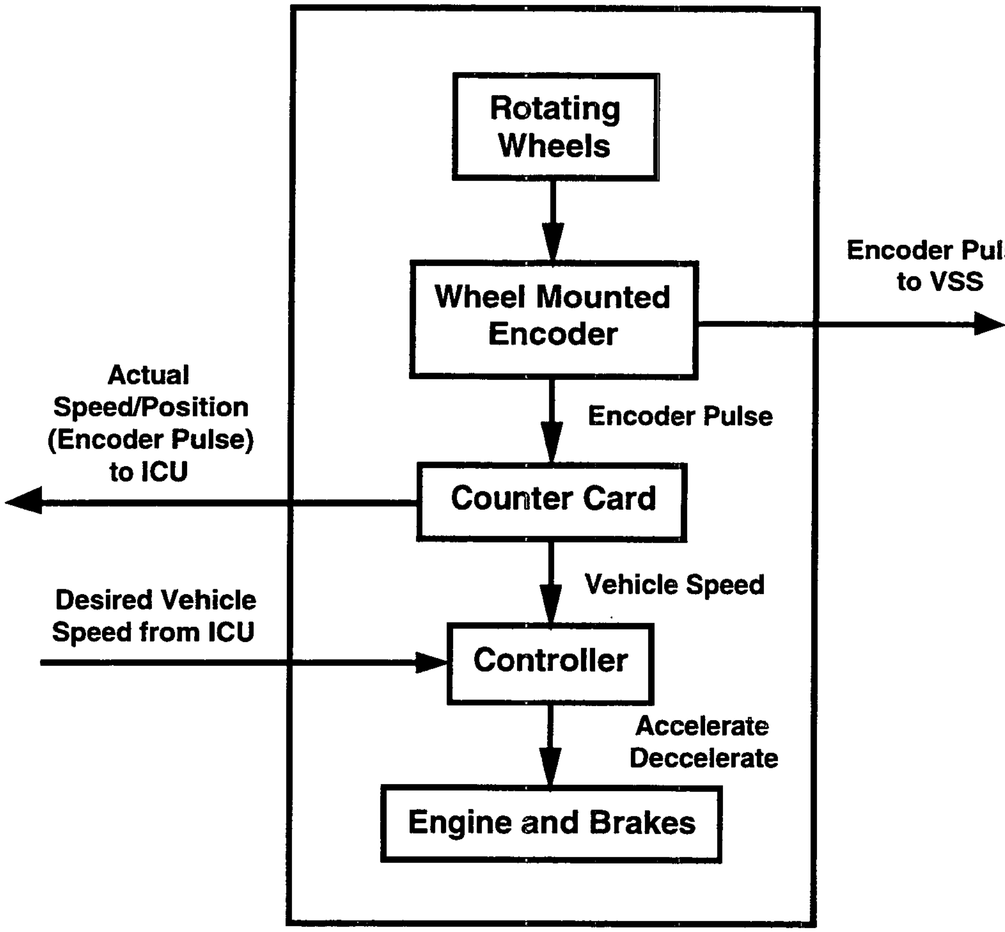


Figure 1.8 - Vehicle Orientation And Control System Block Diagram.

1.4 - Machine Concept

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

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

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

Furthermore, the support vehicle must provide the continuous movement of the machine at extremely slow speed which is difficult to perform.

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

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

Furthermore, for the simpler longitudinal operations, the use of the support vehicle to provide a continuous movement of the machine is relatively easy. As such, the positioning system concept for the longitudinal portion of the machine is significantly simpler than the general machine.

Figure 1.9 is a computer rendition of the initial machine concept developed. This concept was animated early in the project and a video of this animation was used extensively to demonstrate the operation of the machine.

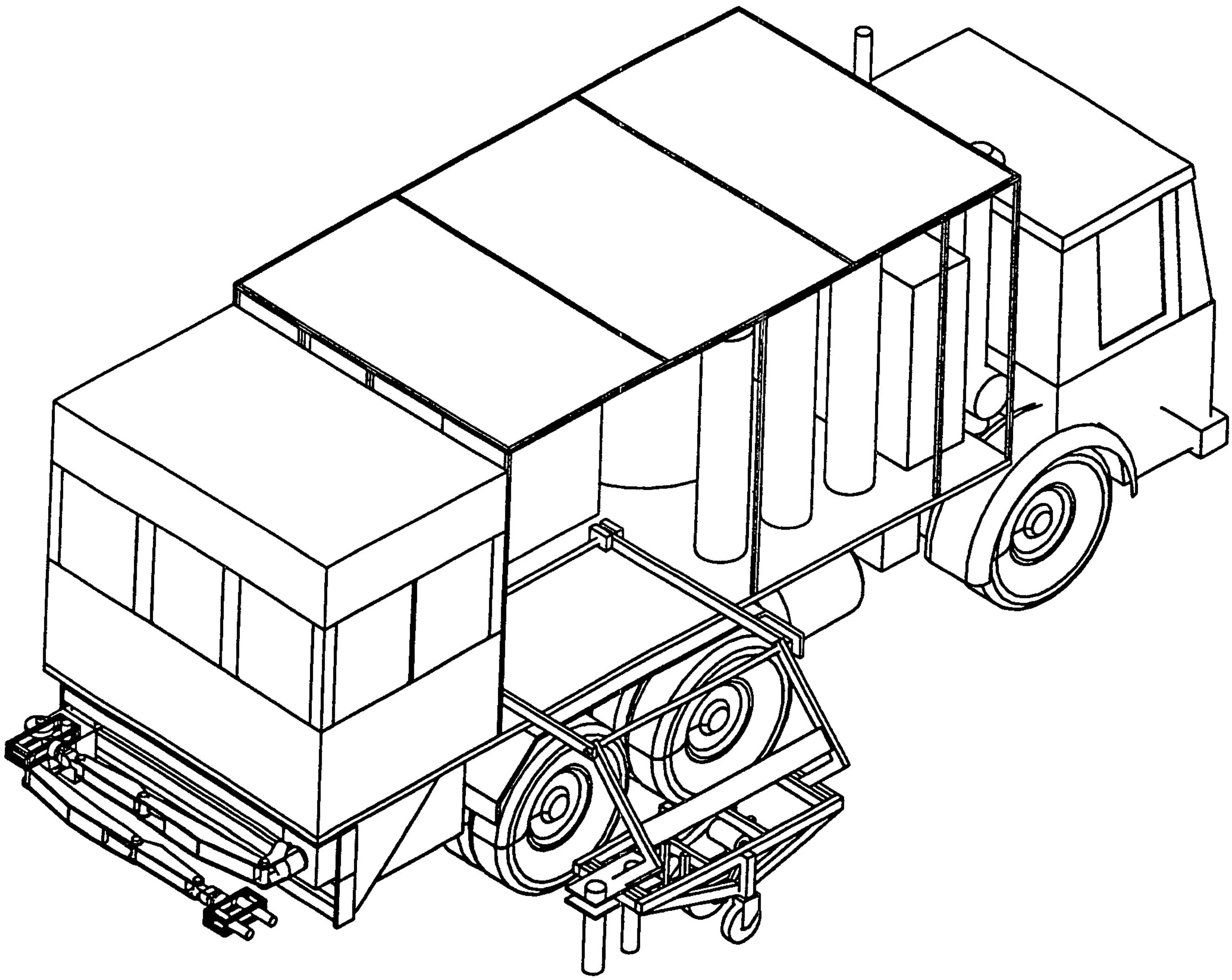


Figure 1.9 - Integrated machine concept.

The general crack sealing operation takes place off the rear of the vehicle. In order to provide for crack following capability, commercially available robots mounted on linear slides were initially proposed. Since robots generally have poor strength to weight ability, a secondary arm is used to support the load of the end-effectors. This secondary arm is a passive linkage, and is driven by the robot arm and its linear slide. Figure 1.10 shows the sealant applicator end effector attached to the secondary arm. The robot itself is only required to position its tooling and move it along the crack.

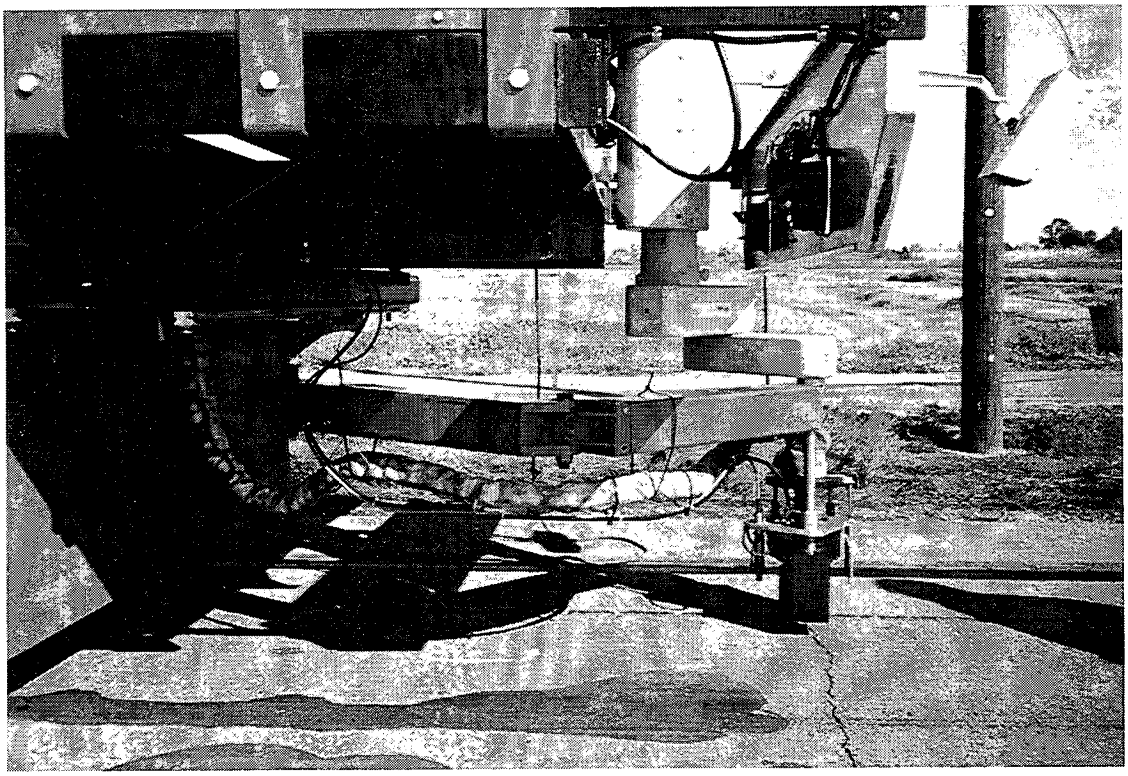


Figure 1.10 - Sealant Applicator Attached to the Secondary Arm.

The longitudinal positioning system relies on hydraulic positioning of a simple linkage supported off the side of the support vehicle. The system is designed in such manner that the weight of the end-effectors are supported by a support frame mounted on casters, and the casters provide positioning of the end-effectors relative to the roadway. The routing, heating/blowing, and dispensing end-effectors are all supported by the same frame, as is the Local Sensing System. The positioning system provides motion of the frame normal to the direction of vehicle motion. Placement of this part of the machine allows it to be easily stowed for travel to and from the job site. This design was chosen for ease in fabrication with many commercially available components.

This section of the report illustrates the initial machine concept selected. Details of the integrated machine and the positioning systems will be discussed in much additional detail later in this document. However, it is important to stress the critical aspects of the overall machine development plan which include:

- The use of two main machine systems to address longitudinal cracks and general cracks independently. This has allowed for on-road testing of numerous components within the longitudinal machine, while the general machine is still in development. Also, this provides for a means of phased commercialization, starting with the simpler and less expensive longitudinal machine.

- Modularity - the use of stand alone subsystem components and the use of identical components in both machine systems. This has allowed for the independent development of components, the ability to tailor the machine to each end-user's crack sealing method, and a minimal parts inventory necessary.

- The incorporation of feasibility testing into first generation component testing whenever possible. Primarily, this has allowed for the expedited development of the machinery.

- The use of commercially available components whenever possible. This has provided for the expedited development of the machinery in addition to higher component reliability.

We believe that these critical factors have allowed for the successful development of the integrated machinery in the short duration of this project.

1.5 - Report Summary

This document is the Final Report of SHRP H-107A: Fabrication and Testing of Maintenance Equipment Used for Pavement Surface Repairs. Phase I of this project involved a detailed feasibility study, creation of a machine development plan, development of an integrated machine concept, and the design of first generation machine components. A report at the end of that phase details all of the noted items. Phase II involved the fabrication and testing of the first generation components which led to the development of second generation components. A two part report discussed details of these activities.

This document reports on the prototype integrated machine developed, in addition to the final components used. Chapters 2 and 3 discuss the integrated longitudinal and general crack sealing systems, respectively. The important features and the coordinated activities of the numerous components are emphasized.

In Chapter 4, detailed second generation component descriptions and discussions on the principles of operation of each of the machine components and subsystems are presented. Engineering drawings of the various components have been included along with photographs of the manufactured components. These drawings and photographs are primarily contained in the Appendices which also contain the manufacturer and model number information for much of the equipment purchased. Performance specifications of the components are also discussed. Chapter 5 discusses the testing of the integrated prototype machine including the test plan, test results and corresponding machine performance.

Chapter 6 concentrates on commercialization issues of the integrated machine. This includes machine cost projections and cost benefit analysis, in addition to recommended machine modifications that will allow the machinery to address all types of crack and joint sealing/filling operations. Chapter 7 presents ideas as to how the automated machinery could be integrated into the maintenance programs of highway agencies. Chapter 8 summarizes the conclusions and recommendations of this project. Chapter 9 provides a list of abbreviations and a glossary of terms used in the report. Chapter 10 gives an extensive bibliography of source material relevant to crack sealing and the subsystems on the ACSM.

2

Integrated Longitudinal Crack Sealing System

2.1 - Method of Operation

The longitudinal crack sealing machine consists of the Longitudinal Robotic Positioning System (LRPS), the Local Sensing System (LSS), the Applicator and Peripherals System (APS), and a control computer. The detailed descriptions of the LRPS, the LSS, and the APS are given in Chapter 4, and the role of the control computer will be described below. Here, the interaction between these components during the operation of the longitudinal machine is described.

Unlike the general machine, there is no need for a global vision system to identify the location of the cracks when using the longitudinal machine, since the nature of the cracks addressed by the longitudinal machine is much more restricted. In addition, there is no need to pre-plan a path for the longitudinal machine. During operation of the longitudinal machine, the driver of the vehicle merely needs to maintain the center of the LRPS near the position of the longitudinal crack to be sealed. This can be done visually using a pointing device, or using a camera and a monitor.

The position of the LRPS is controlled by a hydraulic actuator, with the loop closed by a position transducer located on the hydraulic cylinder. This controller is capable of accurately positioning the center of the LRPS in the lateral direction, i.e. perpendicular to the centerline of the cart. The longitudinal motion of the system is dictated entirely by the motion of the vehicle.

The LSS is mounted as part of the crack sealing tooling for the LRPS. This sensor provides an error signal, which represents the offset of the center of the LRPS to the center of the longitudinal crack. This signal is used by the control computer to modify the desired position input for the closed-loop control system. This signal is then communicated to the actual closed-loop controller using an RS-232 serial communication line. With this updated position command, the LRPS can then track in to the actual crack position.

If, due to either large motion of the crack or the crack sealing vehicle, the longitudinal crack moves out of the 4 inch field of view of the LSS, the LSS will issue a saturated error signal, which will then drive the position command in the direction that the crack was last seen. In most cases, this will drive the LRPS back to the crack, and then the closed-loop control to follow the crack can proceed. If the LSS does not detect a crack again within the range of motion of the LRPS, then an error signal can be generated to the ICU, which will then handle the situation by sending a signal to the operator.

The ICU will be used to maintain high-level control of the LRPS, and to receive status information from the control computer and the LSS. The ICU will function to initiate and terminate the sealant flow and the router. However, the LRPS, LSS and the control computer have been designed so that they can operate as a stand-alone unit, without the assistance of the ICU.

Finally, as opposed to using the LSS for LRPS position control, the LRPS can be manually controlled by an operator with a joystick. The operator moves the joystick in one DOF, and the LRPS cart extends or retracts based on the position of the joystick. The operator uses a video screen to monitor the position of the centerline of the LRPS cart and the crack, and jogs the stick to keep the cart centered over the crack. Using this method, the LRPS can follow and seal cracks at approximately 10 mph.

As noted in the introduction, the ACSM has been developed in a modular fashion allowing for each subsystem and component to be operated independently. This allows for a variety of machine/component configurations which will satisfy the needs of a large number of potential uses. Each state, and often region within each state, employs its own crack sealing methods. That is, California does not usually route or heat pavement prior to sealant application, whereas cold weather states normally employ both of these preparation procedures. As such, a potential buyer will select which options necessary for their particular approach. Furthermore, each buyer will have different a equipment budget, procurement procedures, user capabilities, etc. As such, the modular nature of the ACSM allows for the possibility of incrementally automating the crack sealing operation by starting with the simpler longitudinal types of cracks and only dispensing sealant, and ultimately incorporating automation until the full spectrum of preparations, etc. are employed in general sealing operations. It is anticipated that the successful incorporation of the less automated versions of the machine into the maintenance program will ultimately lead to the purchase of the fully automated ACSM.

Accordingly, the machine cost projection of Chapter 6 estimates costs for a variety of machine configurations. At the current time, general sealing operations can only be automated with the complete ACSM systems with the only options being related to the desired tooling. However, longitudinal sealing operations provide a great deal of flexibility in machine configuration options and, to follow, the hierarchy of possible longitudinal machine/component configurations is reviewed. It should be noted that all of the configurations require and include the SHRP H-107A sealant applicator which forms the basis for any automation.

The lowest level of automation involves the user purchasing the SHRP H-107A sealant applicator only and using their own vehicle with their own linkage to hold the sealant applicator. The applicator will need to be positioned by the driver steering the vehicle. The user will provide their own sealant tank, hosing, support vehicle, etc. This configuration will remove the workers from the highway for much improved safety and the sealing task will be accomplished by a one-man operation. The SHRP H-107A team has developed this type of vehicle for Caltrans, and field testing has been initiated. This is certainly the least expensive configuration, yet it can speed the sealing process considerably.

The next level of automation includes the SHRP H-107A longitudinal positioning system linkage assembly which will allow for stowing of the longitudinal system. The user will need their own flatbed truck in addition to their melter, etc. and positioning of sealant applicator will still be accomplished by the driver. There will be no speed increase over the previous configuration.

Once a user incorporates our linkage assembly, the addition of the hydraulic actuator and controller allows for joystick positioning of the sealant applicator over the crack by an additional operator. The driver will merely drive the vehicle down the road in such a manner that the applicator is within one foot of the crack. In addition to the items noted above, the user will need a source of hydraulic power to supply the actuator (can come from a separate power supply of the power take-off of the truck). Although the task will be a two-man operation, there will be a significant increase in operational speed. We have sufficiently dispensed sealant in this type of operation at speeds as high as 15 mph (24 km/hr).

The next level of automation involves the inclusion of the Local Sensing System. This will allow for the automated positioning of the sealant applicator over the crack eliminating the second operator (i.e., driver only, one-man operation). The resultant speed of the operation is dictated by the LSS, and although we have yet to exercise this configuration, we anticipate the process to take place at approximately 8 - 10 mph (13 - 16 km/hr).

Any of the above configurations can additionally include other tooling. For example, the router and/or heating and blowing systems can easily be added to all noted. To incorporate the router, a hydraulic power source is required with sufficient power to accomplish routing and, if desired, positioning. The option of heating and blowing will allow for blowing away debris and additionally preheating the pavement prior to sealing. Furthermore, it will allow for vacuuming of routed debris if desired. The user will need to provide a propane supply for the heater and adequate hydraulic power for the blower and any other options (i.e., router, positioning, etc.). The full operation, routing, heating and blowing, debris removal, and sealing can be performed at 2 mph (3.2 km/hr).

3

Integrated General Crack Sealing System

3.1 - Method of Operation

The general crack sealing machine is composed of the Vision Sensing System (VSS), the Integration and Control Unit (ICU), the path planning module (which resides on the ICU), the Vehicle Orientation and Control (VOC) system, the general Robot Positioning System (RPS), the Applicator and Peripherals System (APS), and the Local Sensing System (LSS). The detailed descriptions for these components are given in Chapter 4. In this section, the interaction between these components during operation of the general machine is described.

As the vehicle moves down the road, the VSS will buffer an image of the roadway for 20 feet, approximately half the length of the truck. The VSS identifies potential crack locations using the algorithm described in Section 4.2. The output of the VSS consists of row and column numbers for the tiles in the current frame where the VSS located a potential crack, as well as the integer-valued direction number determined by the algorithm. This data is translated into real-world coordinates using information from the VOC; this will be described in more detail later. The VSS data is not in a form that is usable by the RPS, as there is no relationship between the identified crack points as output by the algorithm. The path planning algorithm will convert the data into a format that is useful to the RPS. The VSS sends this information to the ICU over an Ethernet connection, and then begins to buffer up the next frame of data.

The ICU is the main coordinating process for the general crack sealing machine. All data for the various subsystems is routed through the ICU, and the ICU issues signals to the subsystems and handles signals received from the various subsystems. The ICU will take in the data from the vision system, initiate the path planning process, coordinate the transformation of the planned paths with the VOC data, and issue the paths to the RPS when the identified cracks are in the manipulator workspace. The ICU will also coordinate with the RPS by obtaining information regarding the current status of the crack sealing process. This status information is based mainly on the readings from the LSS, which is used to verify the planned path based on the VSS data, as well as to verify the presence and location of actual cracks. The ICU does not communicate directly with the LSS; instead, it receives LSS data indirectly by way of the RPS.

Once the VSS frame data has been received, the ICU notifies the path planning algorithm that data is ready. The path planning algorithm is part of the ICU, but is a separate process that runs in parallel with the main ICU routines. Path planning is used to clean up the VSS data, form connections between isolated but possibly connected crack segments, and form the data points into ordered sets that constitute reasonable paths for the RPS to follow to complete the crack sealing process. The path planning process begins by forming the VSS data into a matrix which represents an image of the road as identified by the VSS algorithm, and filters the data to clean it up. Then the planner identifies end points of individual segments and attempts to form connections between isolated points according to an empirically determined distance which represents the distance that actually connected crack segments may be separated by when processed by the vision system. The connections are made by placing a circular growth region, with a radius equal to half the above empirically determined distance, around each end point in the frame data. If segments are separated by less than the above distance, then they will be connected after this phase of the planning algorithm. The path planner next 'thins' this data to bring it back to images of cracks, using a thinning algorithm to strip out points in the data set while maintaining the general shape and connectivity of the image. After this, the path planner forms a data structure that represents all the connected crack paths for the entire frame of VSS data. When the ICU passes the coordinates of the current manipulator workspace to the path planning algorithm, it then extracts a data structure representing the connected crack paths for that workspace. This data is then transformed using information from the ICU, and passed to the RPS for sealing of the cracks. For a more detailed description of the path planning algorithm and its relation to the rest of the Integrated General Crack Sealing System, see "Path Planning for Robotic Applications in Roadway Crack Sealing" by T. A. Lasky and B. Ravani.

The VOC system tracks the position and orientation of the crack sealing vehicle relative to a world coordinate reference frame. As the VSS identifies potential crack locations, the VOC uses the position of the truck relative to the world frame, in conjunction with known and fixed transformations between the subsystem reference frames on the vehicle, to mark the position of the crack locations with respect to the world reference frame. At any subsequent time, the VOC can transform this point in the world reference frame into the RPS reference frame, using the known and fixed transformation from the vehicle frame to the RPS frame, along with the current transformation from the world frame to the vehicle frame. Thus, the paths that are established by the path planning algorithm, since they are essentially collections of points identified by the VSS, can be transformed into the RPS reference frame so that the RPS can guide its tooling along this path to seal the cracks.

The RPS takes the planned and transformed path from the ICU, and uses this path to position the tooling to prepare and seal the identified crack. The communication between the ICU and the RPS is over an RS-232 serial line. The RPS will initially use the pre-planned path to get to the start of the crack, and will subsequently use this path as a nominal position trajectory. Using the LSS sensor, which is mounted on the manipulator tooling, the RPS can verify the presence or absence of the identified crack. This is required for at least two reasons. First, the VSS cannot distinguish between cracks, oil on the roadway, and previously sealed cracks. As long as the image has the appropriate light/dark histogram to pass the VSS comparison algorithm, it will be identified as a crack. Only the LSS, with its ability to measure the height profile of the road, can actually verify the presence of the crack. Second, there will be accumulated error introduced by the VSS, the path planning algorithm, and the VOC. Without any local feedback of the position of the crack, the RPS would have no way to adjust for this accumulated error. The RPS will use the orientation information from the planned path without modifying it, as the LSS information is insufficient to determine a good measure of the crack orientation. The RPS can use this orientation information to align the tooling with the crack, the offset error of the tooling from the center of the crack can be identified with the LSS, and the RPS can modify its trajectory in a closed-loop fashion to eliminate this error. In the case that the accumulated error exceeds the range of the local sensor, the RPS can enter a search mode, in which it scans perpendicular to the assumed direction of the crack, until it locates a crack. The RPS will pass signals back to the ICU indicating the status of its operation. For example, the RPS can pass the LSS error signal back to the ICU periodically, and the ICU can monitor this information over time, and use it to identify the need for system or component recalibration.

4

Second Generation Machine Components

4.1 - Integration And Control Unit (ICU)

4.1.1 - Introduction

The development of an Automated Crack Sealing machine (ACSM) included the integration of a variety of sensing, command, and actuating systems, which synchronously perform tasks in real-time. A control architecture was developed to assure that these systems act in a coordinated manner to achieve the overall goal of sealing pavement cracks at an acceptable performance level. It is important to note that control system architectures have the definitive purpose of ensuring that a task is achieved and correcting for any deviations affecting the execution of this plan. From a technical standpoint, the control architecture requires a modular configuration in order to profoundly affect the versatility and maintainability of the resulting product. There is also a direct connection between the control architecture and design time, integration and overall functionality of the product. Furthermore, from an industrial standpoint, architecture choices are commercially important in the production costs and marketing appeal considerations. In short, the choice of the control architecture for a particular product can have a profound affect on the development as well as the commercialization of that product.

During the Phase I feasibility study, it was determined that the Integration and Control Unit (ICU) of the Automated Crack Sealing Machine oversee all operations from start to finish. This control unit needs to coordinate and initiate information and control flow between the separate systems of the machine. The ICU, therefore, acts as a liaison between the otherwise disassociated systems.

In addition, the control system must perform efficiently to sustain ACSM operation at the required speeds. The following diagram, Figure 4.1.1, provides some insight into the ICU architecture and information flow from other subsystems.

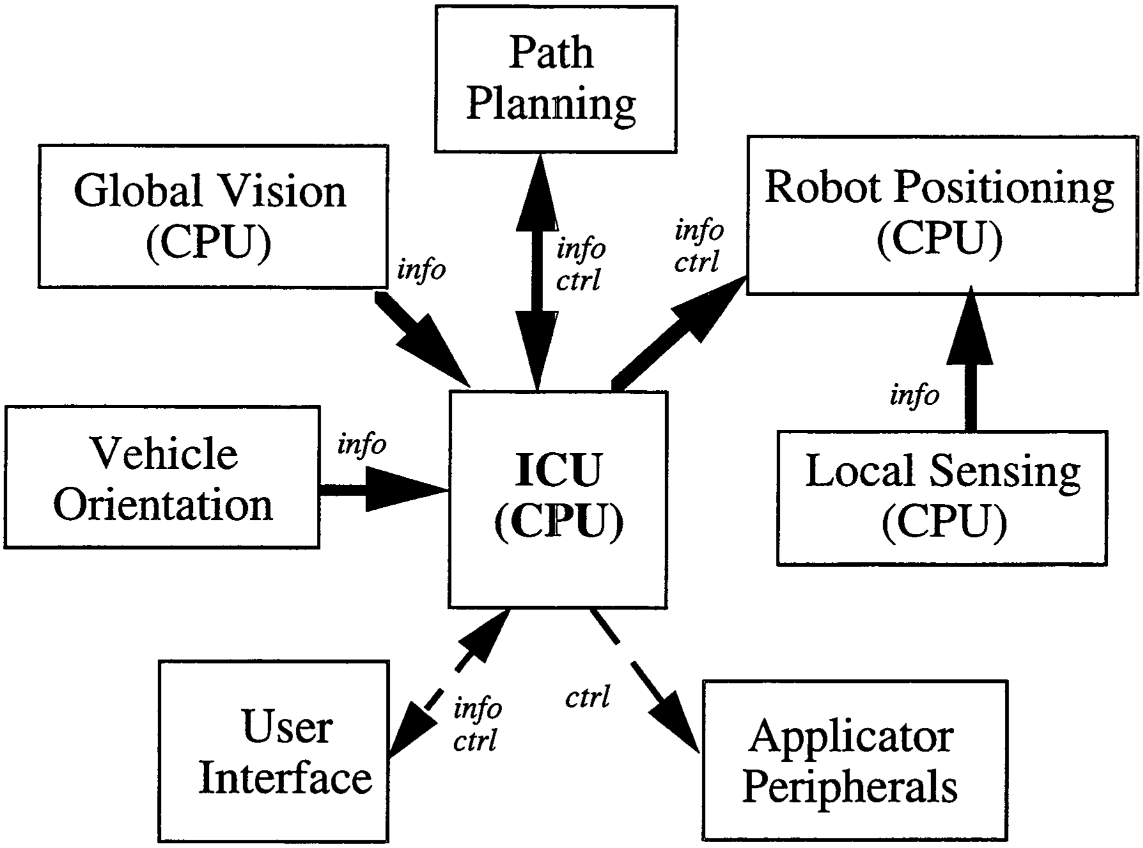


Figure 4.1.1 - ICU Functional Architecture, Minor Links Are Not Shown.

Specifically, the ICU takes crack location information from the Vision Sensing System (VSS) and uses Vehicle Orientation and Control (VOC) system information to translate that path into a form usable by the Robot Positioning System (RPS) and valid for the current reference frame. Thus, the ICU accommodates path planning and updating algorithms necessary for accurate crack/joint sealing/filling. The ICU also interacts with the Applicator and Peripherals System (APS) in order to synchronize applicator positioning and usage. Figure 4.1.6 illustrates overall logic followed by the ICU main program.

In review of the machine requirements, it is apparently necessary for the ICU to meet the following criteria:

- fast and efficient computation

- able to recognize and process prioritized interrupts
- process concurrent information rapidly (multitasking)
- retain sufficient spare capacity and flexibility to expand
- support multiple processors
- expandable backplane

In addition to these necessary requirements, other system development requirements were recommended as follows:

- modular in both hardware and software design
- application software should be developed in a user-friendly environment that is common to many programmers
- system software should be ROMable to enable an embedded application
- vehicle mounted ICU needs to be rugged to operate in a hostile environment (the environment as described in the Phase I report)
- compatible with other Caltrans/UCD in-house development efforts and expertise

Considering the responsibilities of task monitoring as well as the development requirements, the ICU team assessed, recommended and purchased a "mother system" for the crack sealing machine and acquired a development system. Based on compatibility with other subsystems, ruggedness, bus transfer rate, multiprocessing capability, and compatibility with other highway maintenance automation projects, the Single Board, Smart I/O, STD Bus, PC/AT, and MultiBus options were eliminated. The VME system bus architecture utilizing the OS-9 real-time operating system was selected as the most desirable based on all considerations and requirements. The VME bus provides the highest bus transfer rate, is rugged enough to perform in the maintenance vehicle environment and is a truly flexible system. The VME bus provides the flexibility, compatibility, modularity, and multiprocessing necessary for the efficient operation of the ACSM. OS-9 was recommended as the operating system for the VME bus because it is increasingly accepted as a standard and complies with the requirement to be compatible with other ACSM subsystems and other Caltrans and UC Davis automated highway maintenance projects.

4.1.2 - The Development Environment

A Sun SPARC II workstation was used as the development system for the ICU software, since it provided the user-friendly programming environment required for a development system. This workstation has been loaned to the project by Caltrans and is used only for ICU development; the final ICU employs only the VME hardware without the workstation. The Sun workstation is connected to the VME system (target system) via an Ethernet backbone. The Sun workstation combined with the VME system is referred to as the 'development environment' and serves as the programming environment when connected via the 'telnet' command. Using the VME system terminal, only one process, such as editing a program or executing code, can be run at once. In using the Sun workstation development system, however, multiple windows and multiple tasks are accommodated. Thus, several windows and processes can be open and running on the workstation. In this manner, the programmers can edit a program in one window while another program is compiling in another window and, perhaps, even executing through another window. Therefore, many processes can be executed at once, allowing for quicker program development and accurate testing of the multitasking capability of the VME system. Since it is connected to the VME system via Ethernet, the Sun workstation also serves to simulate the Vision Sensing System (VSS).

In order to provide a user-friendly graphical interface, the RAVE (Real-time Audio Visual Environment) system was added to the system recommended in the Phase I report. The RAVE system, with software developed by Microware, Inc. and hardware developed by Vigra Corporation, is designed to allow development of a graphical user interface. The RAVE software provides a library of graphics, representing dials, meters, buttons, etc., and allows the programmer to create an interactive operator screen. RAVE generates the resulting code for the graphics portion of the interface, while the programmer adds the code to be executed upon user interaction. For example, the programmer can specify that a red and black vertical meter be placed on the interactive screen in a certain position; RAVE will generate the code to recreate this graphic image; the programmer can then add code to cause the vertical meter to move according to certain input. In this manner, a complete user interface screen to serve as the "Crack Sealing Machine Control Panel" was easily defined and developed. Correspondingly, an Input/Output program has been developed.

4.1.3 - Detailed Component Description

The components of the ICU are of two types - hardware and software. Throughout the project, hardware components were added and several software components were developed. These components were developed individually and then integrated to form the ICU. Following is a current list of ICU components with detailed descriptions of each. Appendix B contains manufacturer and model number information for many of the items discussed below.

4.1.3.1 - Hardware Components

Backplane (HSE/17R-12V-W60-F3-S150-Ethernet Cables)

The backplane integrates all the cards of the ICU. It includes a 17.5 inch (height) rack mount enclosure with 12-slot VME card cage, 500 Watt power supply, 60 MB Embedded SCSI hard disk drive, 2 MB 3.5" (38W7 format type) floppy disk drive, 150 MB 1/4" Archive Streamer Tape Drive and Ethernet Cable Package which includes an Ethernet Transceiver, Transceiver cable, 10 ft. Thin Net Cable, T-connector (Thin-Net) and 2-Terminators (Thin-Net).

CPU Card (HK68H/V3E-16 MB)

Includes a 50 MHz 68030 CPU with 16 MB DRAM, 128 bytes non-volatile RAM, 4 RS-232 ports, single parallel port, VSB compatible bus interface, SCSI interface, time of day clock and full interface to VME bus with four level system controller functions.

Analog I/O Card (XVME540)

Analog I/O card. 12-bit A/D and D/A conversion. 16 channel, 4 channel output. Inputs configurable to bipolar or unipolar with 12-bit conversion resolution.

Digital I/O Card (XVME201)

Digital I/O card. VME bus interface, two 68230 Parallel Interface Timer (PI/T) chips, and TTL buffers to provide 48-bits of digital I/O. 4 bi-directional 8-bit ports and two 16-bit ports.

Communications Card (CMC ENP-10)

Ethernet communications card. Interface between VME bus host system and Ethernet. Processes network protocols, manages the local bus and performs DMA transfers across the bus.

Multimedia Graphics Card (MMI250)

Hardware component of the Real-time Audio Visual Environment (RAVE). A high performance graphics board for the VME bus that combines graphics frame store, keyboard, RS-232C, and sound output functions to provide an effective man-machine interface. It is a standard 6U board with both VME bus and VSB bus interfaces, and provides a bit-mapped color graphics controller, an IBM/PC compatible keyboard interface, two RS-232C compatible serial ports, and 4 MB of multi-ported frame store RAM. The MMI250 provides the hardware necessary to run the user interface screen, keyboard, speaker and the graphical processing required for real-time display of information.

Connection Box

A Connection Box was designed and built to provide a clean connection point between various peripheral lines/wires and the ICU's input/output ports. This box has a side where all input/output wires, bundled together, enter the box. Within the box, there may be signal conditioning devices to eliminate noisy components of desired signals or to boost the signal strength. Also within the box, all wires are terminated to a connection bar. The connection bar accommodates the ribbon cables connected to the ICU. Here, the wires from the peripheral systems are assigned to their expected port bits or analog port wires. This box provides a focal point for signal troubleshooting, as well.

4.1.3.2 - Software Components-Basic System

Software modules developed by the team are typically generic. This simplifies the task of interfacing with other subsystems of the crack sealing machine. Integration will require only minor modifications to software modules.

Operating System (OS-9 Professional)

Real-time, multi-user, multitasking operating system with a system state debugger and a source level debugger.

Software Drivers (ENP-10 and XVME982)

Software drivers for Ethernet and I/O cards with all requisite libraries.

Real-time Audio Visual Environment (RAVE)

A graphical user interface development package which can be customized for a specific application. This has the capability to provide real-time machine control and to provide real-time user feedback.

4.1.3.3 - Software Components-System Test Modules

The following modules were developed to test the I/O cards and to develop multitasking capabilities:

analogio.c	Initializes the analog I/O board(XVME540) and reads analog input signals from input channels.
anrave.c	A modified version of analogio.c to work with RAVE.
diotimer.c	Tests the functionality and initializes the digital I/O board.
demo540.c	Tests the interrupt generating capability of the analog I/O board (XVME201).
proc1.c	Tests the multitasking capabilities of OS-9 operating system. In particular, tests the signal and pipe mechanism while running concurrent processes.

4.1.3.4 - Software Components-Data Modules

icu.data	Disk based crack configurations generated by the Vision Sensing System (VSS).

4.1.3.5 - Software Components-Communication Modules

The following modules were developed to test the communication cards and to develop data transfer capabilities on the Ethernet network:

crckdisp.c	Receives crack information from the Vision Sensing System (VSS) and displays it on the user interface.
drawarray.c	Displays crack information obtained from magnetic media (disk).
hold.c	A network driven interrupt handler to facilitate processing of information exchange on the Ethernet.
send.c	A module to send data from icu.data to comdraw.c over the Ethernet network.

sockets.c	This program makes a request to vision system, actually the request is made to visionhold. Visionhold interrupts visionstub through a pipe "/pipe/hv". Visionstub handles the signal and replies vision data through "/pipe/vh" to visionhold. Visionhold picks up these data and sends them to sockets. The Visionhold and Visionstub programs reside on the VSS.
rpscom.c	Sends path information of the crack to the Robot Positioning System (RPS) over the serial communication port. Receives two types of data from the RPS, i.e. signals indicating the current status of the RPS and the current location of the end-effector. In case of errors it sends a new planned path to the RPS.

4.1.3.6 - Software Components-Main Module

acsm.c	This program integrates the above mentioned Test, Data and Communication modules. Various sub modules are utilized by acsm.c. These include graphics generators, mouse and keyboard facilitators, sound generators communication subroutines. The program also forks out a process to the path planning and VOC subsystems.
dmod.c	This routine deals with process synchronization and concurrency control, i.e. it is used to create, link, unlink, lock and unlock data modules.
utilities.c	Deals with the conversion and formatting of data.
init_anaio.c	Does the diagnostics and initialization of the analog I/O board(XVME540).
init_digio.c	Does the diagnostics and initialization of the digital I/O board(XVME201).
sealantio.c	Provides operator level control to the applicator peripheral systems.

4.1.3.7 - Software Components-User Interface Module

Buttons: vrsbut.c, hydrbut.c, roubut.c, slbut.c, comprbut.c, glowbut.c, lpsbut.c, gnrbut.c, starbut.c, sealbut.c, stpbut.c, lpsbut.c, closebut.c, ssupbut.c, positionbut.c, sealpowerbut.c, moverbut.c, genmcbut.c, longbut.c, powonbut.c, powoffbut.c.

Overlay windows:

statsovl.c, crwinovl.c, vrsovl.c, hydrovl.c, routovl.c, newovl.c, compressovl.c, glowsovl.c, lpsovl.c, generovl.c, statsovl2.c, powupovl.c.

Indicators: mltmtr.c, mltrmtr1.c, sealmeter.c;

Screen: acsmscr.c, standby.c.

4.1.4 - Description of Tasks

Five distinct ICU tasks are as follows:

1. System diagnosis and initialization

2. Data communications with other ACSM subsystems

3. Input/output with machine hardware

4. Operator machine control and monitoring via user interface

5. ACSM information flow and control.

The task of system diagnosis and initialization would be conducted at the beginning of a crack sealing run. Initialization clears any control lines and resets them to an initial setting. Other dependent systems are also reset and prepared for communication. Any system and/or subsystem problems are identified and corrected, if possible, in this stage. The initialization routine for the ICU is executed by several independent routines. These routines specifically initialize and diagnose the XVME540 (Analog I/O), XVME201 (Digital I/O), and HK68H/V3E-16 MB (CPU) boards of the ICU. The initialization and diagnosis processes are shown in Figure 4.1.2.

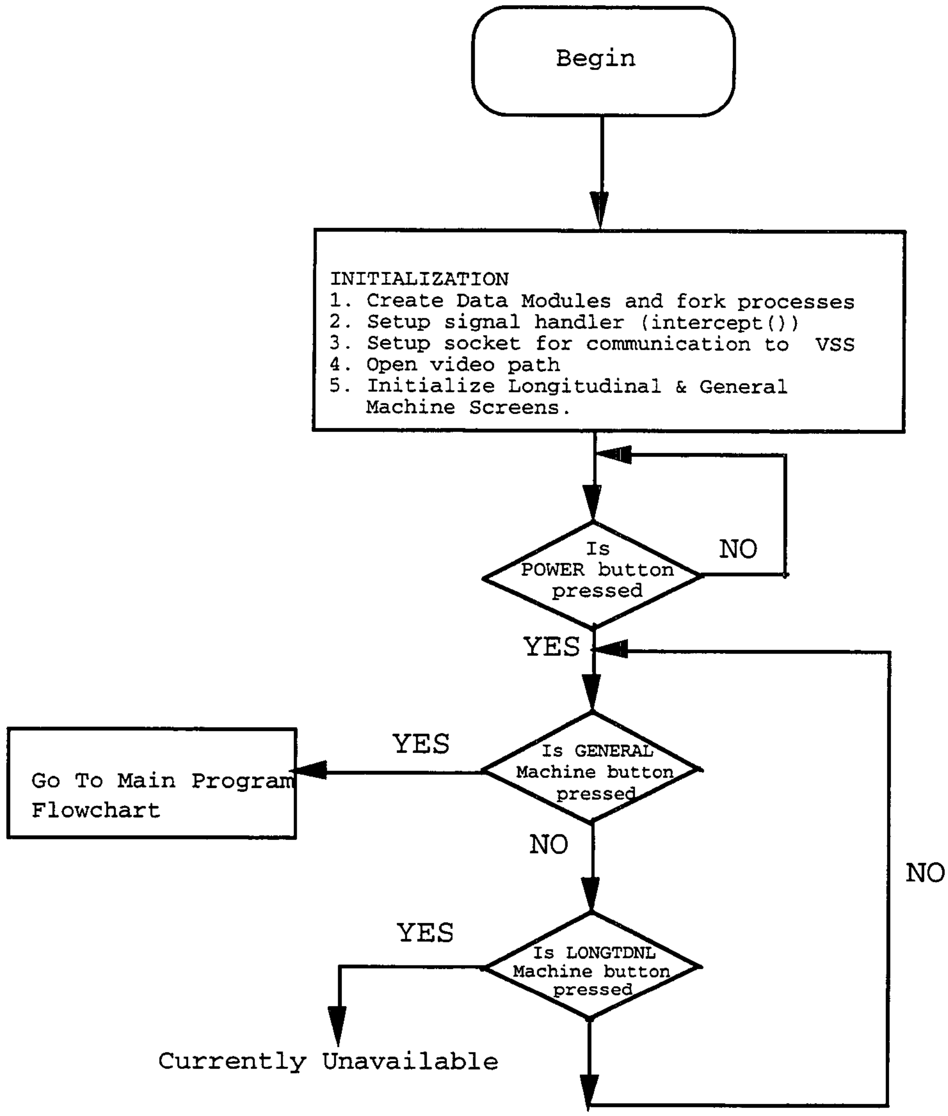


Figure 4.1.2 - ICU Initialization and Powerup.

The task of communicating with ACSM subsystem refers to Ethernet communications through the ENP10 Ethernet board and backbone and to RS232 communications through the serial port. Ethernet communication is used with the Vision Sensing System (VSS). Data from the VSS is sent over the Ethernet network to the ICU. The ICU waits for the data and displays it on the user interface whenever it is transmitted. Figure 4.1.3 is the flowchart for the Ethernet communications between the ICU and VSS.

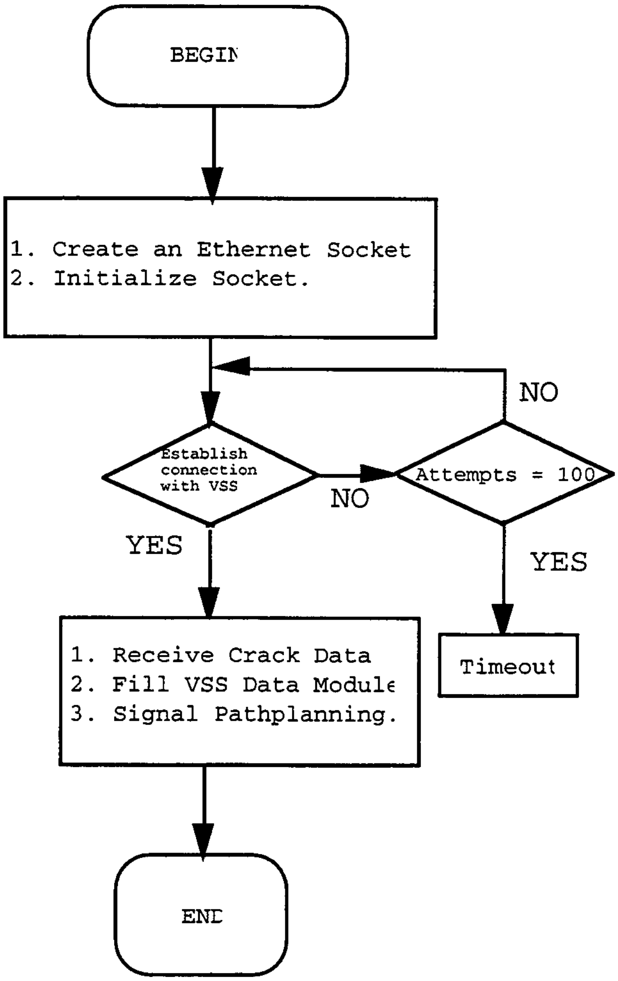


Figure 4.1.3 - ICU and VSS Interaction.

Data exchange between the other sub-systems is via shared memory, or Data Modules, on the ICU OS-9 system. This memory is accessed in real-time by the sub-systems needing to access the crack data. Figure 4.1.4 shows the various tasks and processes involved. Crack data from the VSS is automatically sent to the ICU over an Ethernet link for every twenty feet of forward motion of the vehicle. The ICU receives this data and stores it in a data module called the VSS data module. Then, the ICU signals the Path Planing(PP) that the crack data is available. The PP uses this data to plan a path and writes the result into a data module called the Planned Path data module. The PP signals the VOC that data is available for the VOC to use. The VOC reads this data in and processes it. It then writes to another data module called the VOC data module. The VOC signals the ICU that it has completed its processing. The ICU then sends the processed crack data to the RPS via the RS232C communications port.

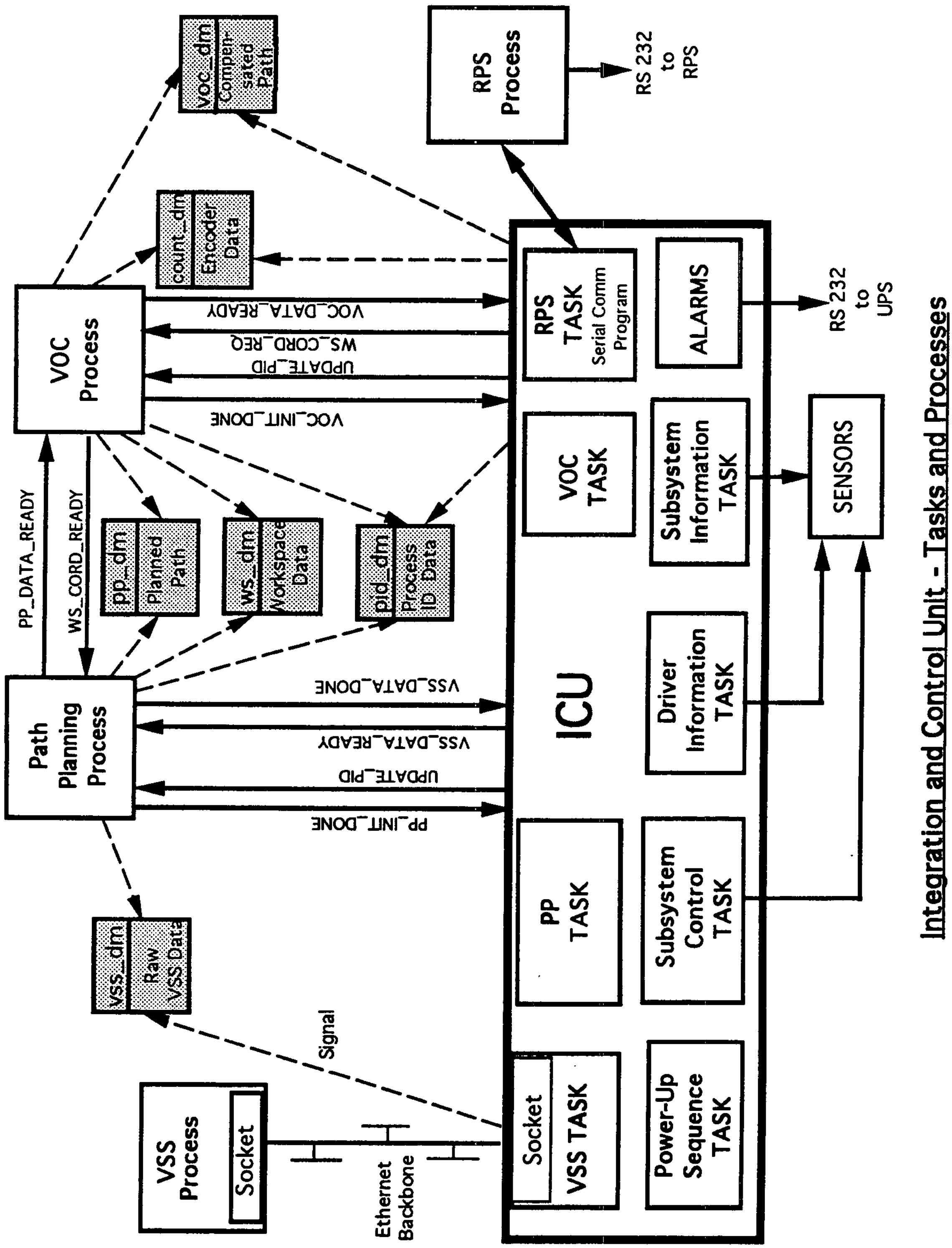


Figure 4.1.4 - ICU Communication and Data Modules.

The ICU communicates with the Robot Positioning System (RPS) through the serial port, 't2'. Information about crack locations is passed to the RPS; information about status of finding and/or following the specified cracks is passed back from the RPS to the ICU. The communication between the ICU and RPS is transparent to the user unless the RPS doesn't find a crack where it was specified. In this case, the user is notified about the search routine in progress and about its success. The ICU transmits crack location data to the RPS when the current frame of data has been updated following the RPS-initiated search routine or when the truck has moved forward, stopped, and the operator has specified that a new workspace is ready to be sealed.

The ICU also receives information from the Uninteruptible Power Supply (UPS) through another serial port. Information activated in emergency situations, such as a power outage, will be transmitted to the ICU over this line.

Subsystem input/output includes information passing through the analog and digital boards. This task handles the subsystem control and/or monitoring not handled through the Ethernet or RS232 links. An example is the control of the sealant supply to the Applicator and Peripherals System (APS) in coordination with the RPS operation. Input/Output wiring terminates in the connector box described in the Hardware Components Section 4.1.3.1 and the digital and analog boards access the peripheral signals at this box. The ICU is prepared to test UPS alarming and specific sensor monitoring and control, however, this testing is reserved for the next generation ACSM. The following is a list of peripheral signals available to the ICU:

Melter: propane pressure, sealant temperature, oil temperature, flame out
Sealant Applicator: sealant level, applicator position, rotation, sealant supply
Heating and Cleaning System: road temperature, system on/off, diverter control, blower on/off, heater exhaust temperature, system failure, propane level
Router: on/off, up/down
Vacuum System: on/off, vacuum pressure, filter pressure loss
Hydraulic Pump: solenoid status
Generator: ammeter, engine temperature, on/off
Longitudinal Positioning System: on/off hydraulics, on/off system, controller output (status)
Air Compressor: pressure, on/off pump

Communication to these peripherals is handled by routines within the main module, acsm.c, as described in the Software Components Section 4.1.3.6.

The user interface allows control of the machine and displays the status of the ACSM in real-time. Figure 4.1.5 is the basic user interface screen. The crack window shows graphical data about the cracks within the current workspace of the robot. In the status window, the operator can see messages regarding the status of the operation. The purpose of the peripheral buttons is for monitoring APS in the next generation ACSM. The melter window is also for constantly displaying this information in the next generation ACSM. (These functions are ready to implement, but haven't been tested. This work is not critical to the operation of the ACSM and will enhance the next generation ACSM). The buttons in the lower left portion of the screen allow the operator to indicate to the system when an operation will begin, when the truck has stopped and sealing can safely commence, and when the operation should be stopped. The VSS data is not processed until the START button is pressed; the RPS is not prompted until the SEAL button is pressed; and the operation continues until the STOP button is pressed.

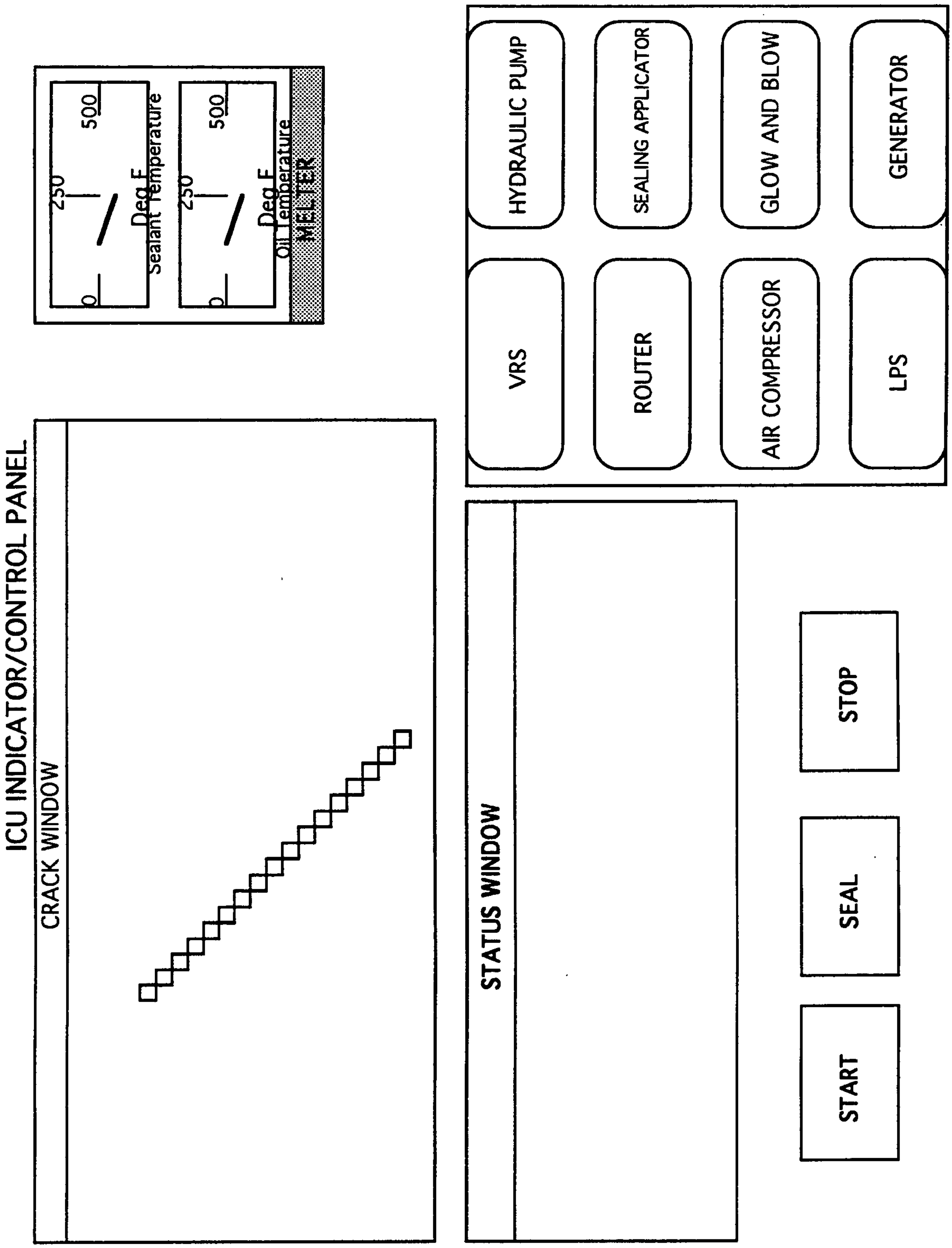


Figure 4.1.5 - User Interface Screen.

Information flow within the ACSM is controlled by the ICU. Specifically the crack data is obtained from the VSS at the right phase of the operation of the machine and transferred through the Path Planning and VOC subsystems before transferring it to the RPS at the appropriate time.

The logic used by the ICU program to coordinate data communications, data processing, and user interaction is shown in Figure 4.1.6.

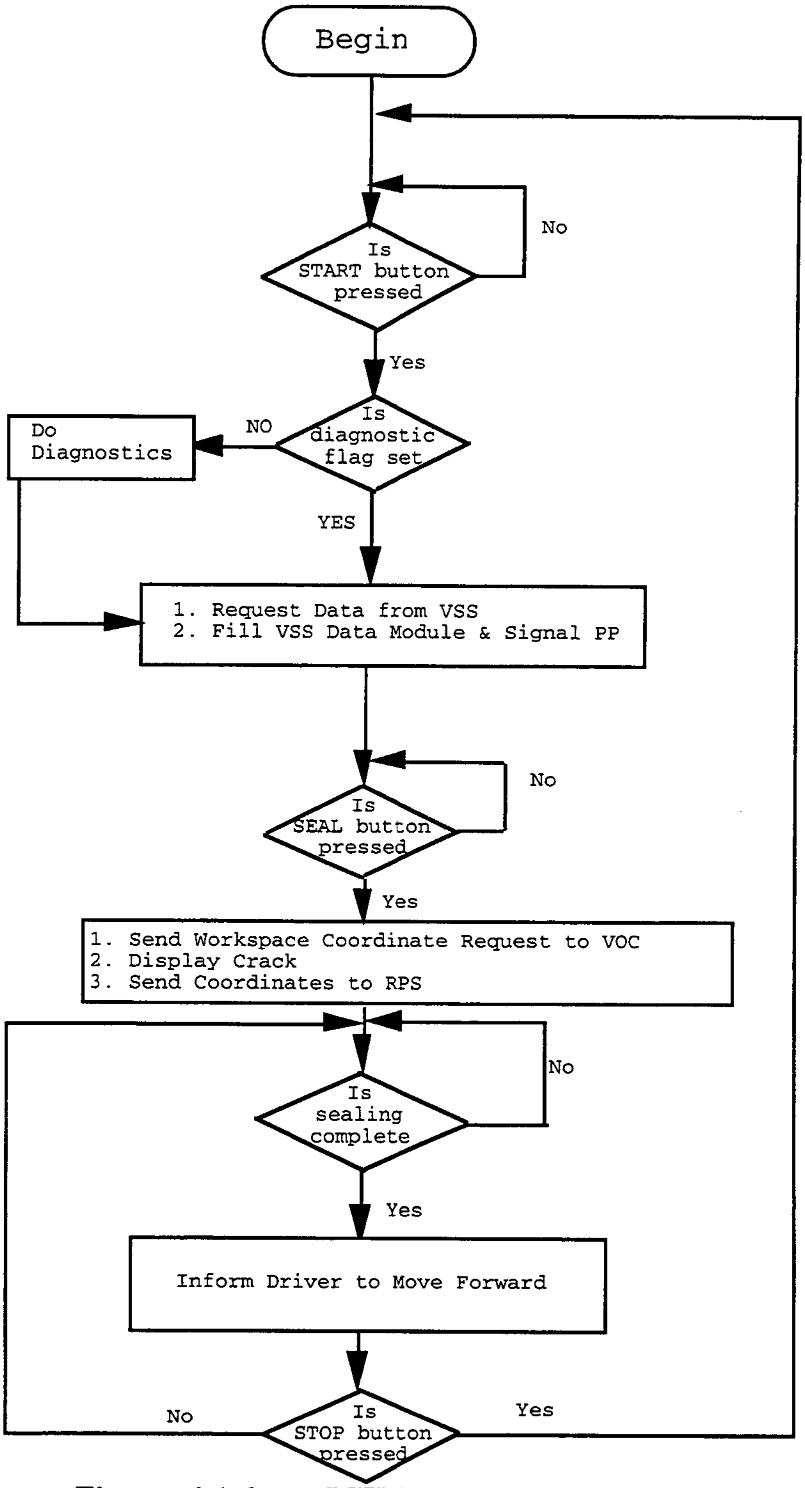


Figure 4.1.6 - ICU Main Program Logic.

4.1.5 - User Operation of the ICU

At the beginning of a sealing operation run, the operator turns on the main power to the computer system. The ICU boots up and automatically runs the ACSM User Interface Program. The operator is, then, prompted to choose the mode of operation (longitudinal crack sealing or general crack sealing) in order to begin. Following diagnostics and initialization, the system is ready for sealing operation. During the operation of the ACSM, several points are valid:

The START button is pressed by the operator when in a crack treatment area and the VSS is sensing for cracks. The SEAL button is pressed by the operator after the driver has completely stopped the vehicle motion. Following the SEAL command, the ICU initiates data processing by the Path Planning and VOC modules and transmits crack coordinates to the RPS for sealing. The STOP button is pressed by the operator when cracks should no longer be sensed. Following the STOP command, the operator is prompted to enter whether the whole operation is done and shutdown can commence or the operation is only interrupted and the machine should remain ready to START again.

4.2 - Vision Sensing System (VSS)

4.2.1 - System Description

The purpose of the Vision Sensing System (VSS) is to locate pavement crack positions using machine vision. This section describes the functional aspects of the VSS. Subsequent sections give a description of the physical system, its components, and how the VSS relates to other parts of the Automated Crack Sealing Machine (ACSM).

The VSS consists of two cameras, lighting, an encoder, and a system unit which encompasses image processing hardware and crack detection algorithms. The VSS is to identify cracks greater than .20 inch wide on Portland Cement Concrete (PCC) and Asphalt Concrete (AC) roadways. The VSS processes information from a gray scale image of the top view of a section of pavement, approximately twelve feet wide (one lane width). Acquisition of the image is coordinated with the rotation of the ACSM wheels in order to maintain a proper aspect ratio of the pavement image. Hence, the generation of the image is driven by the forward movement of the vehicle. As the computer acquires sufficient blocks of image data, a ten-inch long by twelve-foot wide block of video data is built in increments of two-inch square tiles. For each of the tiles the determination is made as to whether a crack exists, and if so, in which of sixteen directions it is oriented. This data is immediately transferred to a remote storage area for path planning, with its position updated from the ICU and Vehicle Orientation and Control System (VOC) as the vehicle continues to move forward. No attempt is made by the VSS to connect indications of crack presence among tiles. This is left for the path planning process. Functional components of the VSS can be seen in Figure 4.2.1. The actual operational steps (single camera shown for convenience only) are shown in Figure 4.2.2.

4.2.2 - Principles of Operation

The most fundamental portion of the Vision Sensing System is the algorithm that determines crack presence. This algorithm consists basically of four steps:

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

We make note that the algorithm makes no attempt to obtain a binary image in order to determine more specific qualities of crack segments through chain coding or other means. To follow is a more detailed description of these four steps.

A video image of the pavement is created with a pixel resolution sufficient to resolve an 1/8 inch feature. In order to satisfy the Nyquist sampling frequency this requires a pixel for every 1/16 inch of highway pavement. A grid is then created to carry information about pavement features contained within tiles (see Figure 4.2.3). Each tile within the grid is represented by 32x32 (1024) pixels. Through the building of a histogram for each tile and a moment computation, the data representing each tile can be reduced from 1024 counts of 8 bit data (8192 bits) to one 32-bit integer representing the statistical moment. This allows quick manipulation of data in order to determine the presence of a crack. The manipulation of the reduced data is further described below.

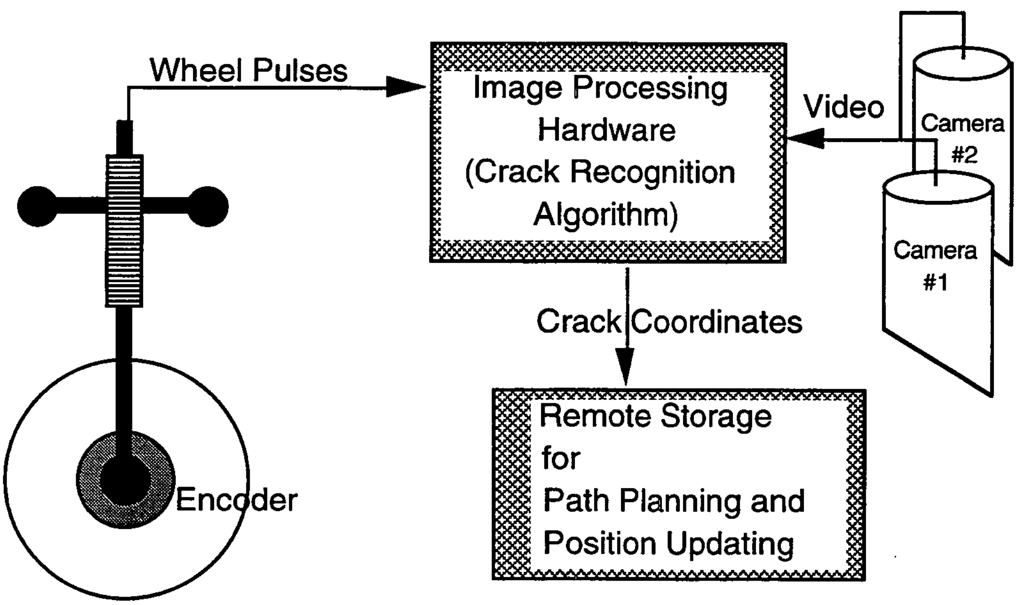
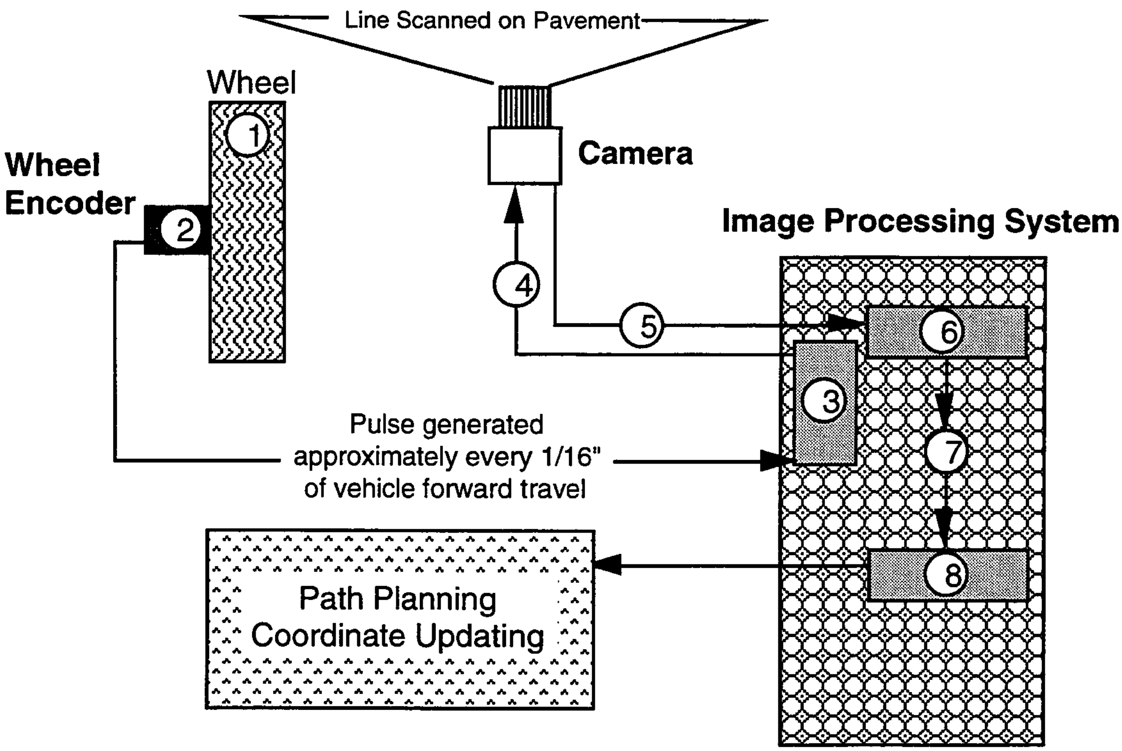


Figure 4.2.1 - Vision Sensing System Functional Layout.



VSS Event Sequence

1. Wheel rotates an incremental amount.
2. Encoder produces a pulse resulting from incremental vehicle travel.
3. Image processing hardware reads pulse from encoder, encoder circuitry filters out vibrations.
4. Encoder circuitry sends control signals for camera to acquire video line.
5. Camera returns a video signal representing one line of pavement back to the Image Processing System.
6. Image Processing Hardware procedure iterates until enough lines are gathered to determine crack presence.
7. Algorithm determines crack presence in image (in local areas called tiles) and transmits crack information to communications device.
8. Communications device then sends crack information to ICU for subsequent path planning and crack sealing (external to Vision Sensing System).

Figure 4.2.2 - Principles of Operation.

The tile size of 32x32 pixels allows for a minimal variance in local modes by reducing the effects of intensity changes within a tile due to differing shades of aggregate and surface defects without significantly affecting the accuracy required to perform the sealing operation. The small variance in modes allows for a comparable measure of darker gray level values among adjacent tiles. This characteristic of local modes is what specifically allows for the recognition of cracks based on moments about local modes. A local region is defined as a 5x5 grouping of tiles. This is the minimum number of tiles required to identify the sixteen directions we have selected to recognize.

Originally, there were eight directions incorporated in the algorithm, but cracks that should have been detected were being thrown out by the original eight comparison routines. Figure 4.2.4 shows the sixteen directions that can occur within a 5x5 grouping of tiles. From the debugging routines, we saw that the majority of the cracks fell in between two comparisons. Thus, the original eight directions did not provide adequate information to Path Planning. Instead of forcing a crack detected between two crack comparisons, eight more crack directions were added.

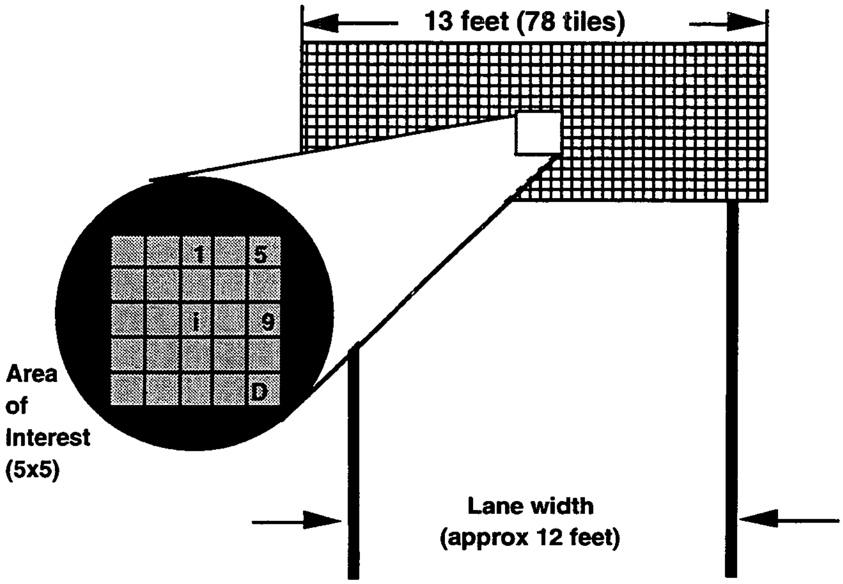


Figure 4.2.3 - Crack Directions Within 5x5 Area of Interest.

Next, histograms are created for each tile. A histogram is an ordering of pixel values based on intensities. The number of pixel values that occur in a given area are represented by 256 vertical bars, one for each image gray level (see Figure 4.2.5).

Following the creation of a histogram, a statistical moment is taken about the mode of the histogram for each tile. The mode is the highest value in the distribution. The moment is taken by summing the product of the cubed distance from the mode and the height of the bar for a given intensity value. This is shown in Figure 4.2.6.

Once the moments are computed for each tile, the moment values are compared within independent 5x5 tile grids. See Figure 4.2.3 for four of the sixteen directions which can occur in this grid. Every tile in the grid (except two tiles on each end) takes its turn as the center tile in the 5x5 area of interest.

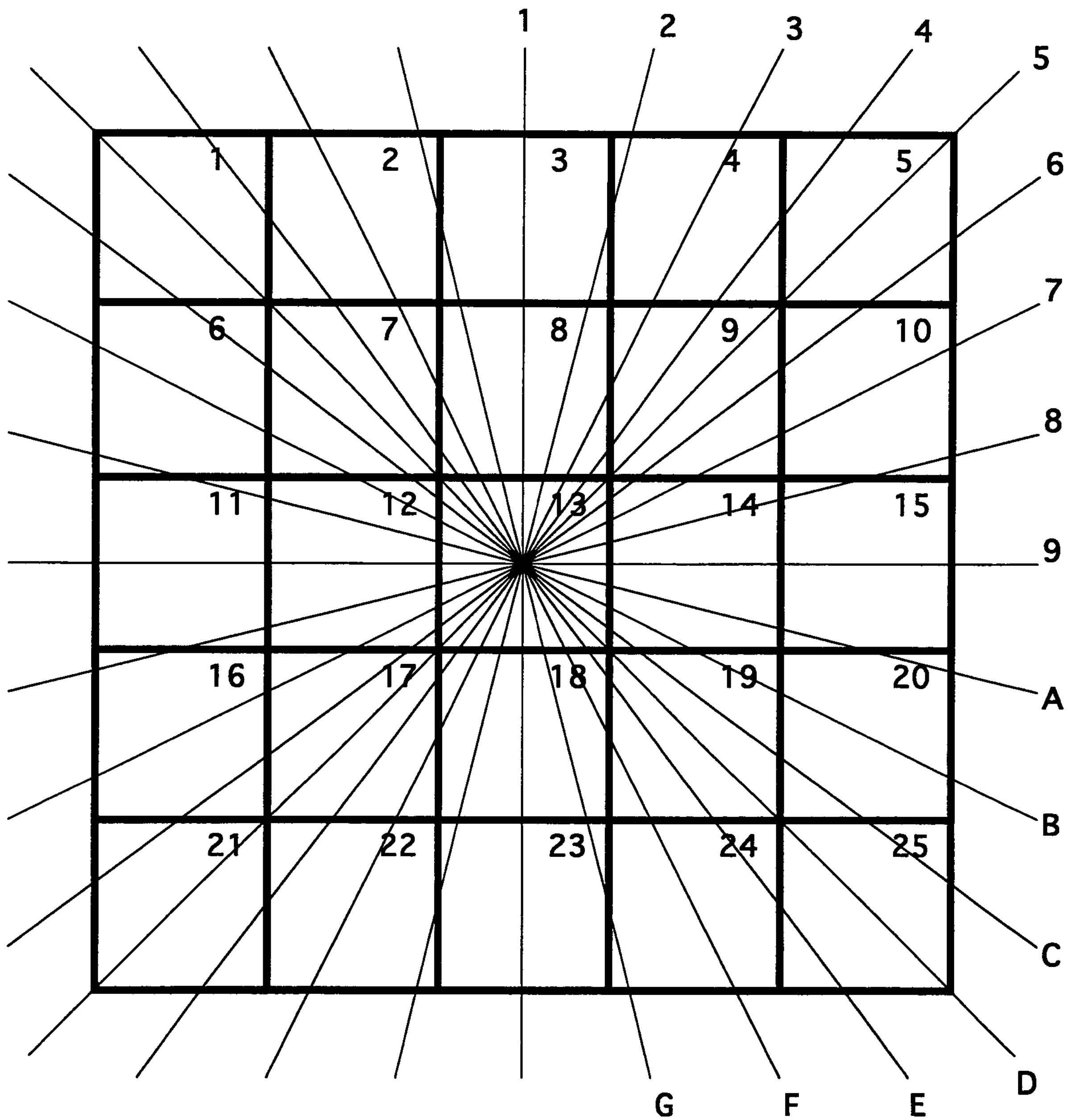


Figure 4.2.4 - Crack Directions.

In the preliminary tests, the comparisons were based on two parameters, the continuity level and the uniformity level. These two parameters determine the extent and the type of comparisons made within the 5x5 area of interest in order to determine the presence of a crack and its direction.

Three crack length selection levels were considered for a crack tò exist. These selection levels were called continuity levels. Figure 4.2.7 shows Direction 5 crack segments and the required continuity levels which will accept or reject a crack based on its length. From Figure 4.2.7, it can be seen that a continuity level of 1 requires a crack to occupy only one tile, a continuity level of 2 requires a crack to occupy three tiles, and a continuity level of 3 requires a crack to occupy five tiles.

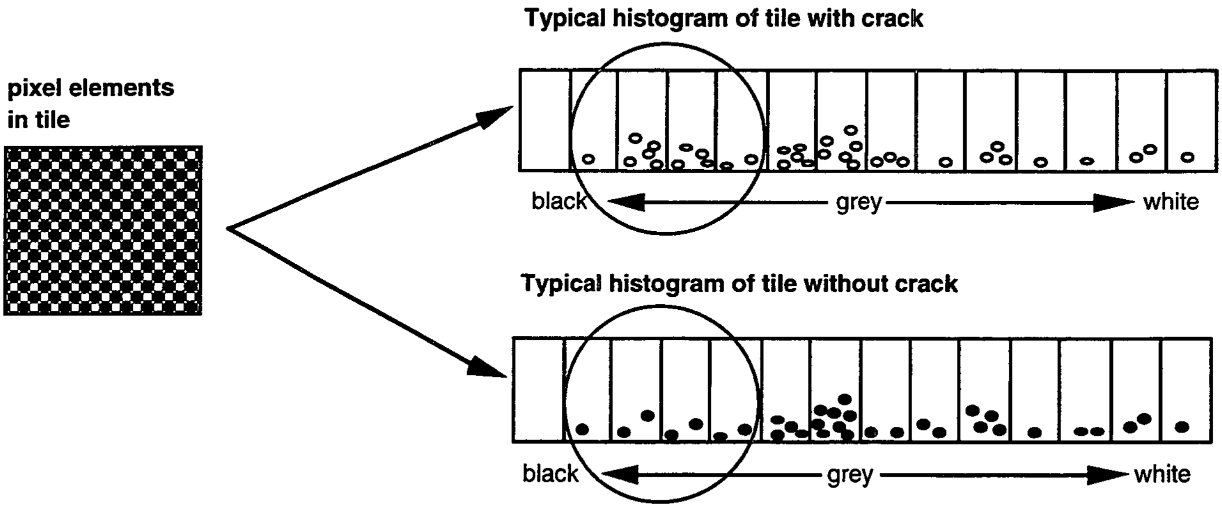
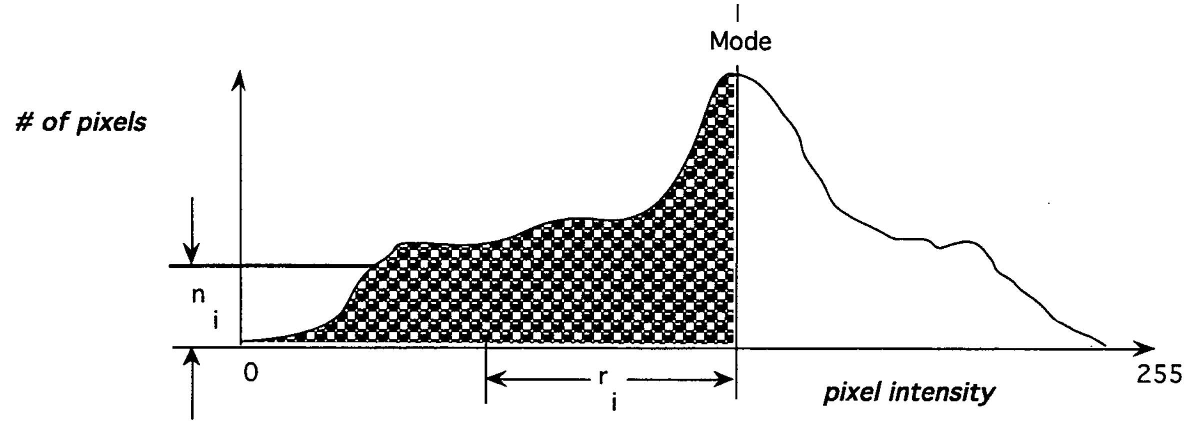


Figure 4.2.5 - Histogram of Cracked and Non-Cracked Tile.

However, since the resulting crack detection rate of forty percent from the extensive field tests on the previous comparison routine was well below the expected rate, average comparison values "C" are now implemented in the algorithm. Cracks that should have been recognized by the original compare algorithm were thrown out if a dark item in one or more of the "C" areas occurs. These areas may have an occurrence of an oil spot or a rock. In order to compensate for these occurrences, a minimum crack value "D" is found by comparing all "D" values in each comparison. As shown in Figure 4.2.8, all "X" areas are compared to each other and the greater is compared to the minimum "D" value. The smallest value of the two, minimum "D," is then compared to the average of all "C" in that comparison routine. If minimum "D" is greater than average "C" then a crack is present and a corresponding value relating to direction is assigned to that crack. This revision has provided much greater crack detection by averaging the area surrounding the crack.



$$\text{moment} = \sum (r_i^{\,e} * n_i)$$

r_i=grey level distance from mode

n_i=number of pixels at r_i

e=power to which r_i is raised

Figure 4.2.6 - Moment Computation.

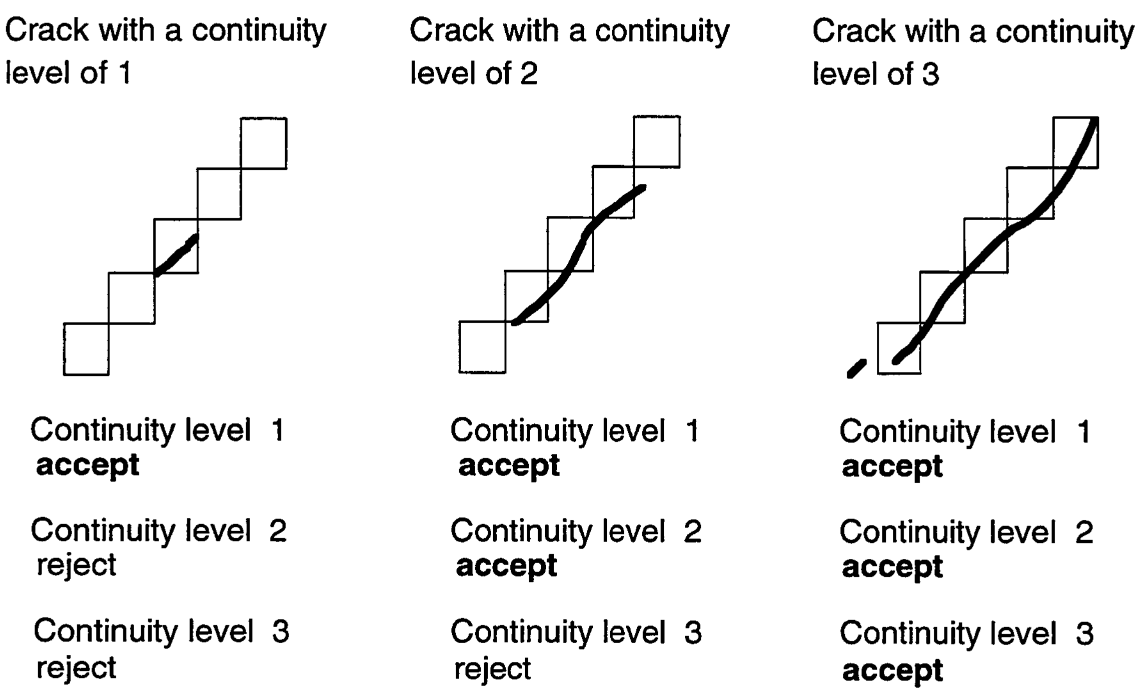


Figure 4.2.7 - Continuity Levels.

C		D		C
C		D		C
C		D		C
C		D		C
C		D		C

Compare 1

C		D		C
C		D		C
C		D		C
	X	X		C
	D			C

Compare 2a

C			D	
C		X	X	
C		D		C
C		D		C
C		D		C

Compare 2b

C	C		D	
C	C	X	X	C
C		D		C
C	X	X	C	C
	D		C	C

Compare 3

C	C		D	
C		X	X	
C		D		C
	D		C	C
D		C	C	C

Compare 4a

C	C	C		D
C	C		D	
C		D		C
	X	X		C
	D		C	C

Compare 4b

C	C			D
C	C		D	
C		D		C
	D		C	C
D		C	C	C

Compare 5

C	C	C		D
C	C		D	
	X	D		C
D	X		C	C
		C	C	C

Compare 6a

C	C	C		
C	C		X	D
C		D	X	
	D		C	C
D		C	C	C

Compare 6b

C	C	C	C	D
C	C		X	
	X	D	X	
D	X		C	C
	C	C	C	C

Compare 7

C	C	C	C	
			X	D
D	D	D	X	
C	C	C	C	C

Compare 8a

C	C	C	C	C
	X	D	D	D
D	X			
	C	C	C	C

Compare 8b

Figure 4.2.8 - Sets of Comparisons Grids for the Sixteen Directions.

C	C	C	C	C
D	D	D	D	D
C	C	C	C	C

Compare 9

	C	C	C	C
D	X			
	X	D	D	D
C	C	C	C	C

Compare Aa

C	C	C	C	C
D	D	D	X	
			X	D
C	C	C	C	

Compare Ab

	C	C	C	C
D	X		C	C
	X	D	X	
C			X	D
C	C	C		

Compare B

D		C	C	C
	D		C	C
C		D	X	
C	C		X	D
C	C	C	C	

Compare Ca

	C	C	C	C
D	X			
	X	D		
C	C		D	
C	C	C		D

Compare Cb

D		C	C	C
	D		C	C
C		D		C
C	C		D	
C	C	C		D

Compare D

	D		C	C
C	X	X	C	C
C		D		C
C	C		D	
C	C	C		D

Compare Ea

D		C	C	C
	D		C	C
C		D		C
C	C	X	X	C
C			D	

Compare Eb

	D		C	C
C	X	X	C	C
C		D		C
C	C	X	X	C
C	C		D	

Compare F

C		D		C
C		D		C
C		D		C
C		X	X	
C	C		D	

Compare Ga

	D		C	C
	X	X		C
C		D		C
C		D		C
C		D		C

Compare Gb

Figure 4.2.8 - Sets of Comparison Grids for the Sixteen Directions (cont).

4.2.3 - Detailed Components Description

4.2.3.1 - Requirements

VSS performance is judged by the criteria presented in Table 4.2.1.

RESOLUTION ALONG SCAN/ENCODER PULSE	1/16"
VERTICAL RESOLUTION	1/16"
FIELD OF VIEW	12' 8"
CAMERA DISTANCE TO SCANNED LINE	6'
CAMERAS MUST ENDURE	15 G from 5 Hz to 60 Hz vibration 150 dB noise environment 100% humidity sand & dust salt atmosphere sea level to 10,000 feet altitude 0.7 ms exposure time
IMAGE PROCESSING MUST DISTINGUISH	cracks oil spots shadows
CRACK RECOGNITION	0.2" TO 0.6" wide >10" length 70% recognition
CONTINUOUS MOVEMENT OF VEHICLE	0-2 mph
CONTROLLED LIGHTING	50% to 75% saturation min. 4500 foot-candles intensity 28" from surface operate and tolerate direct sunlight, rain, and freezing conditions
SYSTEM RESPONSE FREQUENCY	18 Hz
SERVICE LIFE	10 years

Table 4.2.1 - Vision Sensing System Requirements.

4.2.3.2 - Mobile Imaging Laboratory

The Vision Sensing System development was achieved using a Mobile Imaging Laboratory (MIL). The MIL was developed by Caltrans Division of Equipment. The MIL has all the shelves and working spaces that are needed for debugging, modifying, and actual testing of the algorithm. The MIL was customized with a 19-inch computer equipment rack and a 15-kilowatt power generator. The 19-inch rack is capable of accommodating the three needed subsystems: VSS, ICU, VOC. The generator is capable of delivering the power requirements by these systems and the MIL, where the MIL would need power for other various applications, i.e. the air conditioner, lights, etc. Figure 4.2.9 shows the MIL with the shroud on the lighting structure. The shroud is required to eliminate any shadows that would be created by external light sources. The lighting frame and its modifications are described in more detail in Section 4.2.3.4 and Section 4.2.3.5, respectively.

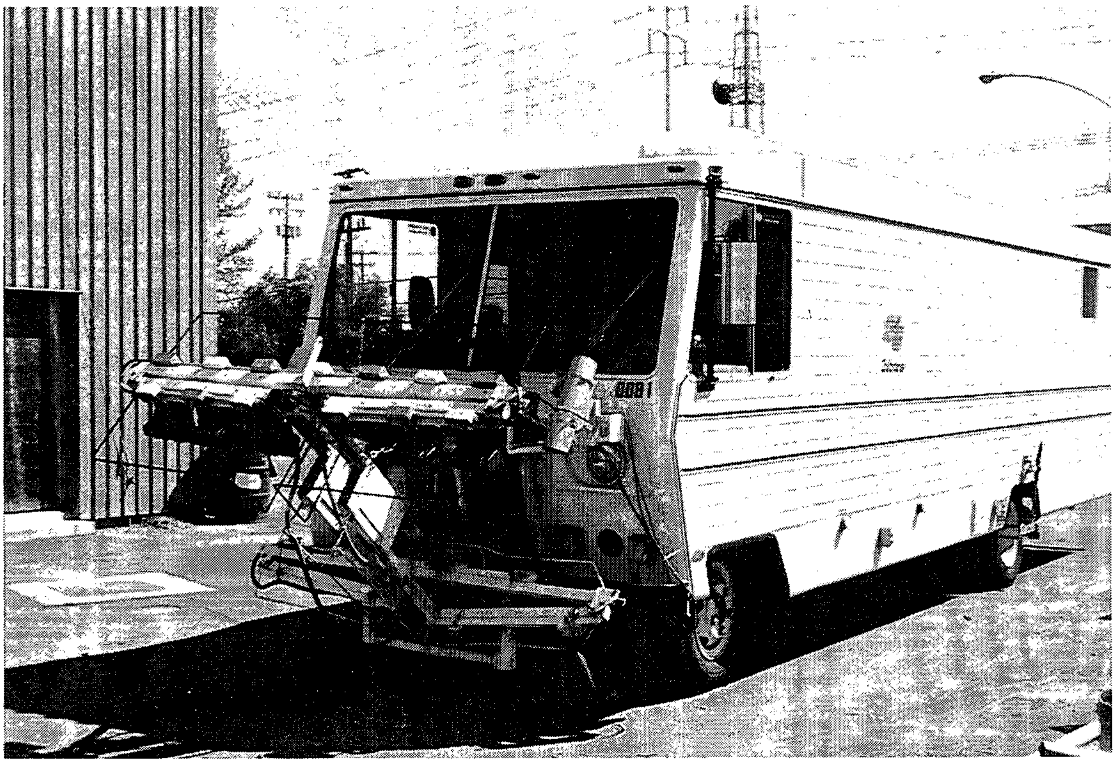


Figure 4.2.9 - Mobile Imaging Laboratory.

4.2.3.3 - Test Cracks

All development tests were conducted at the Caltrans Transportation Laboratory in Sacramento. It is the best possible site since it is closed to the public--eliminating the need for traffic control. This also allowed us to set up permanent marking of crack data on the road surface. A portion of pavement was sawed to imitate cracks; various transverse cracks (less than 3 feet, north and south bound angled cracks, etc.) and longitudinal cracks were tested as well as ineligible cracks. Figure 4.2.10 shows some of these cracks.

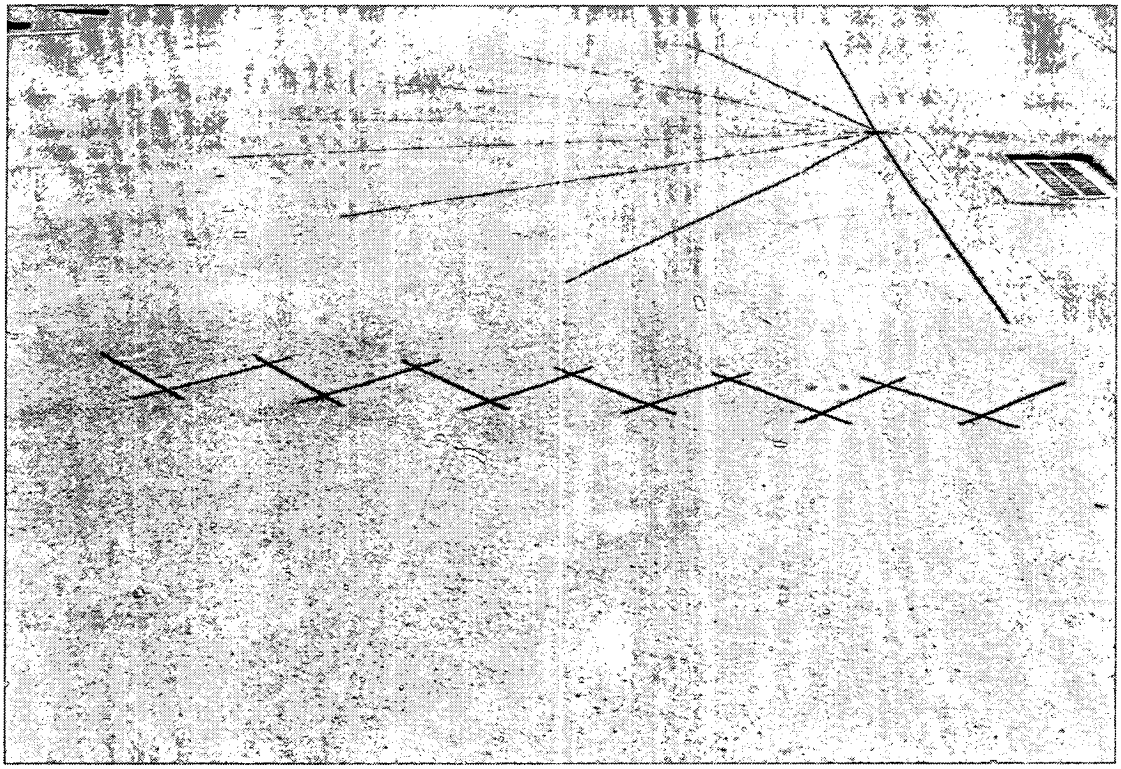


Figure 4.2.10 - Test (Sawcuts) Cracks at the Caltrans Transportation Laboratory

The Caltrans Transportation Laboratory has an assortment of natural cracks. These natural cracks were also used in the development of the VSS. Further, natural cracks at Davis, California were also scanned by the VSS to further validate the algorithm. The scanned cracks were used as part of the ACSM demonstration for the Construction Exposition held in Las Vegas on March, 1993. Figure 4.2.11 and Figure 4.2.12 show two of the cracks scanned at Davis. The faint numbers are the directions of the respective cracks.

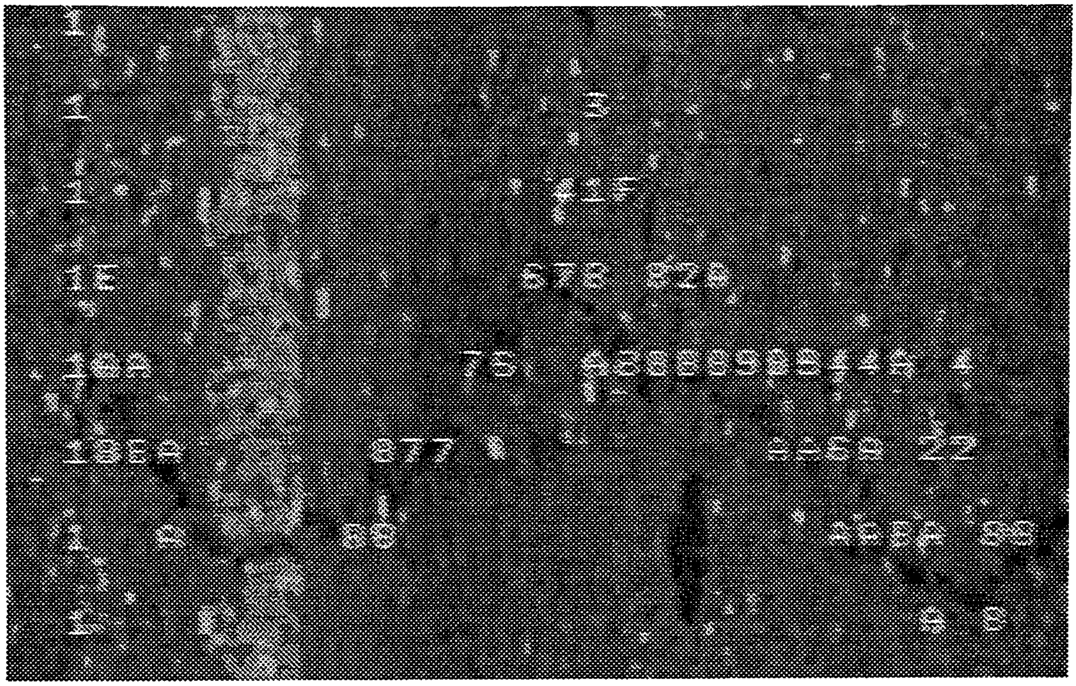


Figure 4.2.11 - Natural Transverse Cracks at Davis

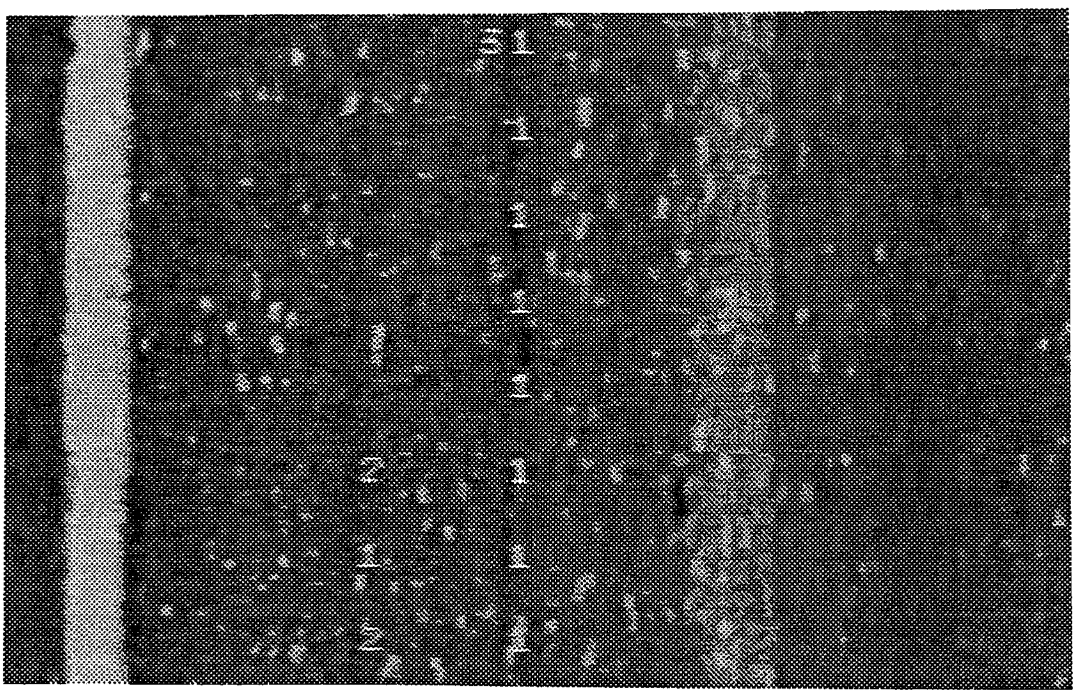


Figure 4.2.12 - Natural Longitudinal Cracks at Davis

4.2.3.4 - Lighting

Through a contract to Odetics Corporation, requirements for lighting were determined and a lighting structure was built to optimize intensity and orientation of the lights necessary for proper illumination of the roadway surface to achieve high resolution images. In order to read both transverse and longitudinal cracks, the light falling on the surface should be non-directional. The only true source of non-directional light is sunlight. The goal of the study was to determine which commercially available lighting system would best simulate this non-directional lighting.

Table 4.2.2 shows the comparison of performance for the three most viable white light sources. The fluorescent light is useful in creating a bright light source, but would have to be used in conjunction with a high frequency ballast in order to compensate for the discontinuous light emission (strobe light effect). The performance output level is 2800 lumens per 40 watts, without the ballast. The high pressure sodium lamp has broad spectral content from 550 to 700 nanometers, with the majority of the light (close to 75 percent) between 580 and 630 nanometers, which is a good range for solid-state video cameras. These lamps require ballast and a start up time of a few minutes. The high frequency ballast for both the fluorescent and high pressure sodium lights can add $200-$500 to the cost of a single unit. For our test purposes, Halogen lamps proved to be the more feasible and cost-effective choice.

SOURCE	OUTPUT	OUTPUT VIS/ALL (*power/cm*^{2})	LIFETIME	COMMENTS
fluorescent	2800 lumens/40W	10mW/12mW @2"	12000 hrs	extended, uniform sources
halogen	5000 lumens/300W	.45mW/1mW @10'	1500 hrs	hot lamp
high pressure sodium, clear bulb	15000 lumens/150W	140mW/155mW @4"	24000 hrs	bright light source

Table 4.2.2 - Comparison of Performance for Various White Light Sources

A simulation program was written to predict illumination reflected from the pavement and measured by a single camera for different lamp configurations. Based on photometric measurements from a single pair of lamps, the program calculates the light distribution in foot-candles.

This simulation was exercised to examine a variety of lighting configurations. Illumination was considered for various numbers of lamps and the heights of the lamps from the pavement. The curves shown in Fig. 4.2.13 provide an indication of the variation in illumination as a function of lamp height. Specifically, we are concerned with illumination intensity and uniformity. This simulation considers the full lane width field of view (156 in.) as seen by a single camera located at the center of the left half of that field of view. In the actual VSS, there are two cameras, one in each half of the field of view, and thus we are only concerned with the usable illumination for that camera, i.e. the left half 78 in. Based on symmetry of the VSS, the illumination for the right camera will be the mirror image of the left half 78 in. In general, for a fixed number of lamps, the illumination level will be higher the closer the lamps are placed relative to the pavement. However, there will be a corresponding loss of uniformity in the lighting. Based on the use of this simulation, 7 lamp pairs located at a height of 28 inches from the pavement was selected as the first generation lighting configuration for the VSS testing of Phase II.

4.2.3.5 - Lighting Frame and Camera Mount Modifications

Front illumination, as shown in Figure 4.2.14, was the previous design for the Vision Sensing System. However, the design developed by Odetics Corporation was not sufficient for our application; most of the longitudinal and some of the diagonal cracks were not very visible to the vision system. The purpose of front illumination is to flood the area of interest with light such that the surface characteristics will act as the defining features in the image.

This technique is used to find heavily contrasting features between the surface and the defect on the surface. As such, this technique would be applicable to road striping identification due to the heavy contrasts between the striping and the road surface. However, as found in the field tests, this technique is not applicable to pavement crack identification due to very small contrasting features between the pavement and the cracks.

Specular Illumination, as shown in Figure 4.2.15, was found to be the optimum technique for pavement crack detection. In this technique, the camera is positioned in line with the reflected rays of the light source. This method is very useful in detecting very small defect contrast with respect to the entire surface--which is, indeed the characteristic of pavement cracks.

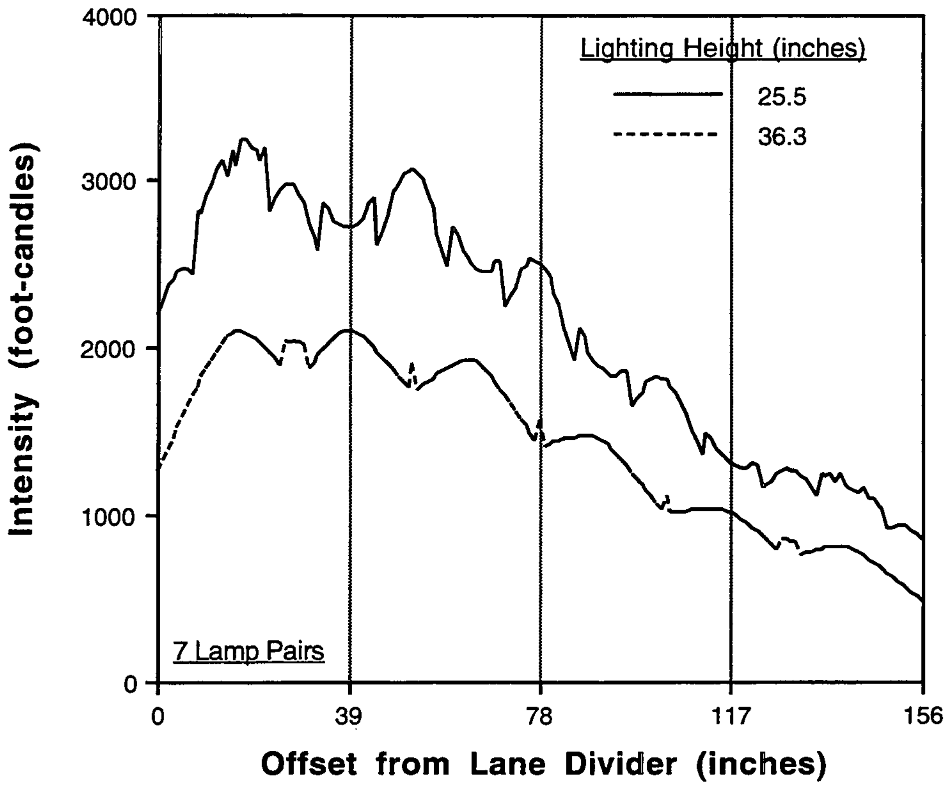


Figure 4.2.13 - Examples of Simulated Illuminations for VSS Lighting.

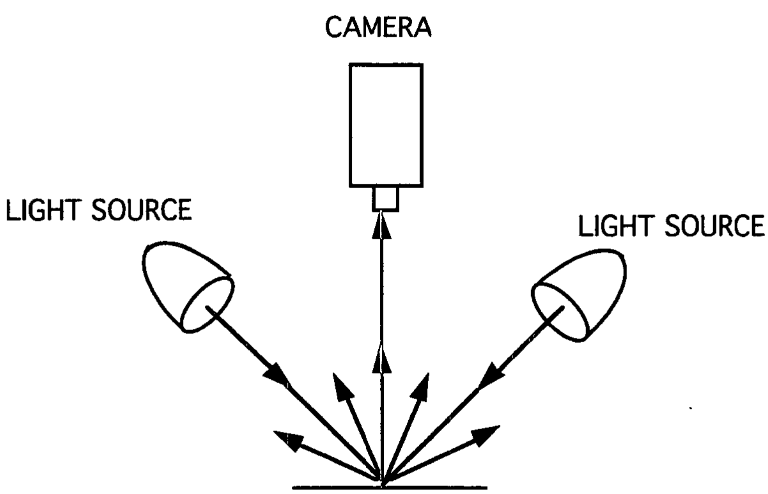


Figure 4.2.14 - Front Illumination.

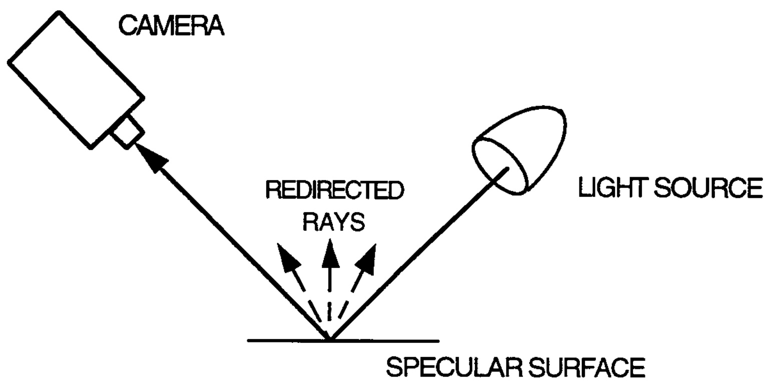


Figure 4.2.15 - Specular Illumination.

With further extensive field tests, the optimum angle of the camera was found to be 30 degrees and 60 degrees from vertical. To minimize the required extension of the existing lighting frame, 30 degrees was chosen. Consequently, six light fixtures from the back of the light frame were moved to the front to provide a more optimum illumination for the cameras.

4.2.3.6 - Cameras

The cameras require sufficient resolution to consistently recognize cracks 0.2 inch wide. The field of view transverse to the vehicle is covered by two cameras (Fairchild CAM 1301R CCD Line scan cameras with JML P/N 71846 12.5 mm, f1.3 lenses) mounted 5.4 feet from the ground at a vertical angle of 30 degrees; the cameras are 6 feet from the scanned line. Each camera has a field of view of 6.4 feet and they are mounted 6.4 feet apart. Each camera's field is divided into 1024 elements representing .075 inch, for a Nyquist resolution of .15 inch.

4.2.3.7 - Encoder

The encoder must trigger a line of video every .0625 inch. The video acquisition is driven by the forward travel of the vehicle using a 4500-pulses-per-revolution optical encoder from Datron Technology. The rolling radius of the wheel on which the encoder is attached is 13.25 inches resulting in a pulse every .0835 inch and pixel spacing of .0835 inch, in the forward traveling direction of the vehicle. Therefore, the theoretical Nyquist resolution of the image is .167 inch which is 20% better than the .20 inch crack width required of the system.

4.2.3.8 - Image Processing Hardware and Software

In order to produce accurate data for external (outside VSS) processing, the image processing hardware and software must interact efficiently. The encoder and cameras supply accurate data to the image processing boards. Upon a rising edge pulse of the encoder, a line of video from each camera is sent to the MaxScan card. Next, raw data is sent to the ROI 512 and ROI 2048 cards. The ROI 512 processes the data which is transferred to MaxGraph for visual observation. The ROI 2048 utilizes the same data to process pertinent information into FeatureMax MKII for crack identification.

The information for crack identification is implemented with an algorithm which interprets the presence of a crack by statistical means. The presence of a crack is determined by establishing its width and length. Cracks less than .2 inch wide and less than 10 inches in length are rejected. Acceptable crack information along with its location and direction are transferred for external processing.

4.2.3.9 - Vision Sensing Program

The vision sensing program consists of two subprograms: Vision and Encoder. The Vision subprogram, which is comprised of the algorithm described previously in Section 4.2.2, sets up and controls the computational processing and crack detection. Figure 4.2.16 shows the flow diagram of the Vision subprogram. The parameters within the algorithm are set up for values to accommodate the various roadways and conditions, such as oil spots, white rocks, etc.

The task of communicating with ACSM subsystem refers to Ethernet communications through the Ethernet board. Ethernet communication is used with the VSS to send data to the ICU. As each vision frame is processed, data from each crack detection is sent through the Ethernet while the vision frame number is sent to the Z-world single board computer (SBC). The SBC sends back the corresponding right encoder pulse. VSS then transfers all data to the ICU through the Ethernet. This process is handled by the Encoder subprogram. Figure 4.2.15 shows the flow diagram of the Encoder subprogram.

4.2.3.10 - Hardware Components

Two Loral Fairchild CAM1301R Line Scan cameras

The CAM 1301R cameras each divide their field of view into 1024 pixels.

Lighting Frame

Fourteen floodlight fixtures, Hubble QL505

Fourteen 500 Watt tungsten halogen lamps (clear), Phillips 500T3Q/CL FCL

Wheel Encoder, DATRON, CORREVIT WPT-4500

The wheel encoder has a resolution of 4500 pulses per revolution. As shown in Figure 4.2.18, the wheel encoder is attached to the left rear wheel hub of the MIL.

External encoder control circuit

The external encoder circuit was designed to:

1. Control the integration cycle of the cameras
2. Provide a means of calibrating the encoder signal in reference to distance traveled.
3. Filter out extraneous encoder pulses due to vehicle vibration.
4. Trigger the DataCube system to collect a line of video in sync with the start of the next camera cycle, after an encoder pulse

Radstone, OS-9 development system

cs-20 2/001 20 slot chassis with

1200 watts power supply

6-slot VSB backplane

WK-3/300 170 MB hard drive

Ethernet Card

FeatureMax MKII

Max Graph

Manuals

DataCube image processing system

Max-Scan 10MHz

ROI Store 2048

ROI Store 512

4.2.3.11 - Software Components

Operating System (Radstone Version 5.1, OS-9 Version 2.4)

ImageFlow (DataCube image processing software)

Vision Sensing Program

The vision sensing program is described in more detail in Section 4.2.3.9. It consists of the following subprograms:

1. Vision Subprogram consists of the following main functions:
   - Crack detection algorithm
   - Computational processing
2. Encoder Subprogram

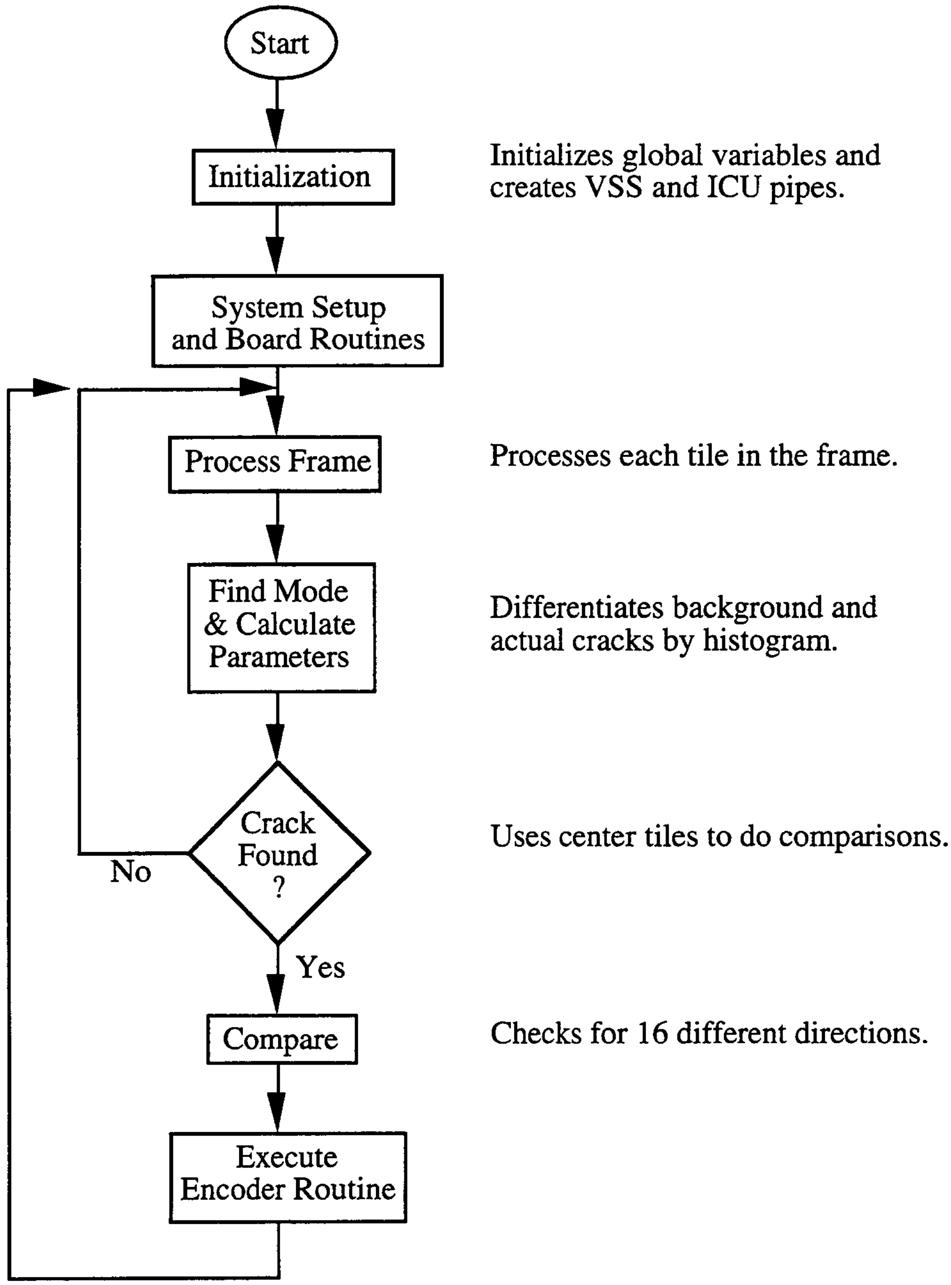


Figure 4.2.16 - Vision Subprogram Flow Diagram

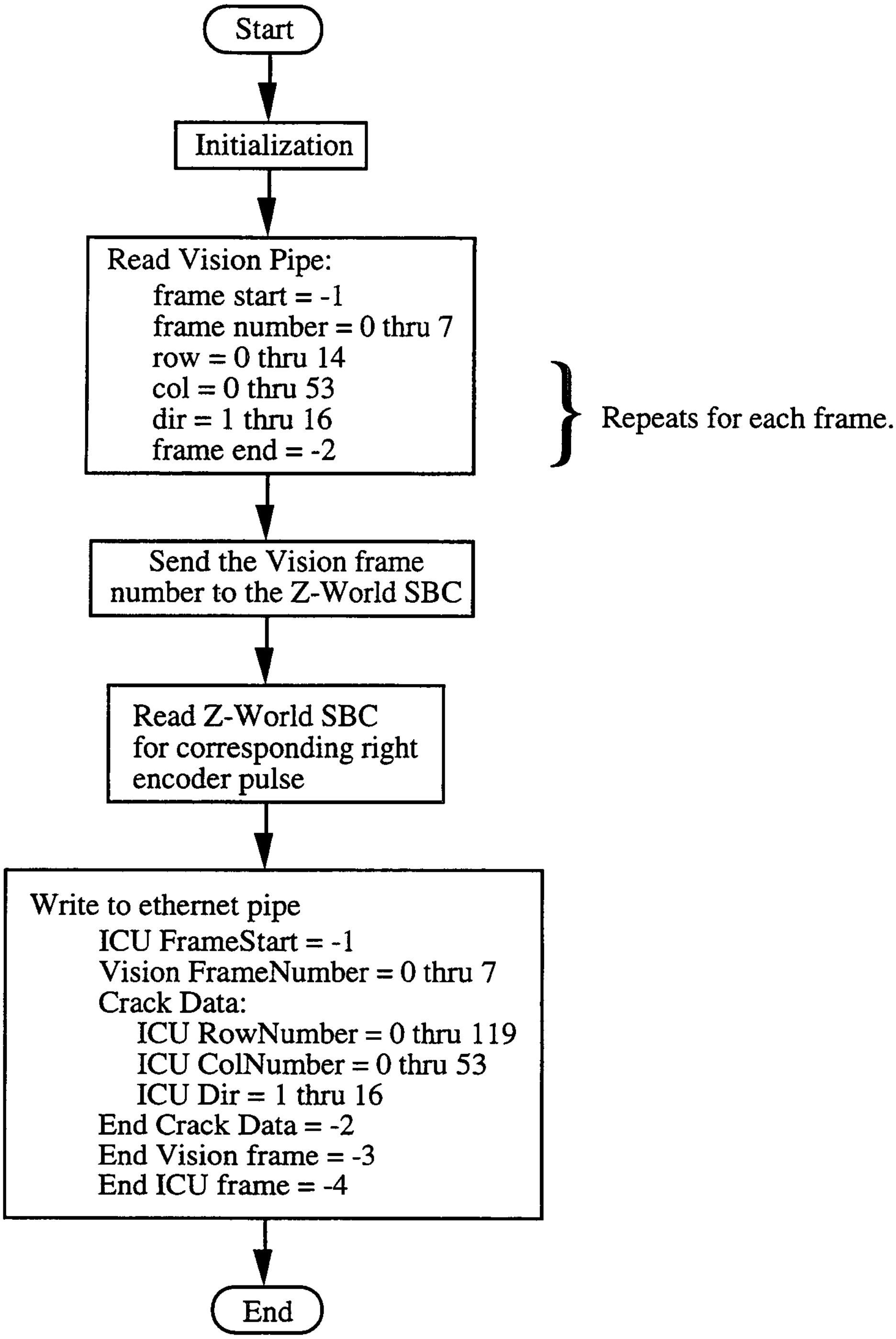


Figure 4.2.17 - Encoder Subprogram Flow Diagram.

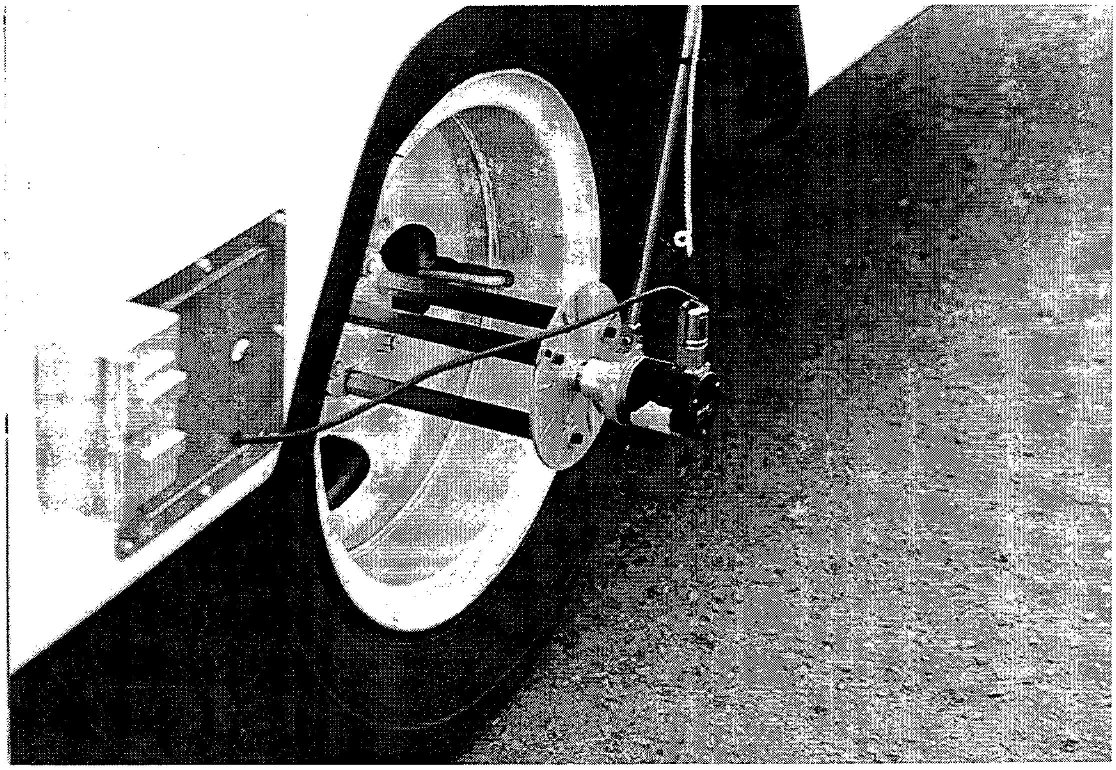


Figure 4.2.18 - Wheel Encoder.

4.2.3.12 - Summary of Results

Prior to the modification to the lighting frame, camera mounts, and algorithm, the crack detection rate was only forty percent. Thus, extensive field tests were accomplished at the Caltrans Transportation Laboratory, where a portion of the pavement were sawcut to imitate actual cracks of different directions.

With the modifications made, the Vision Sensing System is able to detect eighty-seven percent of the cracks scanned with minimal adjustments of the algorithm's parameters. Although this detection rate surpasses the required seventy percent, optimization of the algorithm would bring this number close to 100%. However, fine adjustments of the parameters would require considerably more time, which, for example, would prolong the total road maintenance operation. Path Planning would then connect indications of crack presence among tiles, making the actual crack detection of the ACSM close to 100%.

Figure 4.2.11 and 4.2.12 show some detected cracks. The faint numbers on the cracks are the directions of the respective cracks. Further, the modifications enabled the VSS to ignore fluid spots caused by oil, brake fluid, etc. The shroud completely eliminated shadows that would have been created by external light sources.

4.3 - Local Sensing System (LSS)

4.3.1 - Component Description

The purpose of the Local Sensing System is to locate crack position and measure crack width to a degree of precision such that the crack preparation, sealant application and shaping of the seal can be performed in an automated fashion.

On the general crack sealing machine, the LSS will work in conjunction with the VSS to confirm the presence of a crack within a given area. The VSS will locate the approximate position of a possible crack using a video camera. This camera uses a line scan charged coupled device (CCD) as its sensing element. As the vehicle moves, lines across the lane width will be gathered to form an area view of the road surface. Through measuring the intensity of gray levels which the camera senses, it is possible to determine the position of possible cracks. However, since the line scan camera only has two-dimensional measuring capabilities, it may mistake an oil spot, shadow, or previously filled crack for an actual crack. The purpose of the LSS on the general machine is to scan the area near the potential crack location identified by the VSS to confirm or reject the presence of a crack. Furthermore, there are inherent inaccuracies in the VSS crack identification algorithm which gives it a resolution of approximately +/-1". There are also errors associated with the motion of the vehicle that will result in errors in the crack location identified by the VSS. Therefore, the LSS will also provide more precise position information to the general Robot Positioning System (RPS). Local sensing will provide range information that can accurately sense the presence and position of a crack. However, local sensing alone would not be adequate because the local sensor requires a planned path to scan for random cracks. Given the operating speed of the vehicle, the update rate and field of view of the local sensor are not adequate to track random cracks without prior knowledge of crack direction.

On the longitudinal crack sealing machine, the local sensor will provide all sensing information to the longitudinal RPS. Because the longitudinal cracks do not randomly vary in direction, it is possible to design a sensing system in which the Local Sensing System provides an error feedback signal to the longitudinal RPS. The start of the crack must initially be placed within the local sensor field of view, and then through real-time controls and feedback provided by the local sensor, it will be possible for the longitudinal RPS to follow the longitudinal crack.

A variety of sensors technologies have been researched in order to select a sensing system which best meets the sensing requirements. The Local Sensing System which has been selected is the most cost effective, off-the-shelf component which meets all the requirements. The system selected is a laser vision sensor which measures range information using triangulation. Using triangulation, distance measurements are determined by transmitting a laser light source, then focusing the diffusely reflected light source on a photosensitive device. This method of detection has proved to be reliable and is commercially available and widely used for seam detection during automated welding.

Sensing systems based on triangulation are impervious to color variations. Therefore, a laser range finding sensor will work well on all pavements. Also, laser sensors are not sensitive to a dusty environment. Furthermore, laser triangulation is insensitive to lighting conditions because the sensor provides its own lighting via the laser. Overall, laser triangulation is a proven reliable technique for extracting three-dimensional surface characteristics.

To achieve optimal field of view and update rate from the sensor, a laser vision system using structured light was chosen. Laser vision systems based on structured light offer reliability, design simplicity, compactness, while maintaining cost effectiveness. Structured light extracts a three dimensional surface profile by projecting a laser pattern in a plane perpendicular to the surface being measured. The line of light is then observed by a CCD camera at an angle allowing the surface features to be found.

Because the goal was to use off-the-shelf components, five companies which manufacture laser vision systems were found and considered. Modular Vision Systems (MVS) was the only manufacturer who produced a commercially available sensor which met the requirements. The MVS LaserVision system provides off-the-shelf reliability and its image processing board is completely IBM compatible. It was specifically designed for tracking and inspection in robotics applications. Furthermore, this sensor is simple to use and rugged in harsh environments. The sensor has a built-in heat exchanger for cooling and a cleaning mechanism which prevents dust from settling on the lens which would distort the image. These attributes are attractive given the harsh environment associated with automated crack sealing. The MVS LaserVision system consists of the hardware and software listed in Table 4.3.1. Figure 4.3.1 contains a photo of the unit mounted in a test stand.

The sensor itself is a small package weighing 9 ounces and measuring 4" x 3" x 1.6". This package contains a laser light source, a CCD camera, and appropriate optics. The sensor will be mounted to the robot with a provided precision machined camera bracket. A vibration isolator will be placed between this bracket and the robot arm to protect the sensor from harsh vibrations and to prevent the image from being distorted. It should be noted that moderate vibration will not destroy the reliability of the camera data because the camera captures a "blur" and the image is placed optimally within this blur to compensate for the vibration. Mounting will provide flexibility of vertical and lateral adjustment for initial calibration procedures.

Power for both the laser and the camera is provided by a standard rack mounted power supply. Cabling will run between the sensor and this power supply as shown in Figure 4.3.2. Output from the camera will be input to the laser vision profile processing board, which will be placed in a standard IBM-AT compatible slot, where the camera data will be processed and the profile will be extracted. For increased performance, the profile data will be transferred to a coprocessor board, which also plugs into a standard IBM-AT compatible slot.

One Laser Vision Sensor
One 30mW laser source
One sensor and laser power supply
One Laser Vision Image Processor
One coprocessor board
One Microsoft compatible C5.1 library of driver routines
Menu Driven Program - Profile capture, store, segment, recall - Adjust laser intensity
Segmentation Program
IBM compatible 386-25 MHz - VGA color monitor and graphics card - Four empty full sized slots - Two serial ports - 40 MB hard drive - 4 MB RAM

Table 4.3.1 - Local Sensing System (LSS) software and hardware.

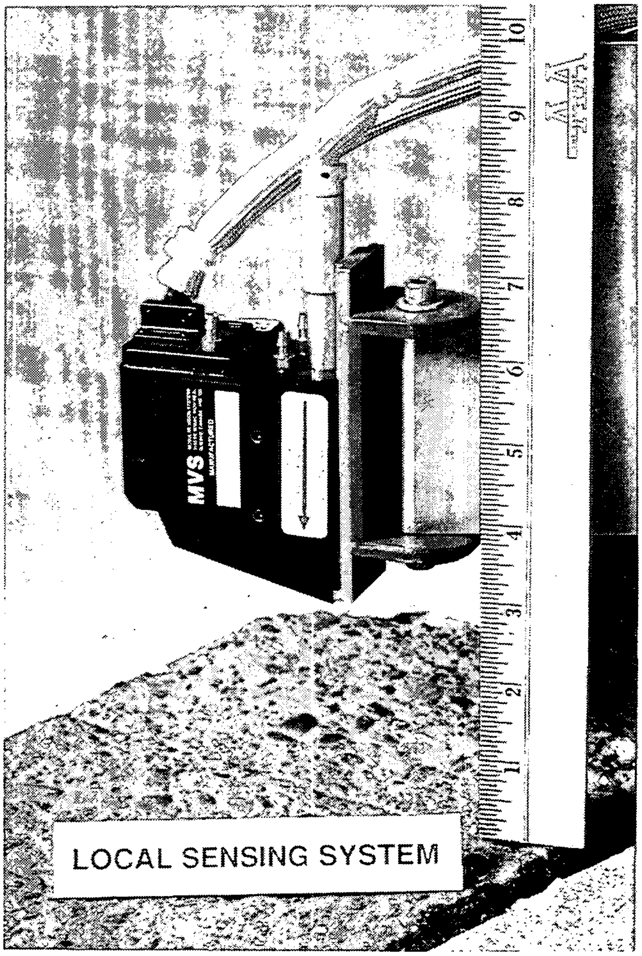


Figure 4.3.1 - Photo Of Local Sensor Mounted In Test Stand.

A summary of the pertinent specifications for the LSS is shown in Table 4.3.2. Appendix B contains the manufacturer and model number information for the LSS.

4.3.2 - Principles of Operation

As previously discussed, a laser vision system using triangulation was chosen to locally locate a crack in pavement. Figure 4.3.3 illustrates the principle of triangulation. Distance measurements are determined by transmitting a focused laser light source onto an object and then imaging the diffusely reflected light onto a photosensitive device. The photosensitive device (PSD) is an analog light sensor that is sensitive to the intensity and position of a light spot in its field of view.

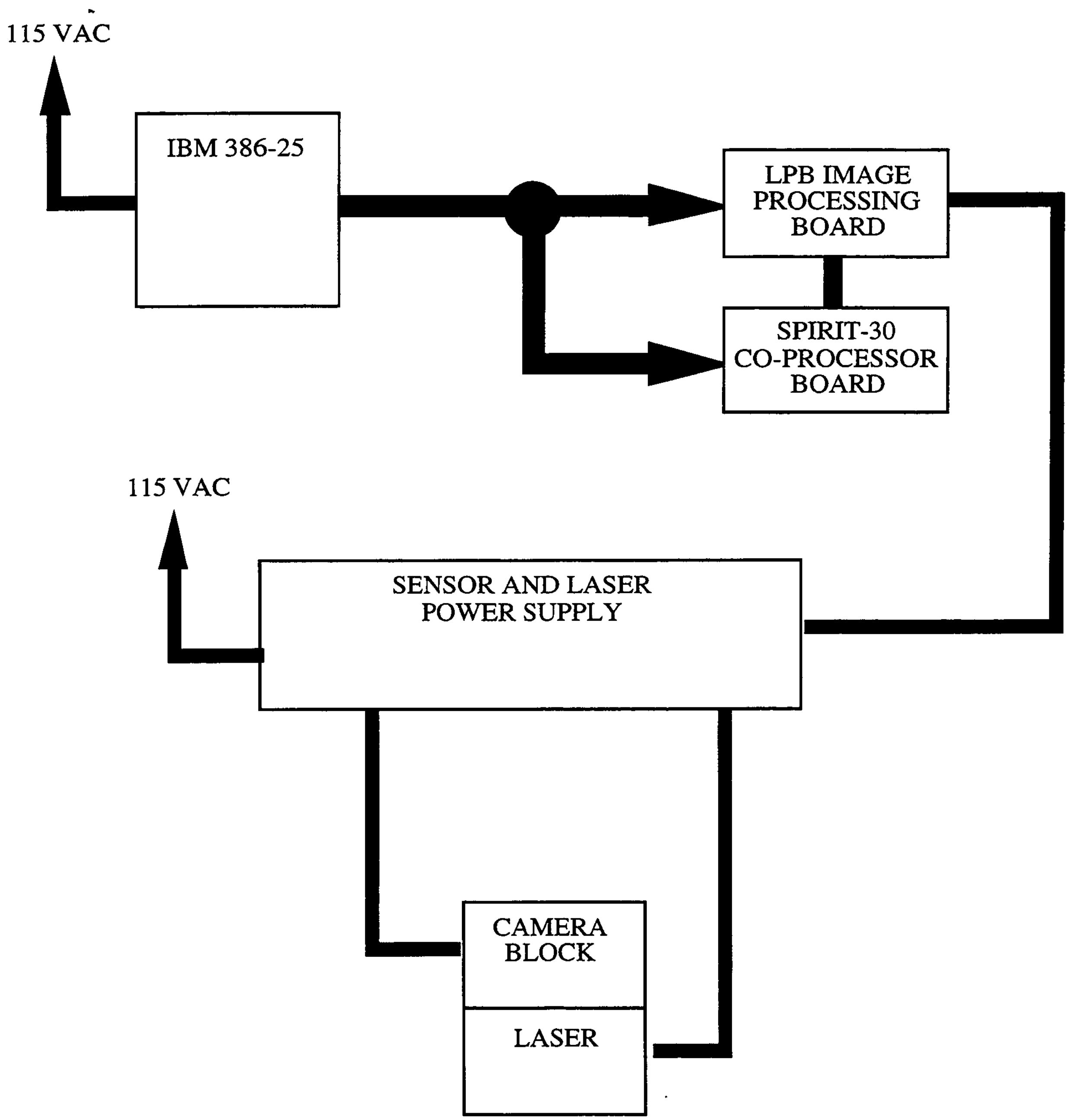


Figure 4.3.2 - LSS Interconnect Diagram.

Knowing the position of the image on the PSD, the distance between the detector lens and light source and the projection angle of the source, the distance measurement can be geometrically determined.

	Horizontal		Vertical
Speed images/sec	60	30	
Resolution*	0.005"	0.0025"	0.006"
Accuracy position*	0.006"	0.003"	0.008"
Accuracy mismatch*			0.002"
Accuracy gap*	0.012"	0.006"	
Mounting distance to road	6.5" max.		
Field of View	4"		
Moisture	to 85%		
Vibration	typical vehicle vibration		
Temperature	-20 to 160° F		
Service Life	10 years.		
Speed	60 images per second - RS170 50 images per second - CCir standard		
Water cooling	0.25 gallon per minute		
Air cooling	0.11 CFM		
Weight	9 oz (250 g)		
Processor	IBM-AT compatible, up to 8 MHz bus speed, requires 64K memory mapped space		

Table 4.3.2 - Laser vision system specifications. *Accuracy and resolution specifications are based on operating the sensor in the optimum area. The sensor will be operated outside this area to achieve a larger field of view.

Figure 4.3.4 illustrates a laser vision system using structured light to develop three dimensional surface profiles. A laser light source is projected approximately perpendicular to the direction of the crack. The bright line produced by this laser source on the surface is then observed by a CCD camera. The analog camera data is then digitized, filtered, and processed using triangulation to determine depth information.

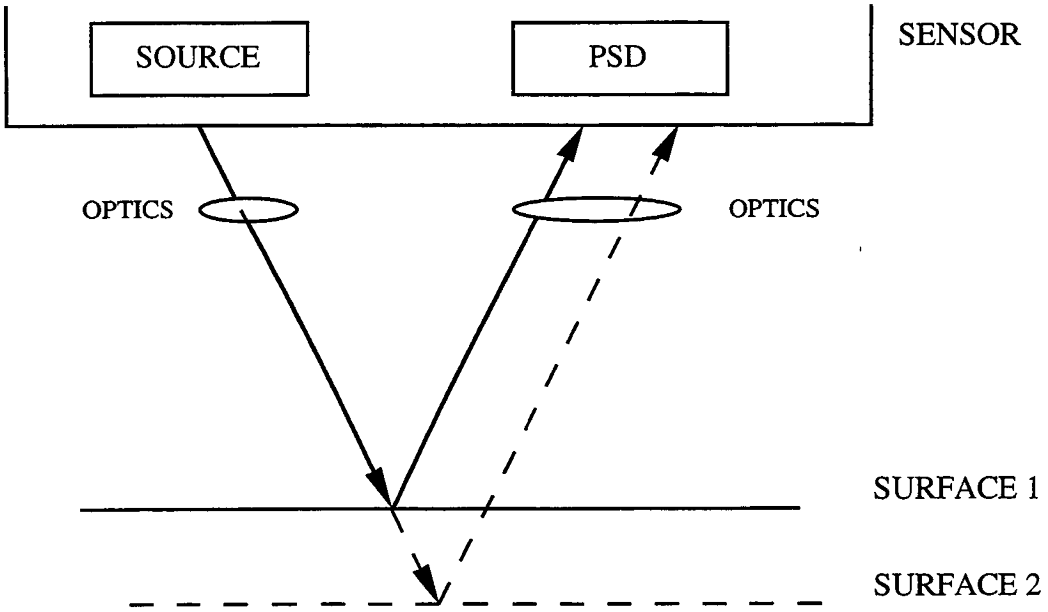


Figure 4.3.3 - Principle of Triangulation.

The MVS LaserVision sensor projects a laser light source approximately perpendicular to the direction of the crack, and observes the line produced by this source using a CCD camera at an angle (20°-30°). At this angle the line will appear to be broken.

The camera output of the laser sensor is then input to the MVS LaserVision Profile Board (LPB-200). The LPB-200 is an image processing board designed to extract the three dimensional profile from the surface of an object. The broken laser line of data acquired by the CCD camera is input to the LPB-200 and the surface profile is extracted at 60 times per second. The LPB can be used in a stand alone configuration, or with an additional coprocessor board for increased performance. For the crack detecting application, a Spirit-30 coprocessor board will be used. The profile data will be transferred to the coprocessor board via a separate output port which is internal to the computer.

Among many features, the LPB-200 contains a histogram circuit which can operate on either an entire frame captured by the camera, or a selected window area of interest. Eight Area of Interest windows are user selectable and may be easily moved around the picture area using software routines. Performing the histogram function in hardware rather than software decreases required processor time.

The Area of Interest window can also be set to work on the extracted profile data. The profile extractor on the LPB stores x, y coordinates and light intensities of the most probable line. The data is digitally filtered in real-time for accurate profile data.

The LPB board also contains an output which can control the laser intensity. This value is set in software using the provided software functions.

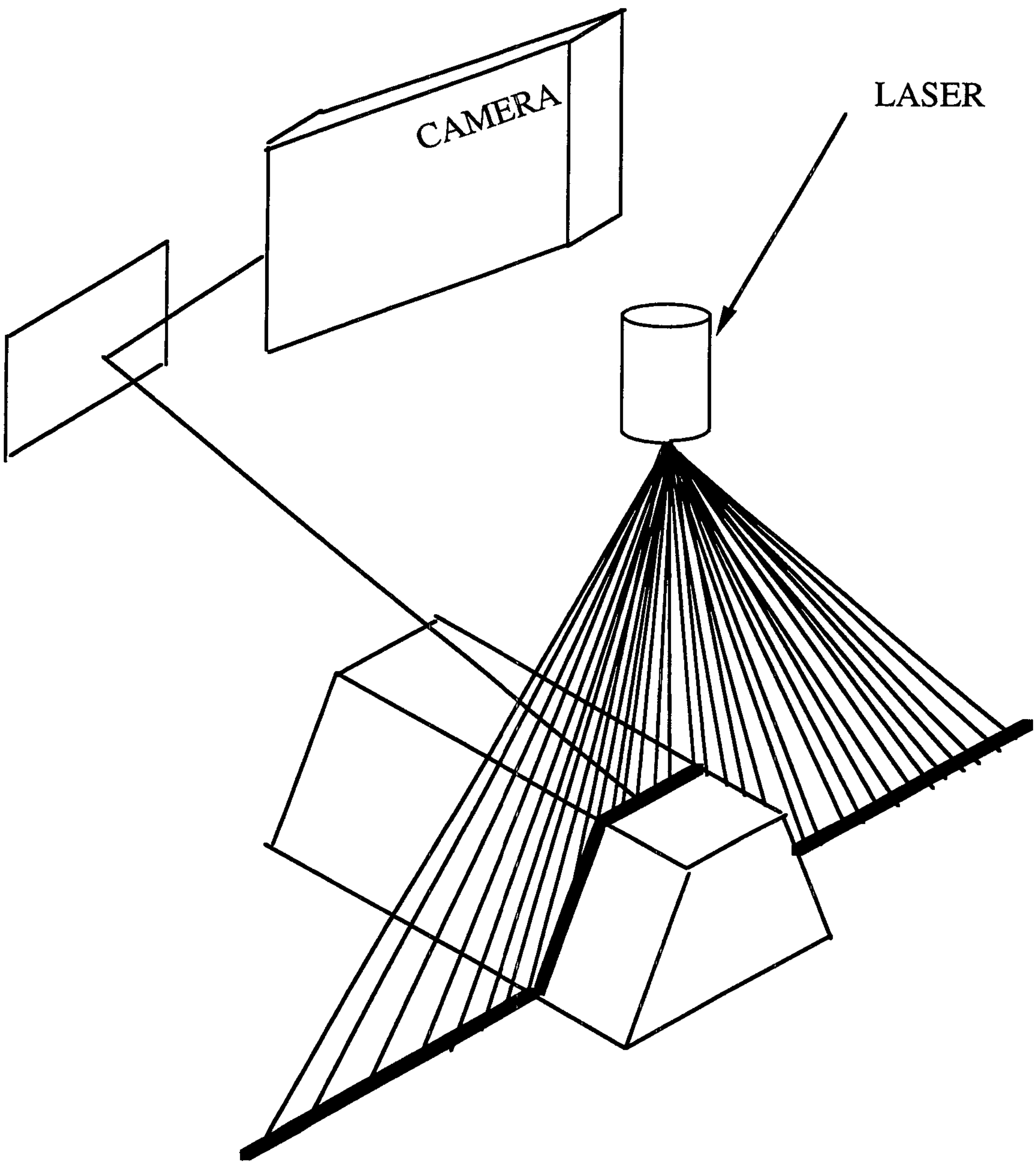


Figure 4.3.4 - Structured Light.

In order to acquire and interpret the depth information gathered by the sensor, a customized software program was developed. This program acquires data, interprets the data and extracts information relating to the position of the crack, and communicates this information to the appropriate systems.

The calling program will operate in real time on an IBM compatible 386-25 MHz computer. The program will be compiled using Microsoft QuickC, which is compatible with the Microsoft compiler which has compiled the functions provided with the MVS sensor. The supplied functions are contained in a library which will be linked to the calling program during compilation.

The program consists of an initialization procedure followed by the main body of the program which senses the presence of cracks in pavement. In the main body, first a profile of the road surface is captured. Next, each individual data point along the profile is analyzed to determine if a crack has been found. If a crack has been located, the program sends position information to the Robot Positioning System and then loops back to the start of the main body and captures the next profile. If the entire profile is analyzed and no crack has been located, a signal is sent to the ICU and then the program loops back the start of the main body and captures the next profile. Details of each task performed by the crack sensing program are described in the following sections.

Before the main body of the program can begin acquiring data and detecting crack location, an initialization procedure in software must be performed. During the initialization procedure, the LSS hardware is initialized. This is done through calls to initialization procedures which were provided with the MVS system software. The laser intensity is also set to maximum intensity by calling a procedure provided with the system software. Maximum intensity has reliably given optimal results on pavement surfaces during testing. Serial communication is also initialized. Two serial ports are used for communications (COM1 and COM2). The baud rate, number of stop bits, and parity (odd, even, or none) must be set for each serial port before communication can be successfully established. Using C function calls to the DOS operating system, the serial ports are initialized. Also, a profile is extracted using MVS system software and the typical roughness of the pavement surface being measured is determined. This measurement is necessary in order to determine typical depth variations from the sensor to the pavement surface. From the typical variance, an acceptable tolerance is set. Depth measurements exceeding the tolerance are therefore considered a crack. Lastly, the average depth of the pavement at the beginning of the profile is determined. This is accomplished by averaging the first twenty-five extracted data points over a typical section of pavement not containing a crack. This average is used to initialize the digital filter.

To compensate for varying surface profiles and normal height deviations in pavement, a digital low pass filter is used on the extracted data. A low pass filter was chosen to filter out normal high frequency variations in the depth measurements since the measurements of concern are low frequency components in the depth measurements - due to the presence of a crack. The digital filter was modeled after a low pass second order filter. The filter constants were determined using a Discrete Fourier Transform (DFT) analysis. Figure 4.3.5 shows the profile of a crack measured by the local sensor before filtering, while Figure 4.3.6 shows the crack profile after filtering.

Before the program continues, it waits for a start signal from the ICU via the COM2 serial port. Once the signal to begin is received, the first task performed by the calling program is to determine if the sensor has located a crack. If the sensor is located over a crack, location is determined and sent to the RPS. This is performed by making a software function call to extract a profile and calibrate the data. The result is x, y coordinates in millimeters, where x is the direction along the line of light, and y is the depth measurement from the sensor to the surface. The zero coordinate along the x direction is located in the center of the scan. The result is stored in an array accessible to the program. Each element in this array is consecutively filtered and then compared to the previous value to determine if the starting edge of a crack has been located. If the current measurement varies by more than the accepted tolerance determined in the initialization procedure, then the program assumes that the leading edge of the crack has been located. If no crack is found, an indicating signal is sent to the ICU as described below.

A simpler routine would be to compare the current data to a set point value. However, this approach was not taken because the road surface profile may vary gradually within the sensor field of view by more than the accepted tolerance without a crack being present. By comparing the current value to the previous value, gradual changes in profile are allowed for, and erroneous indications of the presence of cracks are avoided.

A problem arises in requiring that a previous value be set for both the filtering routine and the crack detection routine. Without an initial value, it would be impossible to detect a crack if it was located at the first data point. To solve this problem, the average value determined during the initialization routine is used.

Once the program has determined that the sensor has detected the leading edge of a crack, a flag is set, and the x coordinate of the leading edge of the crack is stored. This flag will remain set until the trailing edge of the crack is located. The trailing edge of the crack is located by again

UNFILTERED CRACK PROFILE

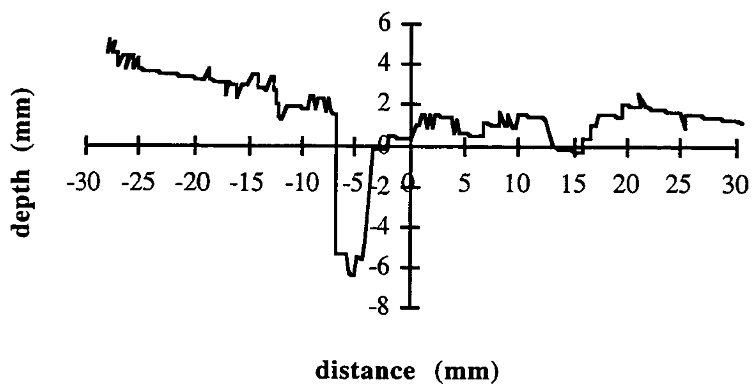


Figure 4.3.5 - Crack Profile Before Filtering.

FILTERED CRACK PROFILE

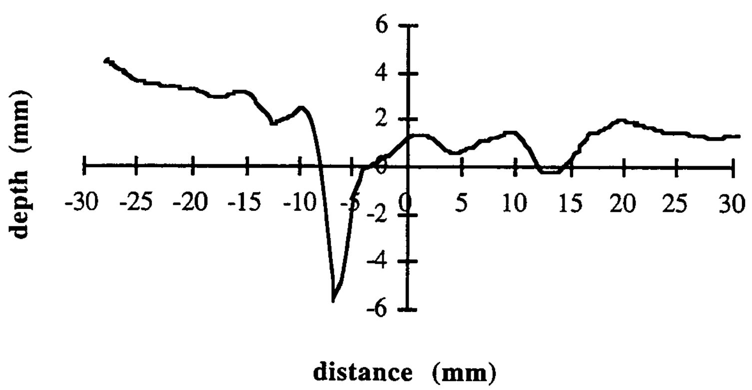


Figure 4.3.6 - Crack Profile After Filtering.

comparing the current depth measurement to the last measurement taken. When the depth variance exceeds the tolerance, the trailing edge of the crack has been located. The x coordinate of the trailing edge of the crack is then stored.

The next software task is to determine the width of the crack. This is simply determined by subtracting the leading edge coordinate from the trailing edge coordinate. Cracks less than 1/8" in width are not sealed (same as no crack located). This effectively serves as a threshold filter which ignores unwanted spikes due to noise in the data. In the case where a crack less than 1/8" wide is located, the program continues to analyze the remainder of data points in the scan line for a crack in the same manner as described above.

Once the crack has been located and the width has been determined to be greater than 1/8", the midpoint of the crack is calculated by averaging the leading edge and trailing edge coordinates. This location constitutes the error feedback signal required by the RPS to follow the crack.

Once the error signal is determined, it is sent to the RPS directly via an RS-232 port. Using C function calls to the DOS operating system, data is sent one byte at a time per the RS-232 standard protocol.

The program then loops back to the beginning, where a profile is once again extracted and analyzed. The remainder of data points extracted during the last measurement are not further analyzed. Currently, branching cracks are handled in the path planning module based on the global vision system information. The RPS will use the global data information to handle situations in which the LSS would detect multiple cracks, such as at a branch point. Thus, the LSS does not attempt to detect more than one crack, as that information is not be used by the RPS in the current operation of the ACSM.

If each element of the extracted profile is analyzed and no crack location is found, an indicating signal (NO_CRACK_FOUND) is sent to the ICU. This signal is also sent over a second serial port (COM2). Under normal conditions, the sensor will be located over a crack and the signal NO_CRACK_FOUND will not be sent to the ICU. Therefore, the ICU must constantly be polling this port to see if a signal has been sent. After the indicating signal is sent to the ICU, the program loops back to the starting point, where once again a profile is extracted and analyzed.

4.4 - Robot Positioning System (RPS)

4.4.1 - General Positioning System

4.4.1.1 Introduction

The following is a component description of the GMF-A510 SCARA manipulator and the Karel controller which have been purchased for the Advanced Highway Maintenance and Construction Technology (AHMCT) crack-sealing project. The purpose of the manipulator is to guide process carts over cracks for the general crack-sealing machine. The A-510 manipulator is inverted and mounted on a linear slide on the back of the crack sealing support vehicle, as shown in Figure 4.4.1. The Karel controller is a fully integrated robot motion controller which will be responsible for all motion of the manipulator. The controller will receive input from the LSS and the ICU which will provide it with necessary information to control the manipulator, which in turn guides the process carts over cracks in the pavement.

4.4.1.2 Principles of Operation

GMF A-510 Manipulator

The GMF A-510 is a SCARA-type four degree-of-freedom manipulator. Manipulators such as this are commonly used for assembly operations, food packing and palletizing. Each joint shown is driven by a servo motor and the relative position of the joint is recorded by encoders. The servo motors and encoders are interfaced with the Karel controller. The Karel controller is able to use information from the encoders to move the end-effector to locations within the workspace of manipulator. Pre-programmed information on the manipulator kinematics allows the controller to move the manipulator to points in Cartesian space with respect to the base of the manipulator. The A-510 manipulator was selected from a field of commercial manipulators on the basis of workspace, payload and controllability. The specifications for the A-510 manipulator are given in Table 4.4.1.

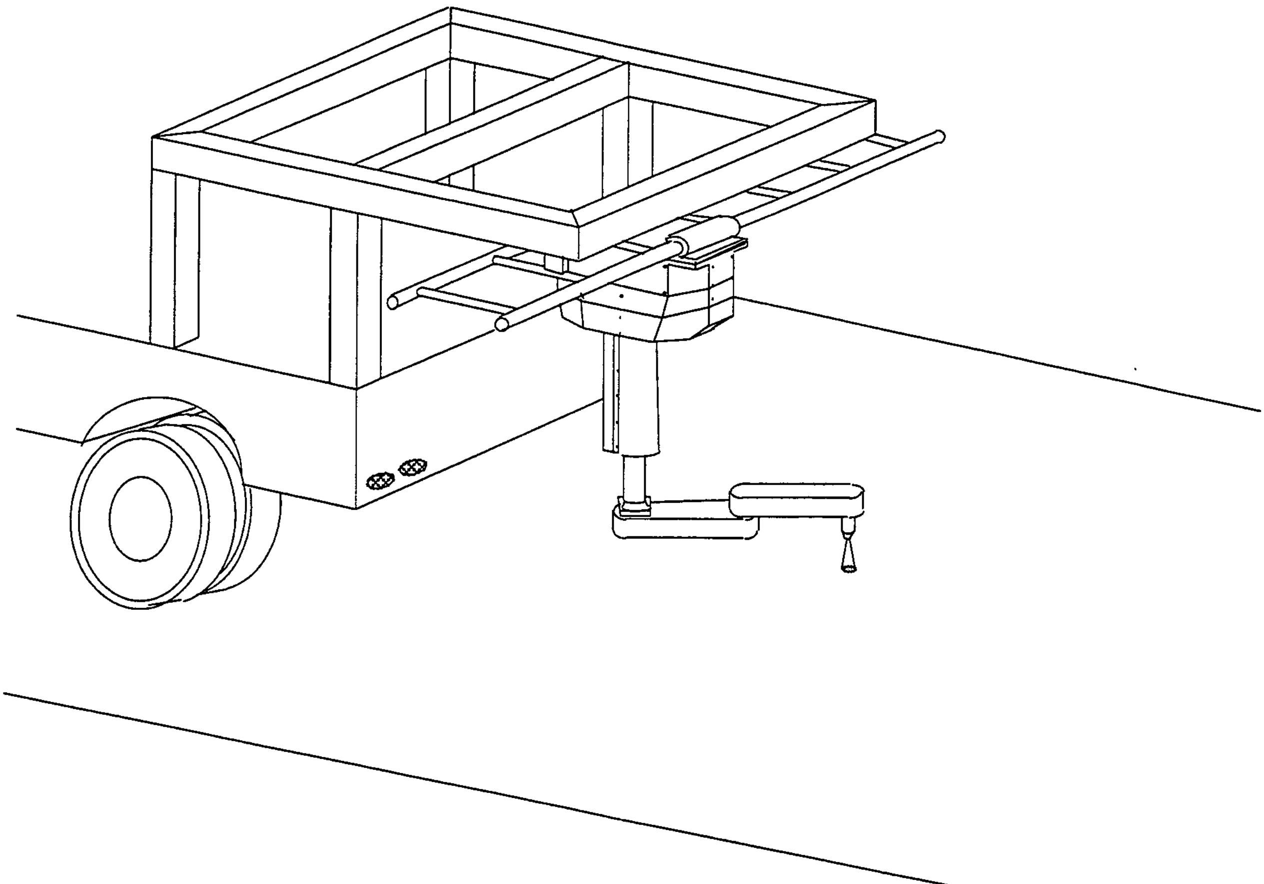


Figure 4.4.1 - The GMF A-510 Mounted On A Linear Slide On The Back Of A Truck.

Karel Controller

The Karel controller is capable of making calculations and running programs similar to many high level programming languages. These programs allow the robot motion to be controlled to execute a variety of complex tasks. In addition, the Karel controller can interface with other systems through digital I/O ports and serial lines. This allows the controller to operate with information from sensors and also to send motion information to other systems. The flexibility of the Karel controller and its ability to integrate with other systems make it an ideal component for use in a research environment. The important specifications for the Karel controller are listed here:

- Operator interface through Karel programming language
- Simultaneous control of up to 9 motion axes
- Capable of remote or local operation
- 2.0 MB RAM
- Serial communication capability

- Analog to Digital module
- 8 Channel Digital I/O
- 4 Channel Analog Input
- 2 Channel Analog Output
- Real-time I/O monitoring
- Complete programming control structures
- Full Cartesian level transformation capability
- Continuous path motions
- Basic and advanced arithmetic functions
- Flexible operator interface

Maximum reach	29.1 in.
Payload	50 lb.
Weight	330 lb.
Maximum overall height	55.3 in.
Joint 1:	
Stroke	11.8 in.
Speed	27.6 in/sec
Joint 2:	
Speed	300 deg/sec
Rotation	300 degrees
Joint 3:	
Speed	300 deg/sec
Rotation	300 degrees
Joint 4:	
Speed	540 deg/sec
Rotation	540 degrees

Table 4.4.1 - Specifications for GMF A-510 Manipulator.

Linear slide

The manipulator is mounted on a custom built, servo controlled linear slide which has been integrated with the Karel controller. The slide has an overall width of 8 feet to fit on the back of the crack sealing truck. The slide has 47 in. (1190 mm) of horizontal travel. The travel of the slide is restricted by such factors as the width of the manipulator base. The linear slide increases the reachable workspace of the manipulator and enhances its dexterity in certain areas near the edge of the workspace. Normally, SCARA configuration manipulators are unable to move in some directions near the outer edge of their workspace. The addition of the linear slide provides a redundant degree of freedom which allows the manipulator to move in any direction when it is near the semicircles that form the lateral boundaries of its workspace. The workspace of the manipulator with and without the linear slide is shown in Figure 4.4.2.

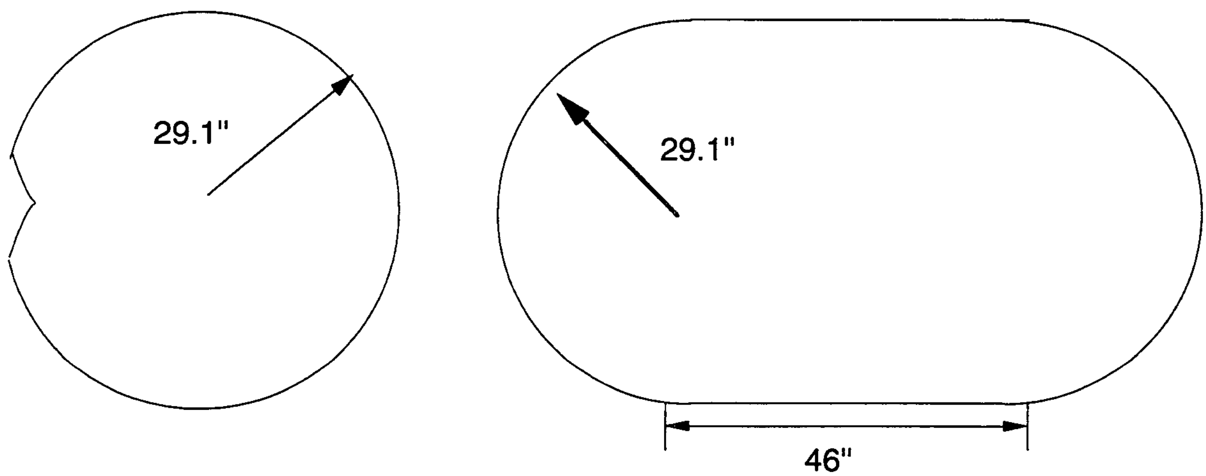


Figure 4.4.2 - Workspace of the A-510 Manipulator, a) Without The Linear Slide and b) With The Linear Slide.

Software and Integration

The software for the Karel controller consists of an operating system, a programming language, and I/O capabilities similar to many personal computers. Applications software is written by the user in the Karel controller language. For the ACSM it was necessary to write applications software to control the motion of the manipulator, to integrate the linear slide with the manipulator, and to communicate with other subsystems including the LSS and the ICU.

The following section will describe how data from the LSS and the VSS is used to control the robot manipulator on the ACSM. A control architecture is developed that combines all available information from the VSS, the Path Planning module and the LSS. The object of the architecture is to implement crack following as quickly and efficiently as possible while making allowances for failures or errors in individual subsystems.

4.4.1.3 Feedback vs. Open-loop Control

Two types of control are available for the controller. The first type is open-loop control using the data from the VSS. Open-loop control assumes that the information from the VSS is available and correct. The data from the VSS will be processed to produce Cartesian locations in the workspace of the manipulator. The location data will consist of points along a crack as well as the crack direction at each point. Open-loop control has no way of correcting for inaccuracy in the data.

The second type of control is closed-loop or feedback control. This is the type of control that is done using the output of the LSS. Feedback data can only reveal past locations and has no a-priori knowledge of the crack. Feedback control can correct errors in the manipulator position by feeding an error signal back to the controller. The LSS is only capable of returning the offset position of the crack in its field of view with respect to the end-effector frame of the manipulator. The crack direction in feedback control can be estimated by looking at previous points along the crack.

Controlling the manipulator can involve open-loop control, feedback control or a combination of both. There will be 3 distinct modes of control based on the type of control selected. Mode 1 will use open-loop data and verify it with the LSS data. Mode 2 will use feedback data from the LSS to control both position and orientation, and Mode 3 will use feedback control to control position and open-loop control to control orientation. An additional mode which is currently being investigated involves a more integrated use of the global vision data and the local sensor data using a compliant control algorithm. In this approach, the robot will use the planned path based on the global VSS data as the nominal path, and will make incremental modifications to the trajectory "on the fly" using the error signal from the LSS. This mode of operation is currently being developed to extend the operation of the general ACSM.

Sources of Error

Two likely sources of errors for sensing cracks are the Vision Sensing System (VSS) and the Vehicle Orientation and Control System (VOC). The VSS will detect cracks in front of the support vehicle by using a line scan camera. Errors of greater than an inch are possible simply due to the pixel resolution of the VSS algorithm. These errors are added to hardware errors such as camera resolution and vibration of the camera mount.

As the vehicle moves down the road, the VOC performs kinematic transformations to transform the cracks detected by the VSS in front of the vehicle into the workspace of the robot, which is behind the vehicle. There will be more than a 40 foot separation between the front and rear of the vehicle. Sources of error for the VOC include slippage of the encoder wheels on the pavement and the resolution of the encoder wheels. Errors from the VOC will be added to the errors already introduced by the VSS.

After a crack is detected, the vehicle moves forward until the crack is in the workspace of the robot. Due to the errors described above, position errors of several inches are possible. It is also possible that no crack actually exists since the VSS can only detect gray shades and therefore may be fooled by grease stains, shadows and previously sealed cracks. The field of view of the LSS is only 3 inches, so it is highly probable that once the manipulator moves to the start of the crack, the error will be great enough that the crack will not even be in the field of view of the LSS. It is also possible that the detected crack does not even exist.

Use of Closed-loop Control

Many of the problems associated with errors from the VSS and the VOC can be eliminated by incorporating a compliant motion control algorithm with the LSS. The compliant motion algorithm uses data from the LSS to follow cracks in the pavement. However, crack following using the compliant motion algorithm with LSS limits the manipulator speed. The speed limitations are due to the fact that the algorithm must define many points to constantly control the manipulator motion. The use of a higher point density causes more joint accelerations and decelerations and hence tends to slow the effective speed of the end-effector.

Mode 1: Open-loop Control

The concept for the open-loop control architecture is to use a pre-planned path generated from VSS data, the VOC and the path planning module as much as possible. The compliant motion algorithm will be used to search for the crack if the errors in the pre-planned path become larger than the field of view of the LSS. Once the crack is located by the compliant motion algorithm, the actual crack location can be sent back to the ICU. The offset in the crack location can then be used to help correct errors in the pre-planned path through the path planning module.

Mode 2: Feedback Control for Position and Orientation

The compliant motion algorithm can also completely override use of a pre-planned path in the event of a system failure of the VSS, the VOC, or the ICU. In this case, the end-effector can be moved to the beginning of the crack and aligned with the starting direction of travel using the teach pendant. The compliant motion algorithm will then be executed for the crack following operation. The end-effector speed using the compliant motion algorithm will be slower than if pre-planned path data were available.

Mode 3: Feedback Control for Position and Open-loop Control for Orientation

A scheme that uses the LSS data to control the position of the end-effector and VSS data to control the orientation of the end-effector can also be used. This algorithm will work well if there are errors in the location of the crack from the VSS, but its shape is generally known. The direction of the crack will be sent to the RPS according to its location along the 'x' axis of the world coordinate system. The control algorithm will use the LSS to follow the crack, but the direction information from the VSS will control the orientation of the end-effector. This scheme will require the approximate Cartesian location of the start of the crack from the VSS

Error Handling

An error handling routine will be called any time the crack is lost from the field of view of the local sensor. The same error handling routine will be used regardless of whether the motion is being controlled by data from the VSS or the LSS. The search algorithm will scan at right angles for the crack according to the most recent crack direction. The searching algorithm is essentially the same as the compliant motion algorithm except that the tangential velocity is set to zero. If the crack is still not found, a search will be conducted in the opposite direction as well. Limits are set on the distance to be searched. If the crack is not found within the specified limits, an error signal is sent to the ICU. On receipt of such an error signal, the ICU can then indicate the need for manual placement of the manipulator on the crack.

Control Architecture

The control architecture will be defined by the following algorithm:

(1) The location of a crack will be determined by the VSS, VOC etc. and a path consisting of Cartesian points within the workspace of the robot will be calculated and sent to the RPS.

(2) The manipulator will move to the beginning of the crack using the path generated by the ICU and path planning.

(3) The local sensor will be checked to determine if a crack is present. If no crack is found, the RPS will signal the ICU and begin searching for the crack at right angles using the LSS. The result of the search--either 'no crack found' or the location of the crack will be sent to the ICU. The RPS will then wait for an updated path to be sent from the ICU and will resume motion with step (2).

(4) Once the location of the crack has been verified by the LSS and the path has been updated, if necessary, the manipulator will follow the crack and the LSS output will be monitored. The LSS data can be used to determine if the manipulator runs off of the crack. If this occurs, the ICU will be signaled, and a search for the crack will begin as in step (3). Once again, the result of the search will be sent to the ICU and the RPS will wait for an updated path before resuming motion as in step (2).

(5) When the manipulator reaches the last point defined on the path it will signal the ICU to indicate that the end of the crack has been reached.

Additional options:

(a) It will be possible to define a maximum offset within the field of view of the sensor. If the offset from the center of the end-effector to the crack exceeds the maximum offset, the manipulator will center itself on the crack using the LSS and signal the ICU in a similar manner to the signaling for the search routine described above.

(b) It will be possible to override all data from the ICU and follow cracks using only the RPS and the LSS. This override will require the manipulator to be moved to the start of the crack and aligned in the direction of travel using the teach pendant. The motion speed for this override will be much slower than if global data were used.

(c) Crack following can also be conducted using crack direction data from the VSS and using closed-loop control with the LSS for position control.

Communications

Communication to and from the RPS will be accomplished by means of serial lines. Two separate lines will be used, one for communication with the LSS and one for communications with the ICU.

4.4.2 - Longitudinal Robotic Positioning System

4.4.2.1 - Component Description

The longitudinal robotic positioning system (LRPS) is the system that supports local sensor, the router, the vacuum and heater/blower ducts and the sealant applicator unit during operations on longitudinal pavement cracks running parallel to the roadway. Design and development of the LRPS was defined by two basic subsystems, the mechanical frame known as the longitudinal machine and the actuator and control components. Initial development and testing during Phase II emphasized the design and fabrication of the longitudinal machine, which includes the cart that carries the Applicator and Peripheral System (APS) components, a linear slide table, and the connecting linkages. Selection and purchase of a commercially available actuator and control system occurred simultaneously during Phase II and delivery and integration occurred in Phase III. Figure 4.4.3 shows a photo of the LRPS with the APS components installed in the final configuration.

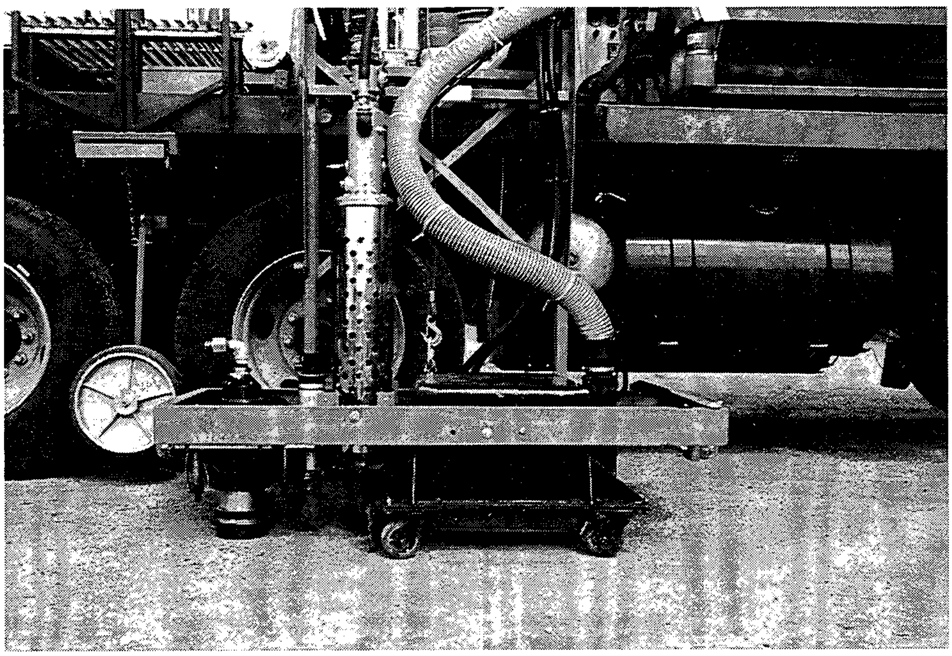


Figure 4.4.3 - LRPS With APS Components.

Longitudinal Machine

The first of two longitudinal machines was fabricated during Phase II to serve as the test vehicle for the APS components and a prototype to the final longitudinal machine. During Phase III Caltrans began sealant applicator testing with the first machine. Drawings were updated with design changes and used to fabricate the second machine which was installed on the truck in the final configuration. Important design criteria that were defined and incorporated during development were as follows:

1) The actuator control system had to be simple and the linear motion was limited to a single degree of freedom. Actuator motion was to be transferred directly to the cart through the linkage.
2) The linkage was designed to minimize lateral translation of the cart due to the changes in elevation and angle of the road surface since this would have to be compensated for by the actuator.
3) Stowage was to be simple.
4) A cart length of 5 feet was required to allow installation of all the APS components in the worst case configuration. Lateral movement of the cart was limited to 12 inches total, representative of driver's abilities when crack sealing.
5) Simplification of the design was important to prove the concept and have a working prototype to support testing. Development for commercialization would address issues such as optimum cart size and stowage design.
6) Configuration of the LRPS was to allow for installation on truck beds of various heights with minor modifications.

Figure 4.4.4 depicts the basic components of the longitudinal machine which are described in the following paragraphs. It should be noted that the item numbers discussed correspond with those of the figure *and* those of the detail assembly drawing, SHRP(LPS)LM-A100 in Appendix A.

1) Linear slide table (item 2) - The base of the table (item 1) is bolted to the truck bed and can be adjusted by shimming to set the slide table parallel to the road, . A linear actuator (item 11) with a 12 inch stroke drives the slide table which is mounted on two linear bearings (item 12), 39 inches in length.
2) Upper link (item 3) - During operation of the machine, this link serves as a structural member rigidly attached to the slide table and extending down to the lower link attached to the cart. The linear movement of the table on top of the truck is transferred by this link down to the cart (item 5) near the road. It is hinged to the table at one end and can be unlocked to allow it to rotate upward lifting the cart up for stowage. The length of the link between the attachment point on the table to the

lower link would be sized for the vehicle to which it is attached, and this is the only part that would need to be modified in mounting the unit to another vehicle.

3) Lower link (item 4) - The link is hinged at the upper link and the center of the cart. The hinge points allow the cart to translate vertically and rotate about its longitudinal axis as it follows the road. Lateral translation of the linear table is transferred to the cart across this link. At nominal dimensions on a flat road the axes of both hinge points line in a plane parallel to the road. The bend in the arms of the link provide clearance to allow the casters (item 10) on the cart to rotate 360°.

4) Cart (item 5) - The cart is a simple rectangular frame usually mounted on a pair of casters. The casters support the weight of the frame and components while maintaining a constant height with respect to the road surface (see Figure 4.4.5). When operated in a configuration that includes the router (see Figure 4.4.6), the casters are removed and the cart is attached to the frame of the router. Rotation of the cart about the transverse axis (pitch) is prevented by the reaction forces across the lower link. So, the cart longitudinal axis is always parallel to the longitudinal axis of the truck. Bolt holes are placed in the frame as required to attach the APS components.

During operation the links allow the cart to follow the road surface defined by the contact points at the casters. The cart is free to move vertically and rotate about the hinges on the lower link as shown in Figure 4.4.7. The stowage of the cart is achieved by rotating the upper link upward as shown. This is presently done by using an overhead hoist attached to the lower link. Modifications to the upper link and the use of hydraulic actuators during commercialization would allow for other stowing configurations.

Actuator and Controller

A commercially available prepackaged electro-hydraulic linear drive system, Parker Electrohydraulics PMC 10 Digital Process Servo Valve Controller and Actuator, was selected for the longitudinal RPS. The system uses a programmable digital controller to operate a servo valve on a hydraulic cylinder and operates in a closed loop with the feedback from a position transducer on the hydraulic cylinder. The controller can be programmed to accept input from the Local Sensing System (LSS) through an RS-232 port. Given a value for position, the controller will then drive the actuator to the location at preprogrammed acceleration and velocity values. Information will be provided by the LSS and the controller operating at 10 Hz. The chosen system has higher speed capabilities with minor hardware and software modifications, although the noted rate is expected to be more than adequate.

4.4.2.2 - Principles Of Operation

The longitudinal RPS is the subsystem that places the APS components over longitudinal pavement cracks running parallel to the roadway. The system consists of a cart in which these APS components can be installed in various configurations and, an actuation and control system that guides it.

The cart is attached to the side of the road maintenance vehicle with a mechanical linkage that allows the cart to move laterally a distance representative of crack geometry and driver capabilities as the vehicle is driven alongside the crack. The lateral movement is controlled automatically to correct for the relative position of the vehicle to the crack. The linkage also allows the cart to be retracted from the road when not in operation.

A single actuator provides the force to move the cart. It is driven by a controller that receives input from the LSS which is mounted at the centerline, forward end of the cart. As the cart is pulled forward, its lateral location is continually updated to keep the cart centerline over the crack, as measured at the local sensor.

The APS components, which are located on the centerline of the cart, prepare and fill the crack as it passes beneath them. These components are modular and can be installed in various configurations to allow for different crack sealing methods used by various DOTs. The support equipment necessary to operate the various components is located on the vehicle.

The configuration of the components installed in the cart imposes design constraints that specify the overall size of the cart, structural strength, stowing configuration options, and the limits on the system's ability to follow changes in crack path. To maintain flexibility in the development of the system and APS components, a worst case configuration was considered. This includes installation of the components in the following order beginning at the forward end of the cart (see Figure 4.4.6):

1) Local Sensor - Required for any configuration which uses the LSS to provide for crack location to automatically position the LRPS. Simpler configurations which use the vehicle or a manual joystick controller to position the LRPS do not require the LSS.
2) Vacuum Duct - Required for use in combination with the router to remove debris from the area around the crack and control exposure to dust created during routing. This ducting is be integrated within the body of the router.
3) Router - Required for some methods of crack preparation prior to sealing.

4) Heater/Blower Duct - Required for some methods of crack preparation. It can be used in conjunction with the router for preparation of the crack. With this configuration, a pyrometer used to sense the road surface temperature is located immediately behind the hot air duct to control the application of heat.

5) Sealant applicator - Required for sealing the crack. It places a five inch wide band over the prepared crack and will always be the last component on the cart.

When following a crack, the combination of all five components is most limiting since they are located on the centerline of the cart and define the minimum distance between the local sensor and sealant applicator. This distance then imposes a limit on the maximum rate of change in relative position between the crack and the maintenance vehicle (see Figure 4.4.8). Actuation of the cart is limited to translation in the direction perpendicular to the centerline of the cart, which is parallel to the direction of travel of the vehicle. The cart follows the crack located by the sensor at the forward end, which has a maximum four inch field of view. The applicator at the aft end lays a band of sealant five inches wide. The router cannot cut a path without a significant forward component since the cart does not have a rotational component which would allow the router to follow a circular path. These basic limitations on the crack following capability are inherent in the definition of longitudinal crack but, as noted, are dependent on factors that include selection of crack preparation components.

The LRPS will operate as a component of the crack sealing machine controlled through the ICU, but it can be used independently as a self-contained unit with the LSS output provided directly to the controller. In addition testing of the sealant applicator alone using the first longitudinal machine has demonstrated successful operation with lateral positioning by the driver. Finally, the LRPS has been manually controlled by an operator using a joystick to position the cart. The capability to operate as a self-contained system, the relative simplicity of its operation, and the modularity of the APS components, support the commercial viability of the LRPS.

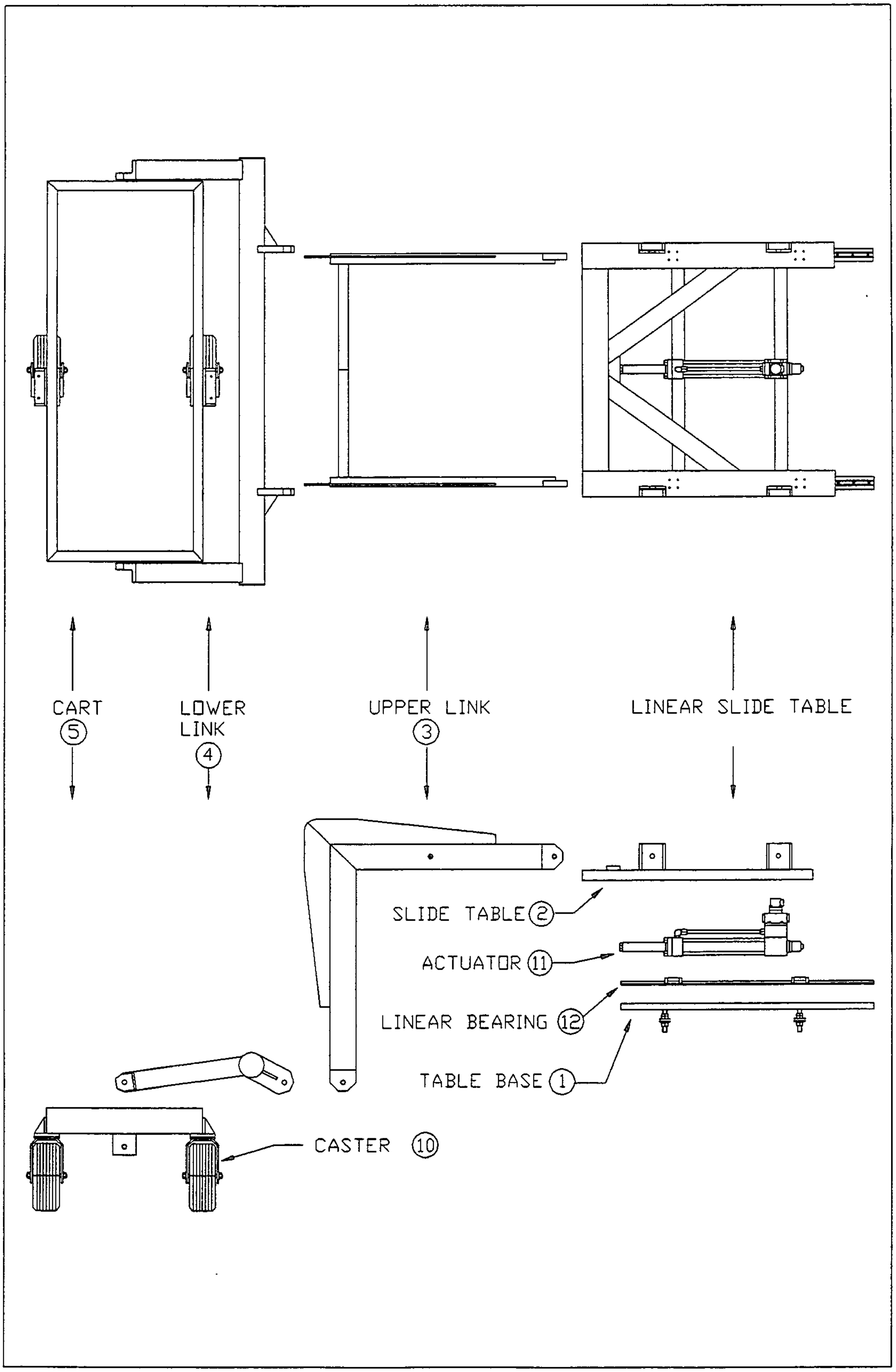


Figure 4.4.4 - Longitudinal Machine Basic Components. Item Numbers Correspond To Assembly Drawing shrp(lps)lm-a100 in appendix A.

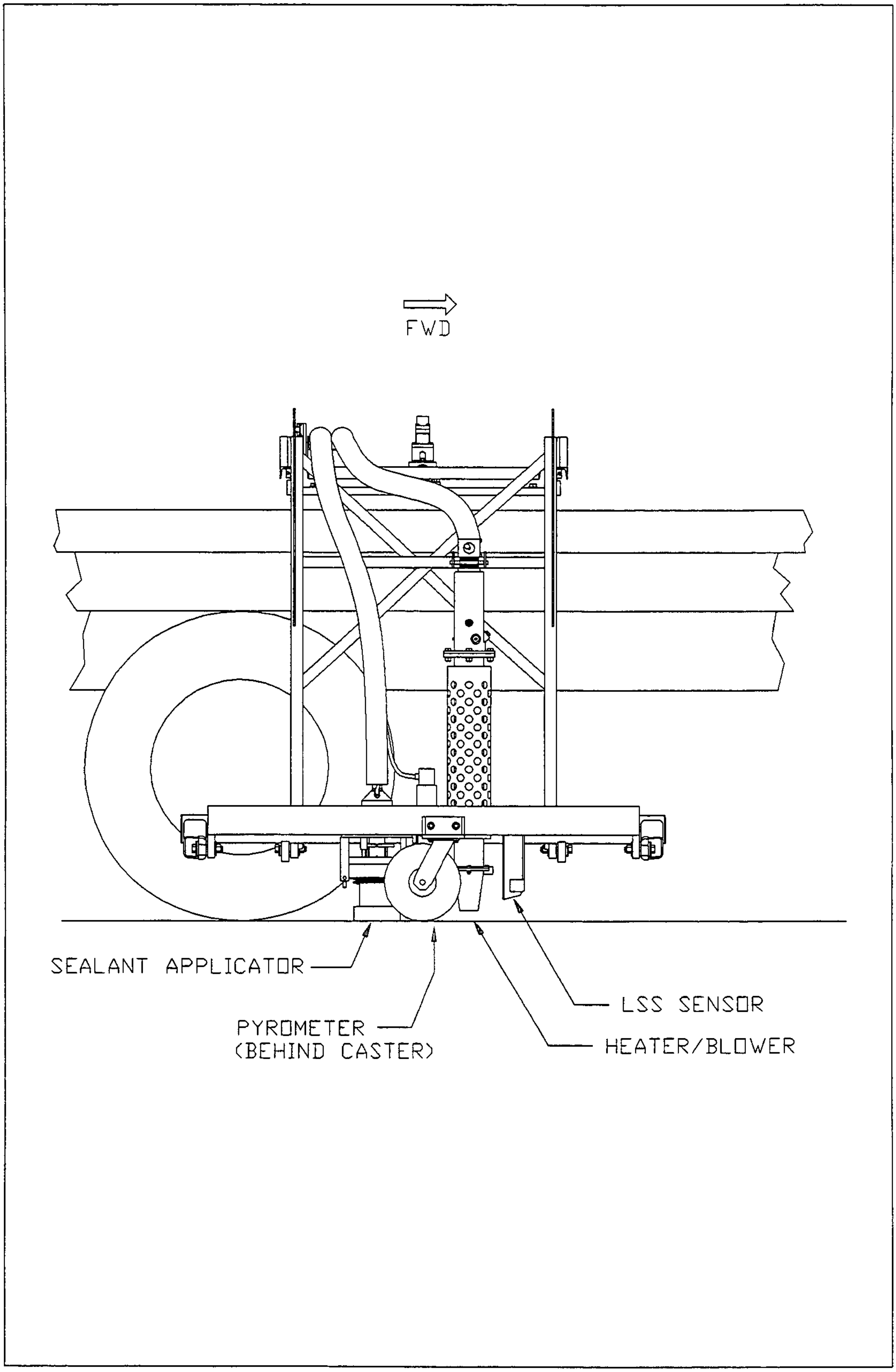


Figure 4.4.5 - Longitudinal Configuration Without Router Attached. Note The Pneumatic Casters Which Support The Linkage.

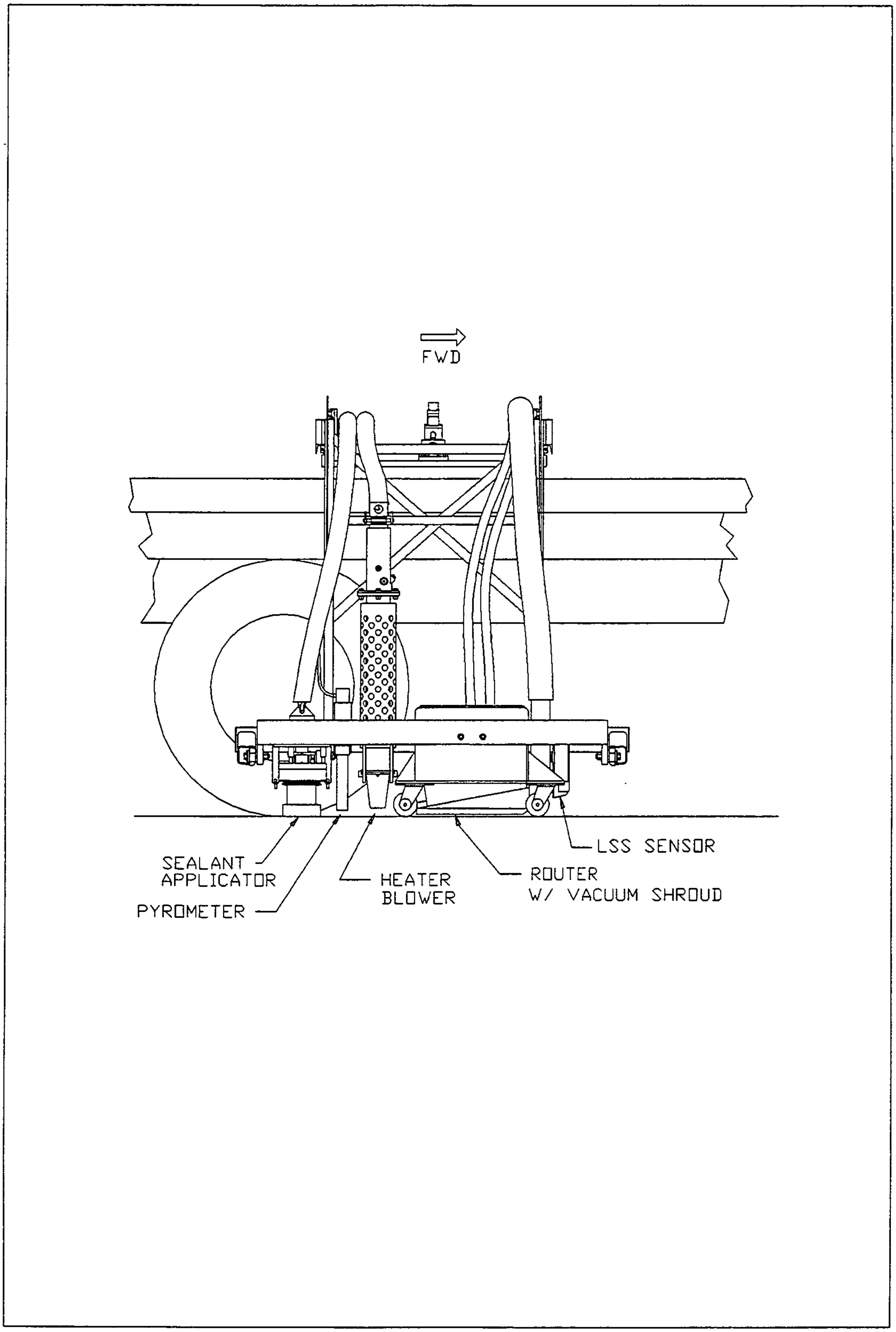


Figure 4.4.6 - Longitudinal Configuration With Router Attached. Note: The Casters Have Been Removed, The Linkage Is Supported By The Router Wheels.

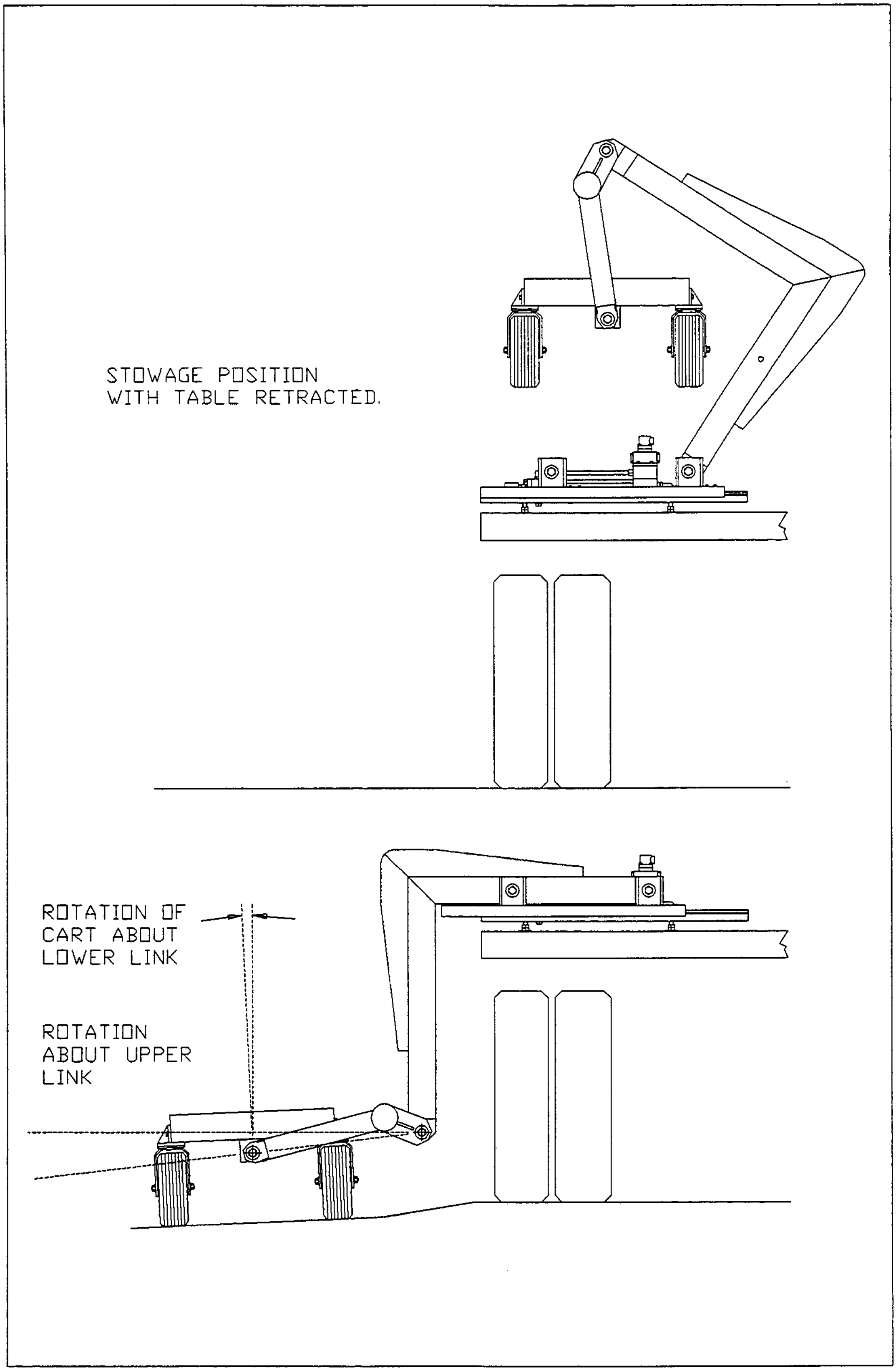


Figure 4.4.7 - Motion Of The Longitudinal Machine.

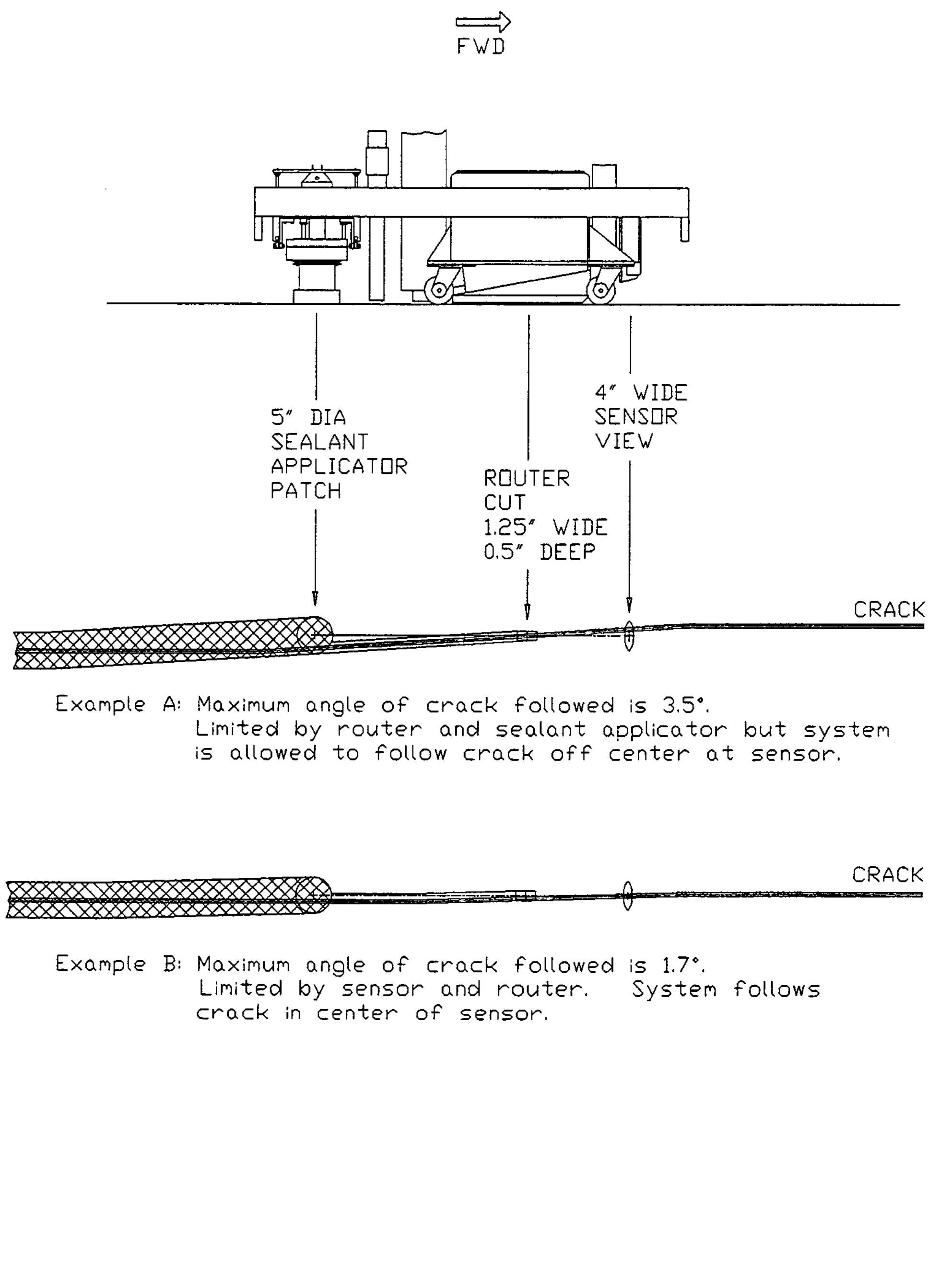


Figure 4.4.8 - Physical Limitations To Longitudinal Crack Sealing Linkage.

4.5 - Applicator & Peripherals System (APS)

4.5.1 - Router

4.5.1.1 - Component Description

The routing component consists of a commercial impact cutting wheel mounted in a frame supported on casters. It is a modular unit that can be attached to the longitudinal or general crack sealing machines. The weight of the router unit is supported entirely by its wheels, and the wheeled frame is designed to resist all forces that act to upset the cart during operation, including forces from the RPS to which it is attached. The cutting wheel is driven by a hydraulic motor with the fluid flow lines running from the cart to the power unit on the truck bed. Detail drawings of the router are located in Appendix A. Figure 4.5.1 depicts the basic components which are described in the following paragraphs. Note that the item numbers in this figure correspond with those of the router assembly drawing SHRP(APS)RM-A100 in Appendix A. Photos of the actual fabricated unit can be seen in Figures 4.5.2 and 4.5.3.

The router cutting wheel (item 14) is a commercial unit removed from the manually operated router described above. The cutting wheel holds six rows of cutters and is designed to run at 2000 RPM. The cutters have a diameter of 4.75 inches and the total effective cutting diameter of the wheel is 15 inches. The maximum cutting width of this particular wheel is 2.25 inches, limited by its cutting wheel design.

The router cutting wheel and hydraulic motor (item 8) are mounted on bearings (item 12) attached to the cutter frame (item 13) which is hinged at the forward end. This allows the cutter to be extended into the road and retracted. The range of motion in the present design allows for a cutting depth of up to 0.85 inches and a retraction of 1 inch. An electric linear drive actuator (items 3 & 7) is used to extend and retract the cutting wheel. The cutter frame rotates about the C-channel pin (item 11) which is bolted to the inner frame (item 6). The inner frame serves as the shroud and the attachment point for the linear drive and linkage which extends and retracts the cutting wheel. This assembly is a very compact, self-contained mechanism which is then bolted to the wheel support frame (item 2).

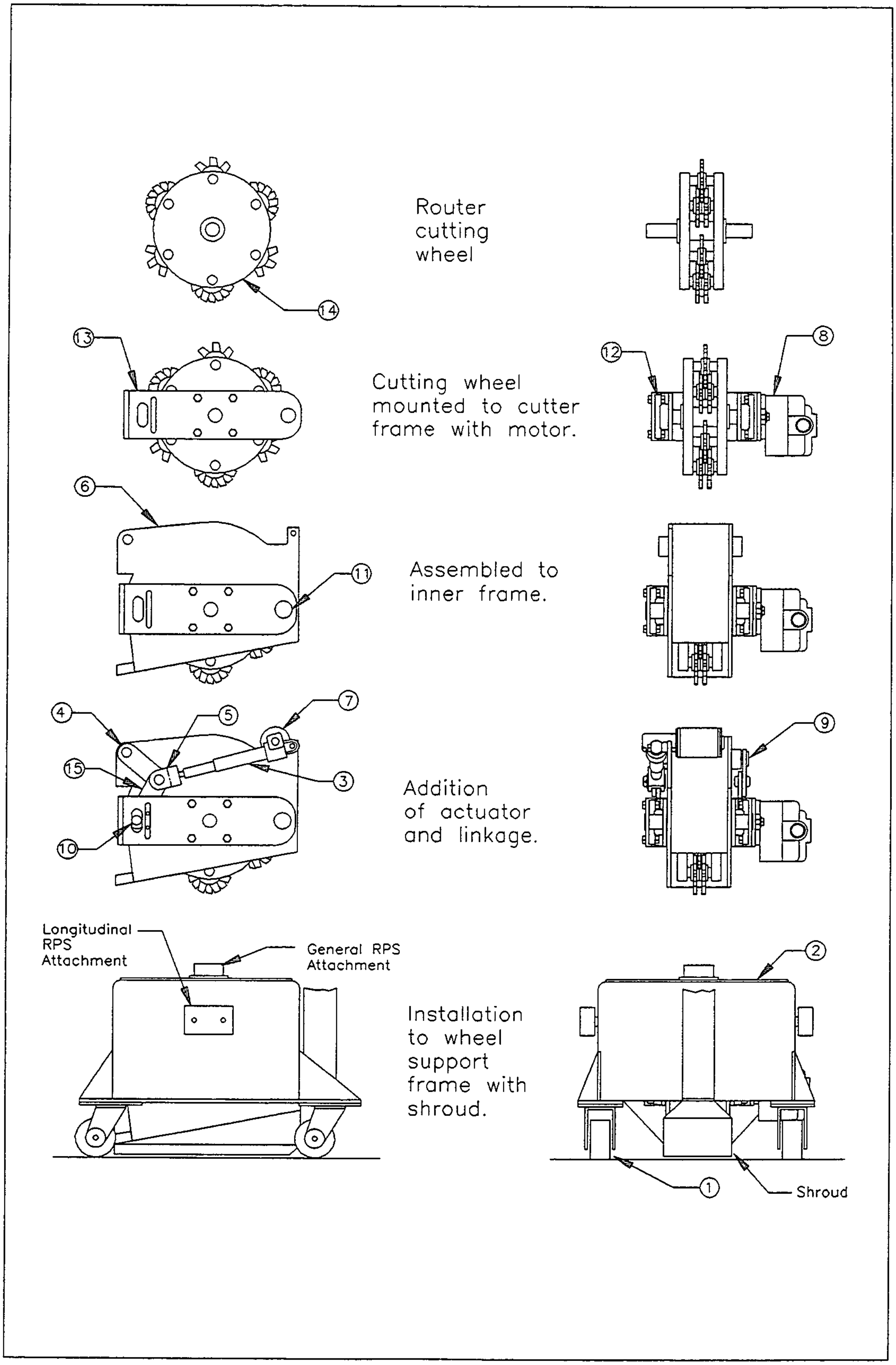


Figure 4.5.1 - Description Of Router Assembly, Items Numbers Are Circled.

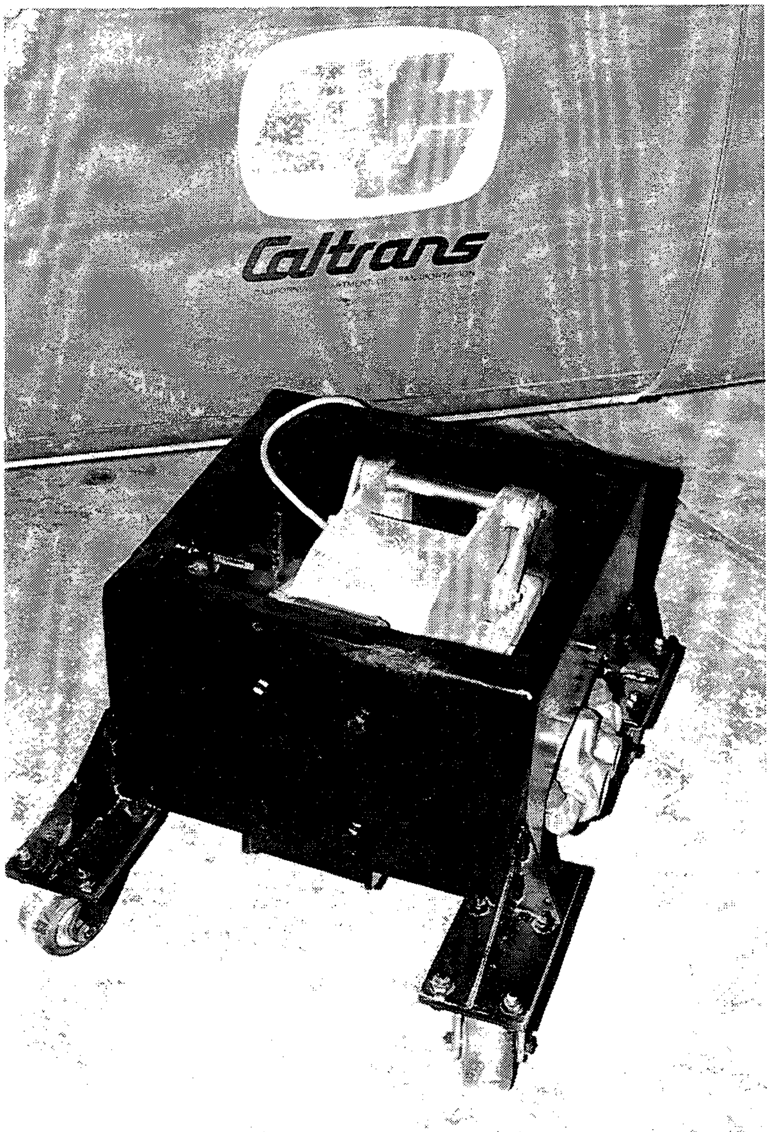


Figure 4.5.2 - Photo Of The Fabricated Router Unit. For Illustration Purposes The Top Cover Was Removed.

The wheel support frame is mounted on four casters (item 1) and supports the weight and cutting forces of the complete router. It also provides the interface to the LRPS. It is designed to sit inside the longitudinal machine cart and in this configuration, the casters of the longitudinal machine are removed and the weight of the longitudinal machine cart and the other APS components is carried by the wheel support frame of the router. An attachment point on the top of the wheel support frame can provide the interface for the general machine robot.. The connection will include a constant velocity joint to allow the router to gimbal over the uneven road surface while still being able to transfer rotation from the robot's end-effector joint. The general machine router joint will also be fitted with a vertical sliding shaft to maintain contact with the road surface without having to change the robots vertical position.

The router's internal linear drive motor has a range of 4 inches and extends and retracts the cutting wheel by rotating two of the links as part of a four bar linkage, as shown in Figure 4.5.4. It acts at the upper and lower link capture (item 5) which is a clevis that shares a pin with two links on the actuator side of the assembly. The two upper links (item 4) are attached to a common shaft at the upper link pin (item 9) and move as a single member acting on the two separate lower links (item 15). The linkage is designed so that at full extension of the actuator, the upper and lower links are in line with each other and the loads transmitted from the router cutting wheel to the inner frame have no component in the direction of the actuator. In order to provide for cutting at different depths, the attachment of the lower link hinge point to the cutter frame is adjusted at the lower link pin block (item 10). The adjustment is set prior to operation of the router. The linkage is designed to retract the cutting wheel 1 inch above the surface of the road. Through the use of a linkage that is self-locking, the actuator will only be subjected to routing impact forces while it is extending the

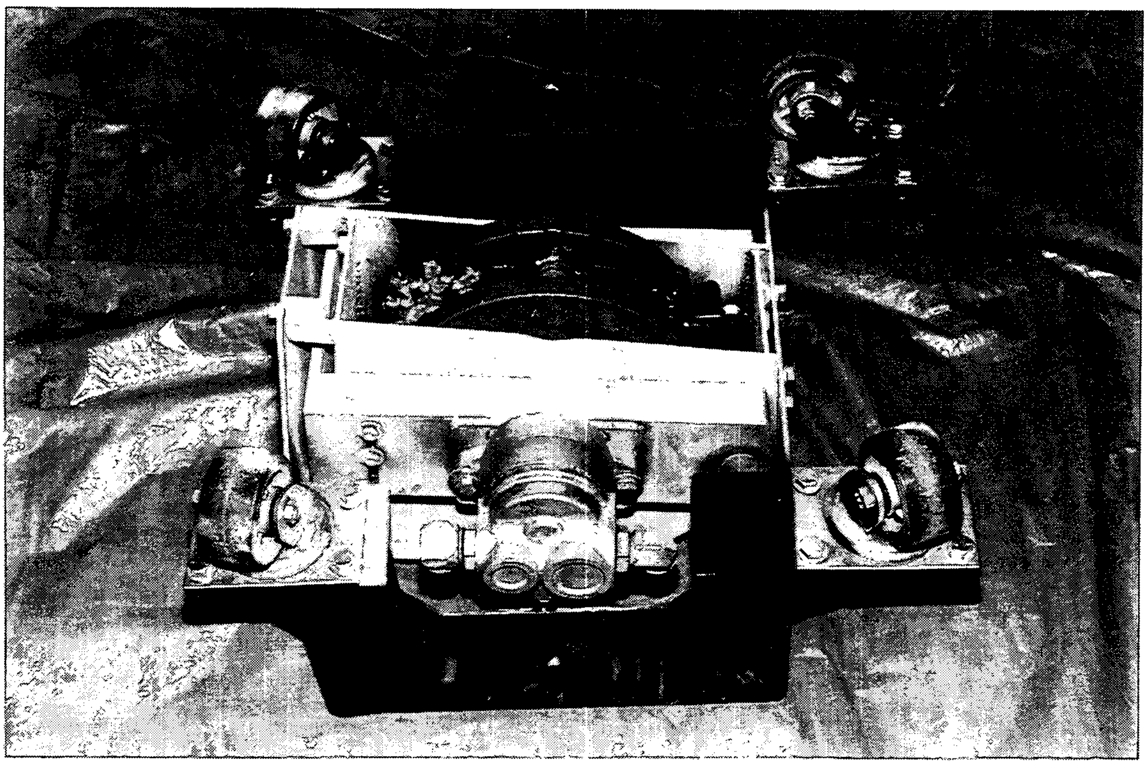


Figure 4.5.3 - The Router Unit Underside. Note The Compact Hydraulic Motor.

cutting wheel into the road. The nominal cutting depth that the router can be set for is 0.1 to 0.85 inches. This accommodates the 0.75 inch cut being evaluated in SHRP H-106.

The router has a debris shroud to facilitate the removal of the asphalt cuttings dislodged during the pavement routing operation. The debris shroud consists of a stainless steel brush strip attached to a removable metal strip that is bolted to the bottom of the router shroud assembly. It includes a deflector plate and vacuum tube forward of the cutting wheel which directs the debris to the vertical tube attached to the vacuum line of the debris removal system. The debris shroud provides a partial vacuum seal with the road surface and will act to retain the debris ejected by the cutting wheel. The debris is emitted forward by the action of the cutting wheel so that the flow of the air will be directed by the vacuum in this same direction and exit forward through a transition from a rectangular cross section into a 3 inch diameter tube.

The hydraulic motor is keyed directly into the end of the shaft that drives the cutting wheel. The displacement of the motor is 1.95 in^3/rev which is designed to have an output of about 17 HP at 2000 RPM. The power for the router is being provided by one of the outlets of the mobile hydraulic power unit which is mounted on the truck platform. Operation is achieved by powering the motor with the router retracted, then extending the cutting wheel into the ground to full extension while stationary. Once extended the router is moved forward to cut the channel.

Operation of the router has been simplified to a start and stop signal that can be sent through the ICU interface screen or manually with buttons on the external control box. When the routing operation is started, the control circuit energizes the hydraulic solenoid and delays the lowering of the cutter until the hydraulic motor is up to full speed. Sending the stop signal to the control circuit will retract the cutters before stopping the cutter rotation, protecting the cutting blades from damage. For safety reasons, the router control circuit is powered by the twelve volt DC current of the truck's electrical system. Thus, if the main AC generator failed during the routing operation, the router could still be correctly shutdown. The hydraulic power unit is diesel engine driven and will continue to run during a power failure.

4.5.1.2 - Principles of Operation

The router, one of the APS components, is used to prepare cracks by cutting a channel along the crack in a profile that allows for increased penetration and adhesion of the sealant. The router was developed to accommodate the unique requirements imposed by the crack sealing machine. The design uses an existing impact router cutting wheel installed in a configuration that will follow random cracks with the general purpose RPS or the nearly linear cracks with the longitudinal RPS. It is hydraulically powered, allowing it to be operated with a remote power supply. As a result, its size and weight are minimized to best accommodate its use with the RPS systems. In addition, the design allows for cutting at the increased speeds necessary for the automated crack sealing applications. The impact cutter design allows for variations in cutting depth and width which can be adjusted by placing the individual cutting wheels in various configurations. Adding cutters and increasing the rotational speed of the cutting wheel assembly also allows for operation at higher road speeds. The router component is a modular unit that could operate in both systems with minor modifications. However, since a commercially available robot had to be used for the general machine, it is currently not possible to drive the router for random cracks, as the robot is not able to provide the end-effector forces necessary to move the router through the pavement. In a commercialized version of the general machine, this will be an important consideration when designing the positioning system.

The basic principles of impact router operation have been verified on a manually operated commercial routing unit. The operator, while walking backwards and pulling the machine, guides the unit by observing the cutting wheel as it follows the crack. Debris is thrown in the direction away from the operator. This mode of cutting runs the cutter wheel in a "down-milling" cut direction (see Figure 4.5.5). Testing showed that the router tended to pull itself up out of the road bed when operated at higher surface speeds. By pushing the router, which results in a conventional "up-milling" cut (see Figure 4.5.5), the operation of the router is considerably smoother. Greater force is required to push the unit since the resulting cutting force acts in the direction opposite the direction of travel. However, a significant advantage is that the routing machine does not pull itself out of the roadway when "up-milling". Test results determined that operating the router in the conventional "up-milling" mode was the most efficient and would be used for the APS router component. This option is not possible with the manually guided machine since the debris would be thrown toward the operator.

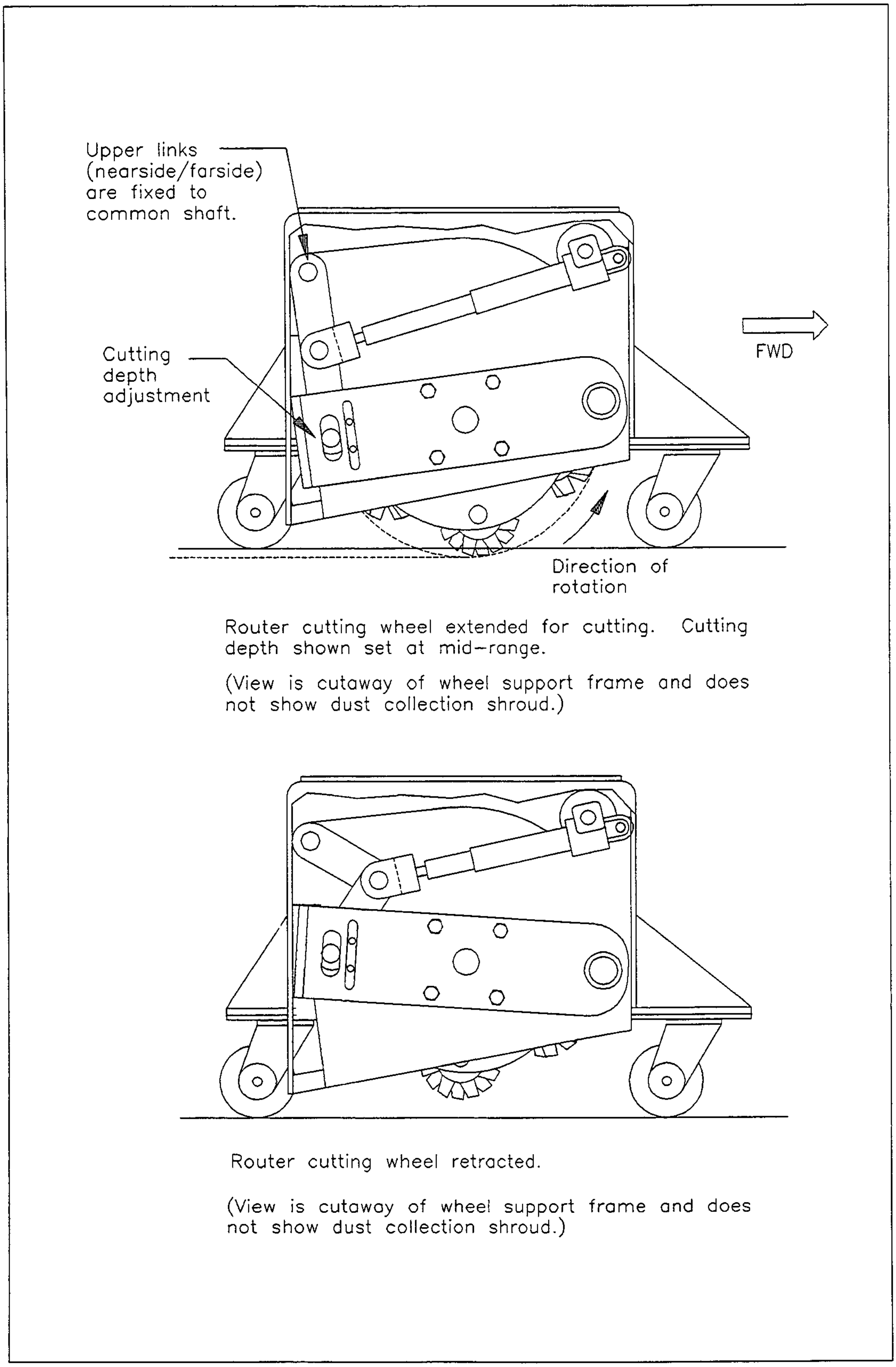


Figure 4.5.4 - Router Cutting Wheel Extension And Retraction.

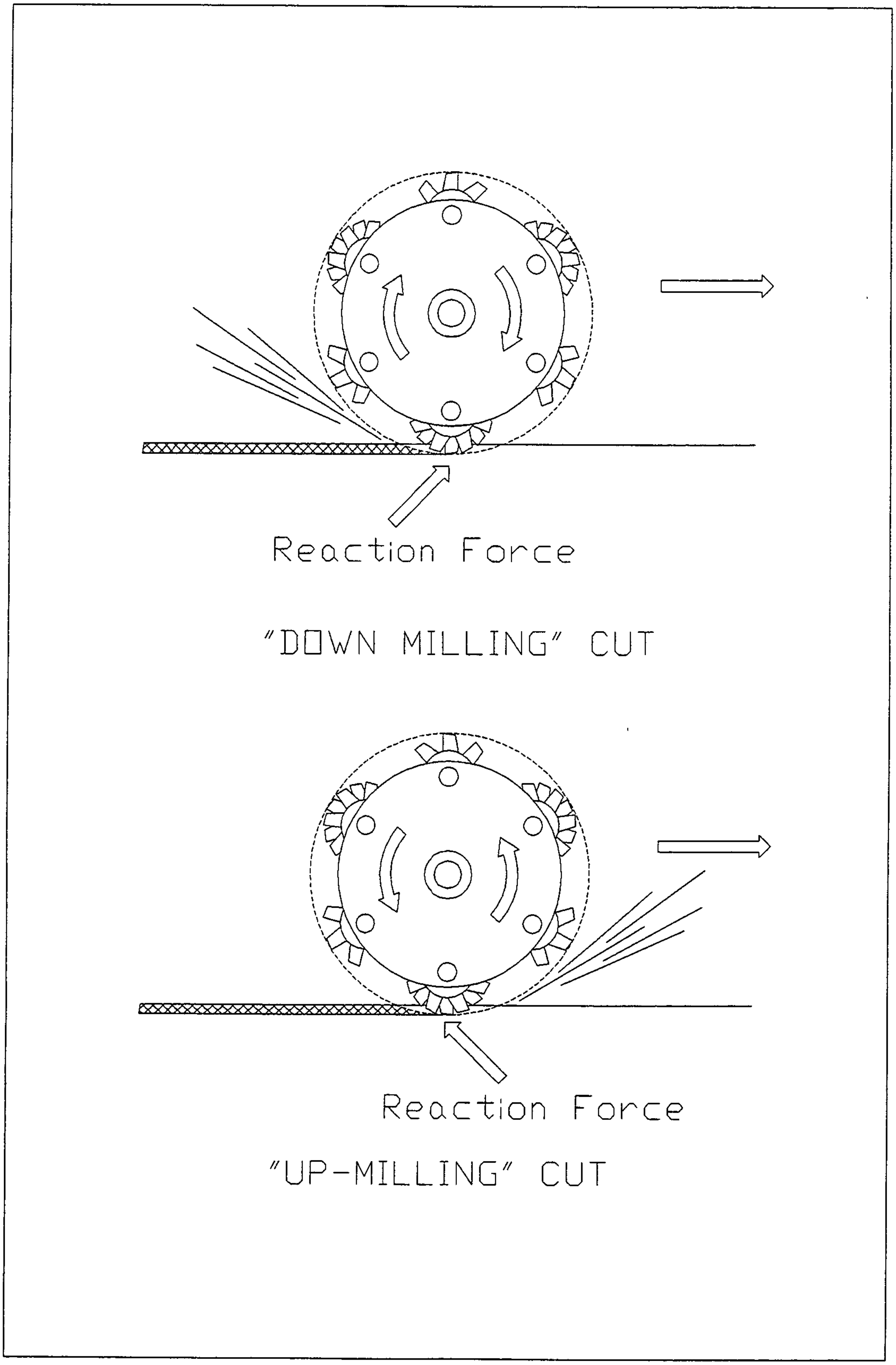


Figure 4.5.5 - Description Of Router Cutting Wheel Operation.

4.5.2 - Heating/Cleaning/Debris Removal

4.5.2.1 - Component Selection

The main component in the Heating, Cleaning and Debris removal (HCD) subsystem is the burner. Four liquid propane heating systems from major burner manufacturing companies were identified using the computational models developed earlier and appeared to closely meet the overall design criteria. However, two were logically concluded to best do so: the previously investigated Sur-Lite burner and the Eclipse Thermal Blast Heater. As mentioned in previous reports, Sur-Lite's modular design affords the possibility of incorporating a larger blower. However, the recently investigated Eclipse Thermal Blast Heater is limited to a maximum 400 SCFM of air flow. Yet, this burner is built for high pressure operation, up to 50 PSI, and has been designed around the operating envelope specific to this application. The Eclipse burner also ejects its hot exhaust via a 4" diameter duct as opposed to Sur-Lite's 6" exit. This means that in order to reduce the exhaust area at the nozzle to increase flow velocity, the Sur-Lite system would experience a much greater pressure drop and generally be more bulky. Also, the Thermal Blast Heater is designed specifically for remote blower placement. In the case of the Sur-Lite burner, less routine modifications would be necessary. Therefore, it seemed reasonable to conclude that if the heat output from the Eclipse burner is not significantly limited by the 400 SCFM maximum flow and the burner can heat the crack to 250°F at a relative speed of 2 MPH, then it should be selected as the preferred method. A simulation using the convective model was run and indeed, a sufficient surface temperature of 260°F was achieved (see Figure 4.5.6 below). Thus, the Eclipse burner was chosen for integration with the automated crack sealing vehicle. Selection of the flame safeguard and fuel train was fairly straight forward since it is made of components commonly available through most burner manufacturing companies. For convenience, a local vendor, Control Technology Specialists, was chosen to provide this portion of the HCD system and to help install and fine tune the heating system as needed.

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

4.5.2.2 - System Description

The automated pavement crack heating, cleaning, and debris removal (HCD) system designed and purchased primarily consists of an EG & G Rotron debris separator, model IVM2000PF (approximately the size of 2 - 55 gallon drums stacked vertically), a 5 PSI, 400 SCFM hydraulically powered centrifugal blower, Paxton Centrifugal Blowers model CB-87, a 692,000 BTU/hr Eclipse Thermal Blast Heater, and an infrared pyrometer, Raytek model ET3LT, which measures crack temperature and thereby modulates fuel flow to the burner. Overseeing safe operation of the burner is a standard flame safeguard control panel built by Control Technology Specialists. It features additional control panel functions for diverter valve actuation (to ensure safe idle operation), CLEAN ONLY operation (no heat), and a PID controller to interface with the pyrometer.

The debris removal portion of this system consists of a debris shroud mounted to the router casing, the EG &G Rotron debris separator unit and waste container located on the truck bed, and two (2) 3" diameter flexible hoses. The Paxton blower provides vacuum air to the debris shroud and separator unit and the waste container houses all collected debris for later disposal. Both the blower and burner units are placed on the truck in a location which minimizes pressure and heat losses through minimal bending and plumbing distance. Proper insulation will protect subsystems and operators from danger. Hydraulic power to the blower is provided by the central hydraulic system. Perhaps in the future, a drive train power take-off unit could be used to power other subsystems. The pyrometer is located just aft of the burner exhaust nozzle on the longitudinal sealant cart and between the sealant applicator and heater nozzle exit on the general process cart. Appendix B contains manufacturer and model number information for many of the items discussed herin.

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

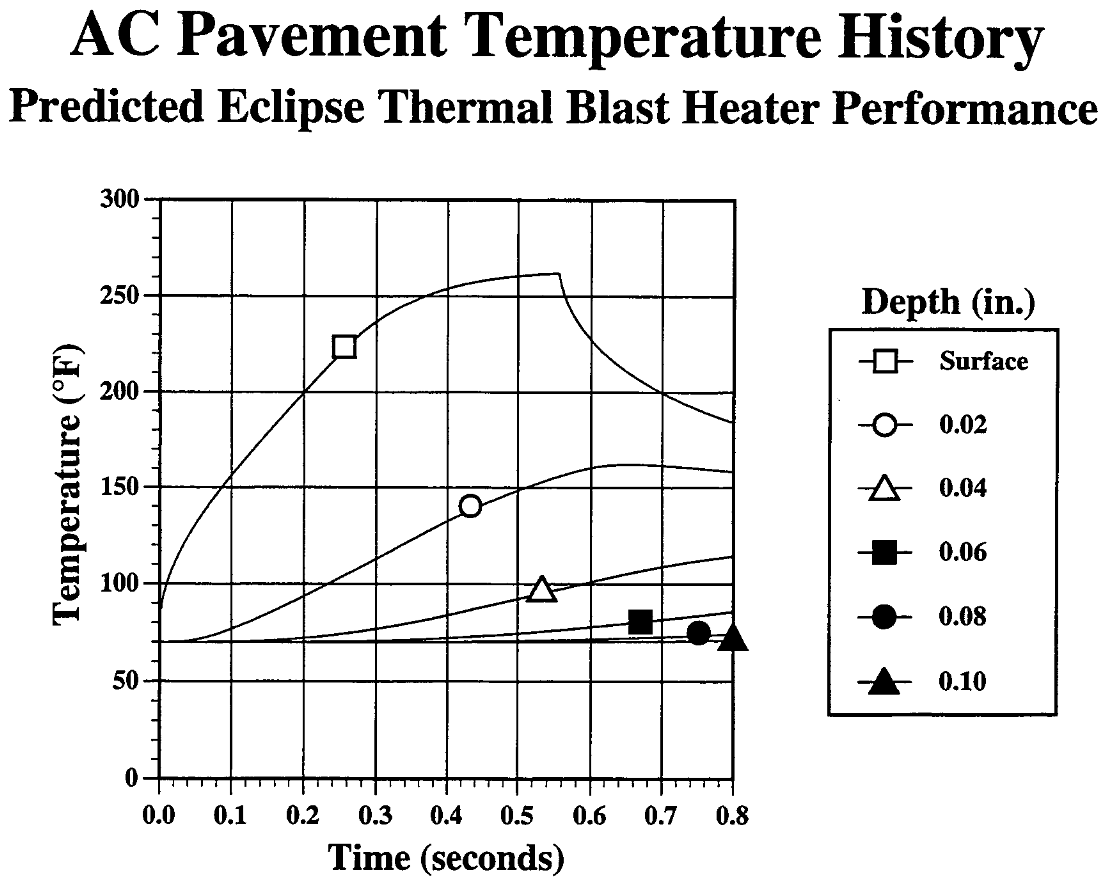


Figure 4.5.6 - Predicted Eclipse Thermal Blast Heater performance. Relative speed is 2 MPH, nozzle exit diameter is necked down to 2.5", and the exit gas temperature is set at 1500°F.

4.5.2.3 - Principles of Operation

Since both the debris removal and the surface heating portions of the HCD system require high volume / low pressure air, it is obvious that combining their required air flows into one centralized system, affords the possibility of utilizing a single blower. Vacuum air from the debris removal portion is therefore cleaned of debris in the separator unit, then exhausted to a burner, and blown onto the road surface to heat it to the proper temperature. This setup provides the best solution in terms of cost and efficiency. Figure 4.5.7 shows a conceptual sketch of this set-up deployed for longitudinal sealing.

The system is also designed such that it can operate in the CLEAN ONLY or HEAT AND CLEAN mode. In the CLEAN ONLY mode, the heater is not ignited and the blower is used by itself, with or without the debris removal attachment. This is a necessary feature since many DOTs do not heat

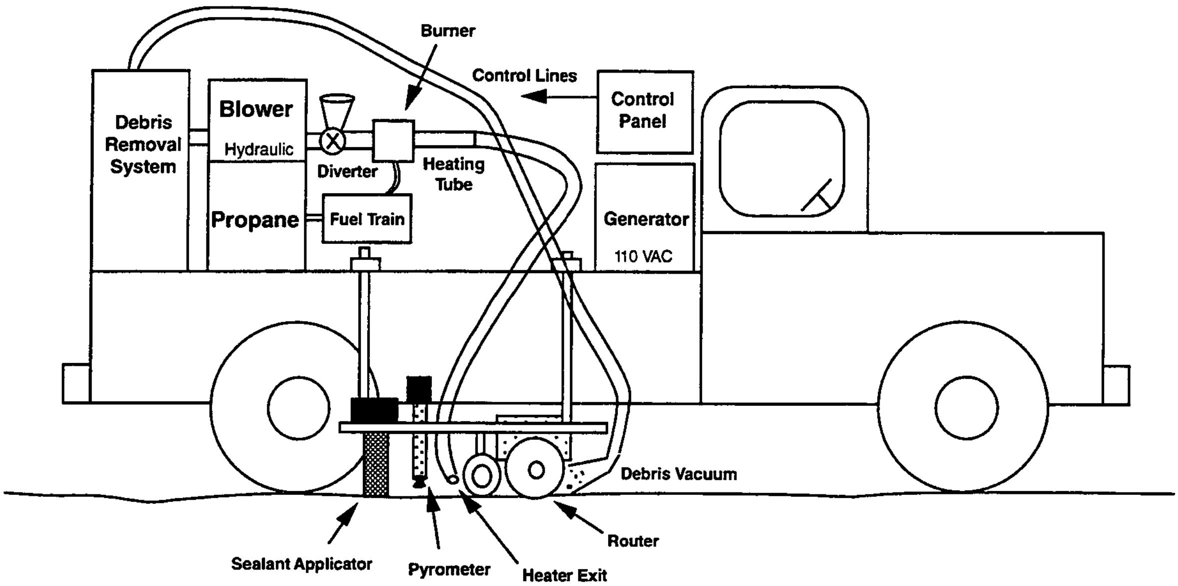


Figure 4.5.7 - Sketch Of HCD System Deployed For Longitudinal Sealing.

the roadway prior to sealing. The diverter valve is also necessary to adjust for the proper component pressure loads during system qualification. This will ensure maximum performance of the components while not causing damage to them.

Operation of the integrated unit takes place via a control panel to be mounted conveniently on the crack sealing vehicle. To begin operation, the unit is first configured for the type of sealing desired. (Some DOT's do not route or heat, others route and heat, while some may only route etc.) After configuration, the system is activated by first switching on the main subsystem power (assuming the ICU is in operation and power is present in the hydraulic system) then flipping solenoid switches that regulate hydraulic fluid flow to the blower. Normally the diverter should be set to divert flow from the pavement for safety reasons during start-up. After the blower reaches operating speed, the diverter valve can be released to deflect flow to the pavement enabling the burner to be ignited.

In general, the burner operates similar to most LP gas burner packages with a few exceptions. Ignition of the burner is automatically controlled by the flame safeguard system and takes place only after an air purge has been verified (1-5 seconds). Once ignited, the burner operates as a self contained unit as long as air flow is present. Should the air lines become clogged or the blower shut down, pressure switches sensing deviant air pressure would trip thereby shutting down the fuel flow. Fuel flow is normally maintained through a PID controller connected to the pyrometer -

as opposed to a manually or permanently set flow rate. Based on the surface temperature of the pavement, the pyrometer returns a signal, roughly between 12 and 16 mA (200°F and 300°F), back to the PID controller which in turn sends out a 4-20 mA signal, linear over the turn down range of the fuel control valve, either increasing or decreasing fuel flow in order to approach the desired surface pre-heat temperature. The burner output is therefore automatically proportionally adjusted for the set point programmed into the PID controller.

4.5.3 - Sealant Applicator

The sealant applicator unit constitutes a significant advancement in crack sealing technology. It was designed to deliver hot thermoplastic sealant at an increased velocity over current crack sealing techniques, as well as shape the material to produce a variety of sealant finish configurations. A significant advantage that this unit possesses over other sealing methods is that it uses a small amount of pressure to force sealant into the crack. The sealant flow rate is automatically adjusted according to the cross-sectional area of the crack as is described below.

During Phase II of this project, the design of the sealant applicator was finalized and a first generation prototype was built (see Figures 4.5.8 and 4.5.9). In Phase III the sealant applicator was successfully field tested (see Figures 4.5.10 and 4.5.11). In the following paragraphs, the principles of operation and a description of the various subassemblies is provided (see Figures 4.5.12 - 4.5.16).

4.5.3.1 - Subassembly A

Figure 4.5.12, Subassembly A shows the sealant supply tube. The hot-pour sealant is supplied to the tube through a Teflon hose from a melter unit mounted on the truck platform. During the time it takes for the sealant to flow from the melter to the pavement crack, the sealant must be kept at a high temperature in order to prevent the sealant from solidifying. To accomplish this, a continuous hot oil line is doubly wrapped around the Teflon hose. The line is broken when it reaches the sealant applicator and each end is mounted to the top of the subassembly (item 10). The entering oil sees a cavity in the shape of a half-circle (item 10, Section A-A), flows through this cavity, then travels through an area between the sealant tube (item 1) and an outer wall (item 2). Two rods press-fitted between the sealant tube and the outer wall (item 34, Section B-B) force the oil to flow down the length of the sealant tube on one side and then back up on the other side where it exits.

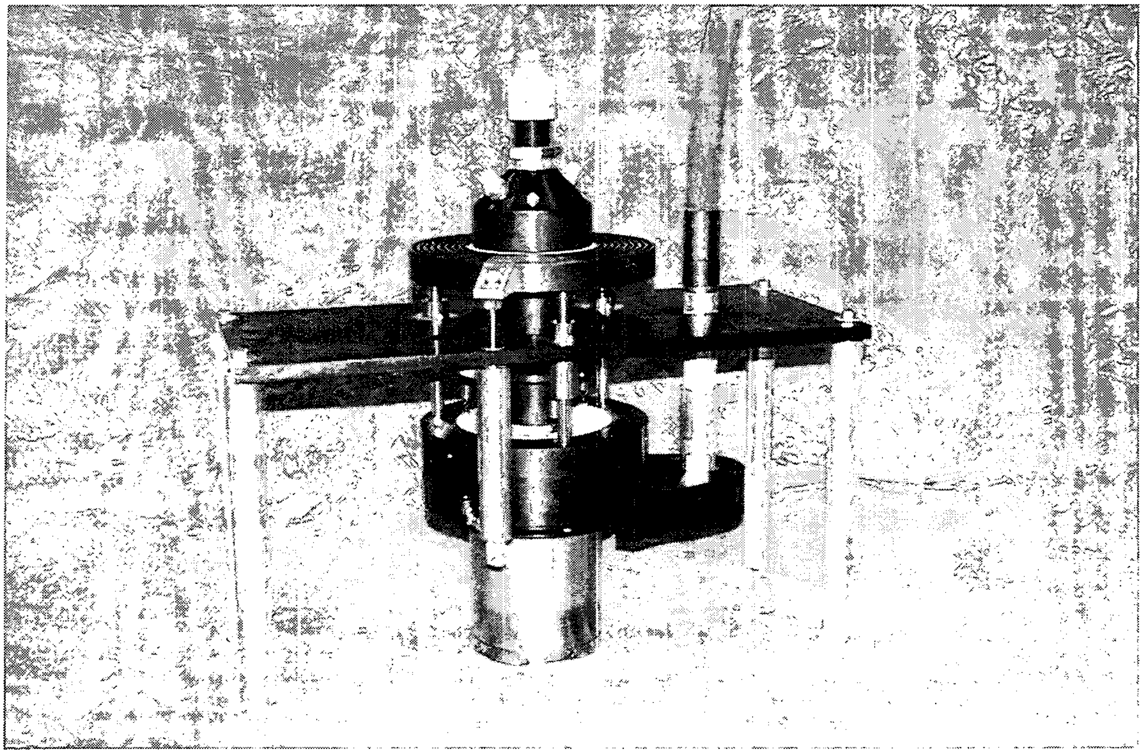


Figure 4.5.8. - The Sealing Dispensing Unit Mounted On The Base Plate For The Longitudinal Crack Sealing Machine.

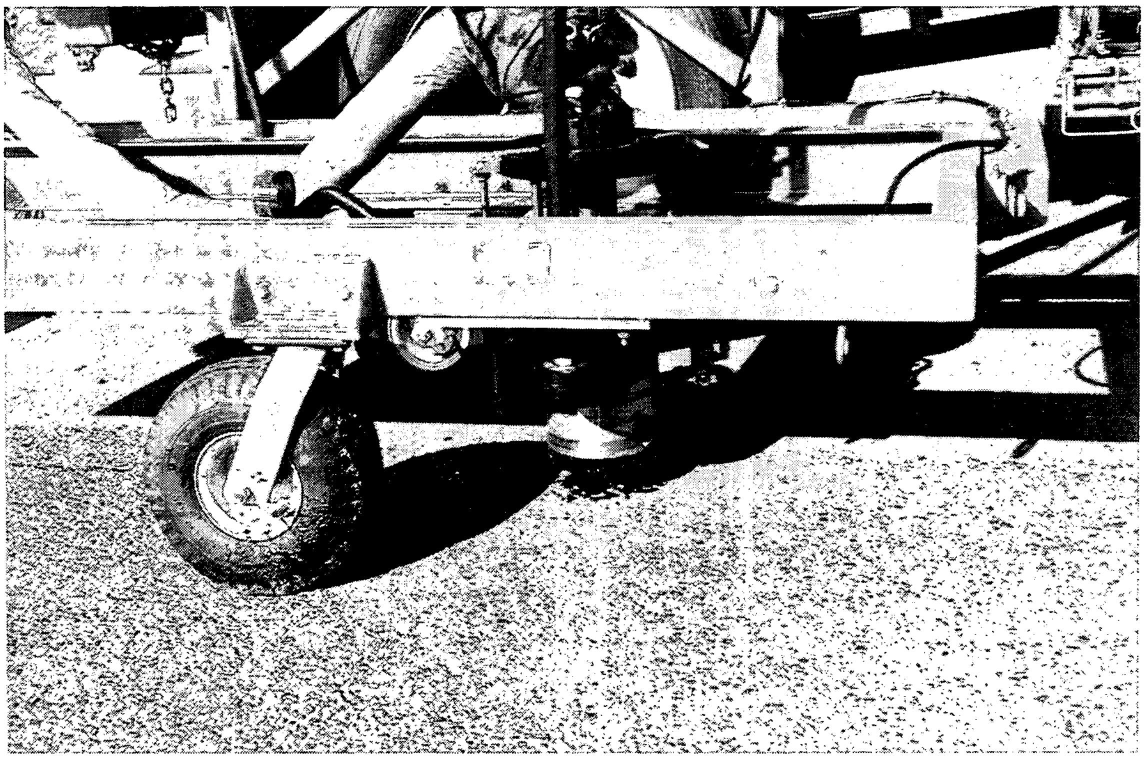


Figure 4.5.9 - The Sealant Applicator At The End Of The Longitudinal Machine.

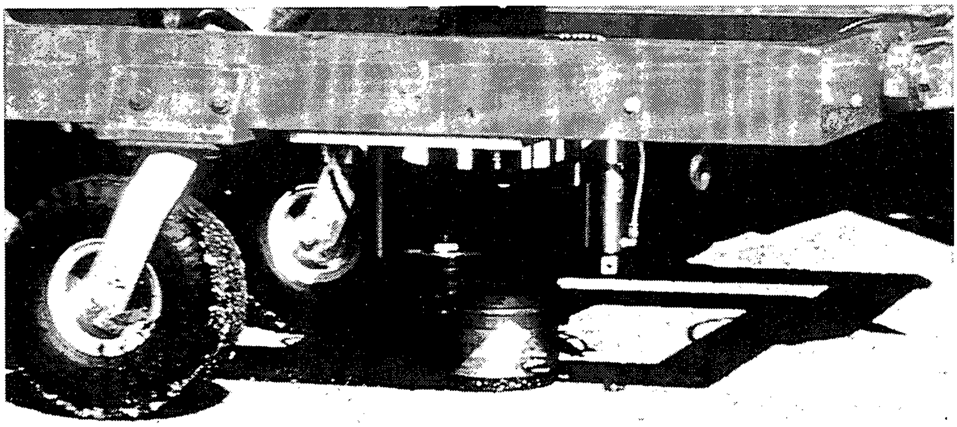


Figure 4.5.10 - The Sealing Dispensing Unit Mounted On The Longitudinal Machine.

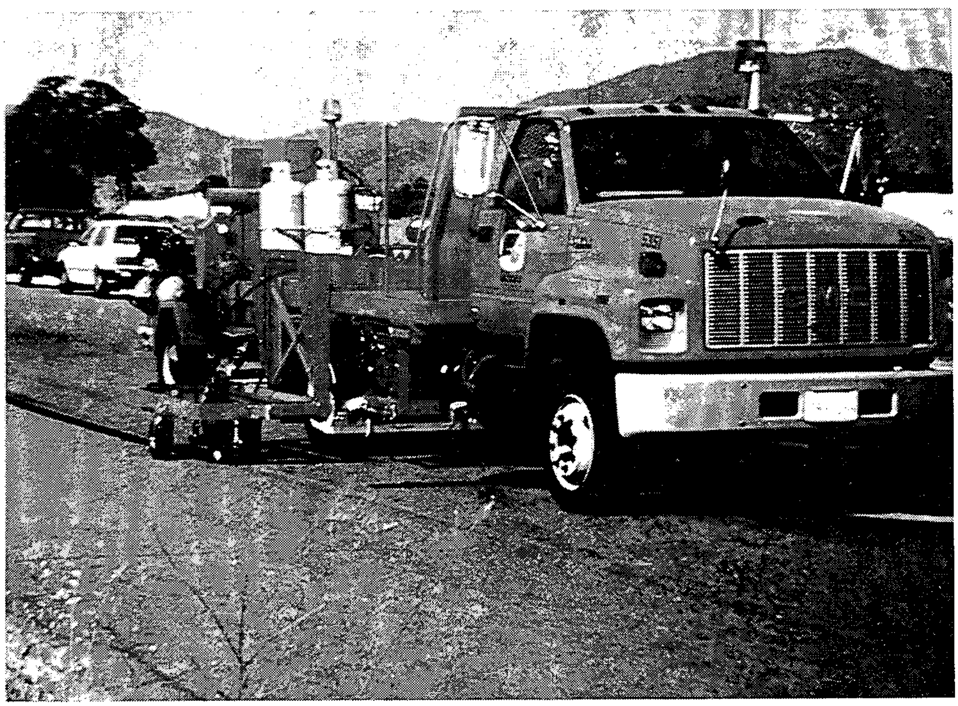


Figure 4.5.11 - The Sealant Applicator Sealing A Crack.

Proper sealant application temperature is maintained by this design. High-temperature O-ring seals in the design insure that both sealant and oil do not leak outside the body or into each other.

At the base of the center tube (item 1) there is a cone-valve (item 7 mounted to item 9). The cone is spring-loaded, so when there is no sealant flowing, the sealant orifice is closed off. The force of the spring is just equal to the weight of a standing column of sealant. At the time when sealant is to be applied, pressure generated by the melter pump opens the cone-valve. When the applicator reaches the end of a crack, the sealant flow is stopped and the cone-valve closes, preventing extra sealant from flowing out of the tube.

4.5.3.2 - Subassembly B

During design it was necessary to address protection of temperature-sensitive parts of the applicator from the very high temperatures necessary to retain sealant fluidity. It is apparent that over a period of time, the entire Subassembly A will reach 350-400°F. This problem was solved in three ways: insulating material was used between Subassembly A and the rest of the applicator (Figure 4.5.13, items 4 and 5), contact points were minimized (item 10), and heat fins were provided for maximum heat dissipation (item 6).

Another design issue concerned the manner in which the applicator would follow the contour of a road. All roads are not perfectly flat; i.e., surface irregularities are always present in pavement. The manner in which this problem is addressed is apparent by considering the drawing of Subassembly B. Three hardened Thompson shafts (item 3) are mounted between the upper and lower sections of the applicator (items 6 and 14). The shafts pass through three linear bearings captured in the frame. The result is that the entire sealant applicator assembly has the ability to move vertically over a range of 5.5" yet still be rigid in the horizontal plane. Overall, the modular design of the sealant applicator allows it to be mounted to the longitudinal machine, the general crack sealing machine, or any other compatible device.

The last design feature described using the Subassembly B drawing is the method by which the applicator controls the flow of sealant over a given crack. Consider the flow of sealant through the sealant tube (item 1). At the base of the tube, the sealant both fills up a crack and pushes a float (item 30) upwards (Circle A). The volume of sealant beneath the float is referred to as the reservoir. The float in turn extends three springs (between items 6 and 14) which are attached to a circular plate (item 13). A linear potentiometer (item 35) also attached to this plate, is part of a circuit where the output current represents the amount of sealant in the reservoir. The circuit controls a proportional valve which adjusts the rate of sealant flow.

As the applicator travels along a crack, a varying amount of sealant (dependent on crack width and depth) is pushed into the crack from the reservoir (Circle A). Note that the spring pushes against the float, forcing sealant into the crack. The internal sealant pressure in the reservoir is maintained between 2 and 8 PSI. As the float lowers due to sealant dispensing, the linear potentiometer circuit signals for an increase in sealant flow into the reservoir. Once the reservoir fills, the sealant flow is again decreased, etc. The closed-loop nature of the applicator provides continuous and complete filling of cracks independent of crack size and applicator surface speed.

4.5.3.3 - Subassembly C

As mentioned in the Phase I final report the sealant applicator is a combination sealant dispenser and shaper (squeegee). To provide for a wide variety of crack seal configurations, the rubber ring/squeegee at the base of the applicator was selected to have a 5" inside diameter (ID). During development and testing, a problem concerning the contact between the rubber ring and the ground was identified. The rubber ring could not flex on the road surface. As such, as is shown in Figure 4.5.15, Subassembly C, a steel cup brush (item 31) is used. This brush flexes on the road surface and provides for a flush sealant configuration over the crack. It is easily replaceable as it slips on and off an outer wall (item 17) and it is held in place by an adjustable clamp.

Proper operation of traditional squeegees requires a downward force of 10 - 20 lb. The weight of the sealant applicator is approximately 35 lb. Accordingly, this weight is counterbalanced by two compressed air cylinders (not shown) so as to provide proper down force.

Angular contact ball bearings permit the rotation of the tubing ring providing for other sealant configurations (e.g., overband) as mentioned in the Phase I final report. This rotation additionally provides for more uniform wear of the tubing ring and reduces the possibility of sealant buildup on the ring (item 31). The bearings are mounted within the applicator body, away from the base to protect them from the environment (items 15, 18, 19 and 27). A V-belt drives all the various rotating components through a pulley (item 11) mounted to the outer wall (item 17).

4.5.3.4 - Subassembly D

Figure 4.5.16, Subassembly D shows a half-view of the entire sealant applicator assembly. On the left, a flexible link connects a variable-speed DC motor on the truck which drives a shaft (item 21). The shaft is mounted to a smaller pulley (item 28). The pulley moves up and down with the main body of the applicator as it travels down the road. The shaft assembly can also be moved back and forth in guiding groves (items 25 and 26) in order to adjust tension and change the belt that rotates the tube assembly. As noted above, this rotation provides for more uniform tubing ring wear and less sealant build-up. It was also determined during testing that a pulse rotation for squeegee wear produced a better seal than continuous rotation.

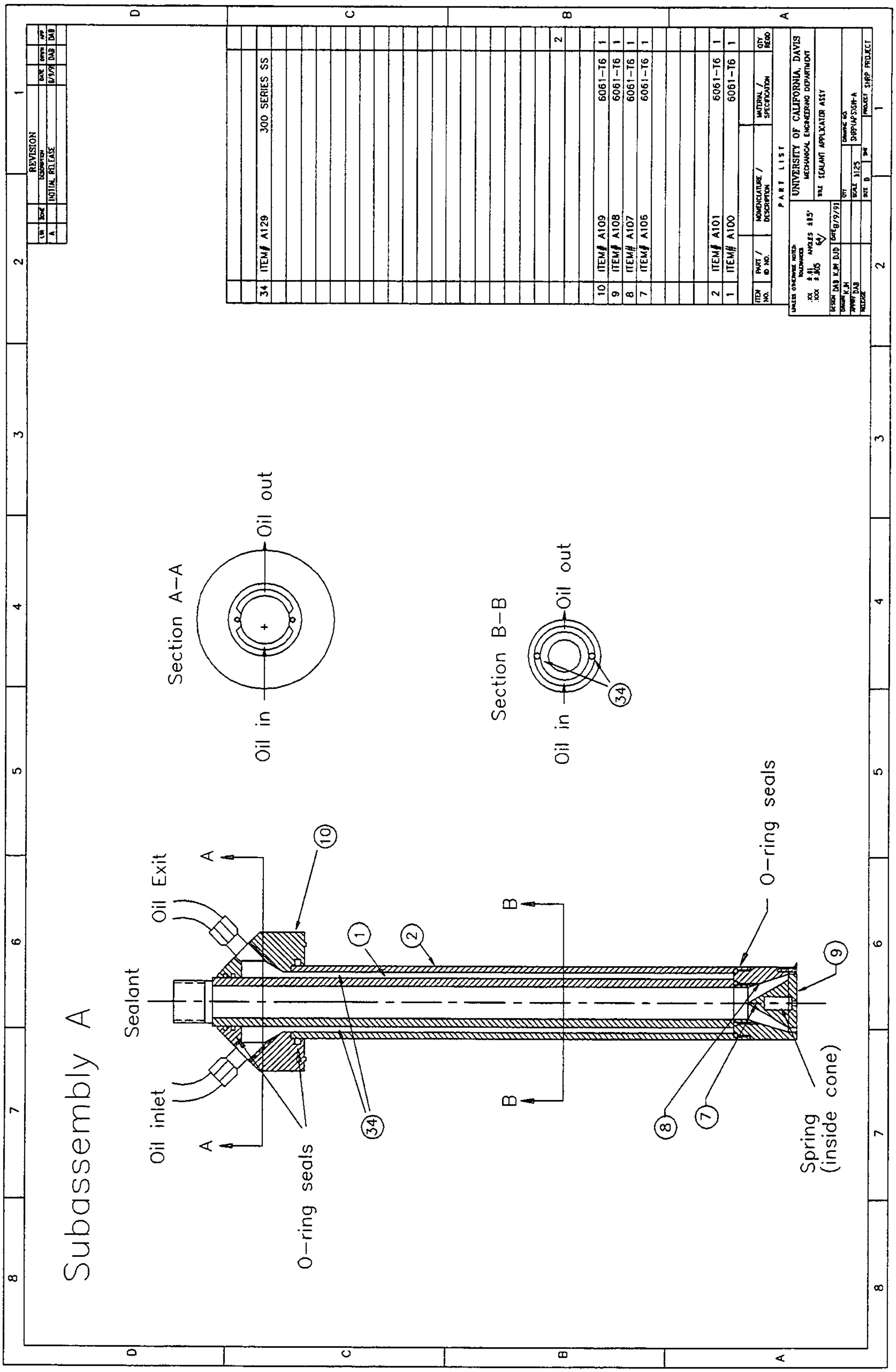


Figure 4.5.12 - Sealant Supply Tube

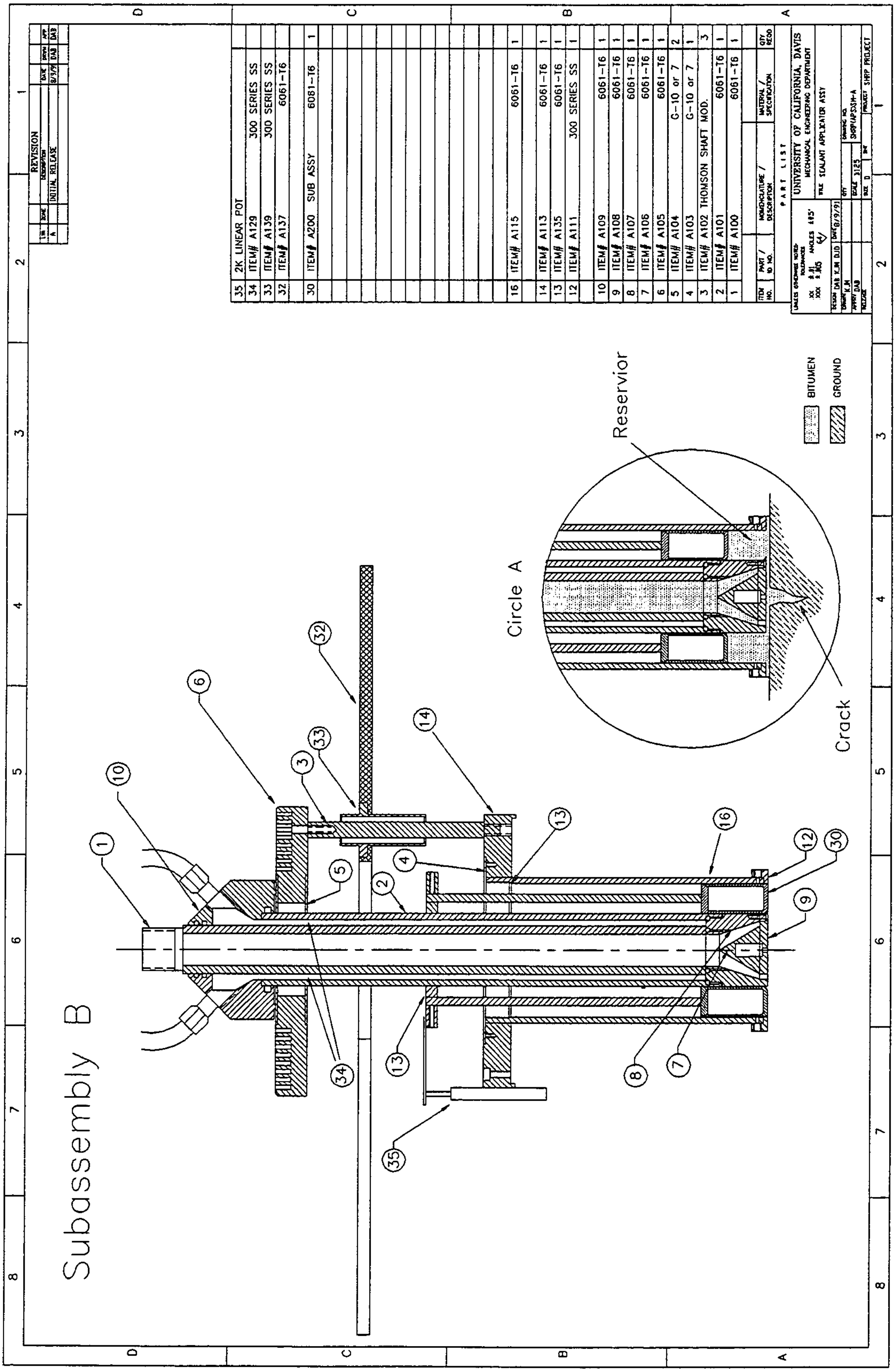


Figure 4.5.13 - Sealant Supply Tube With Reservoir Added

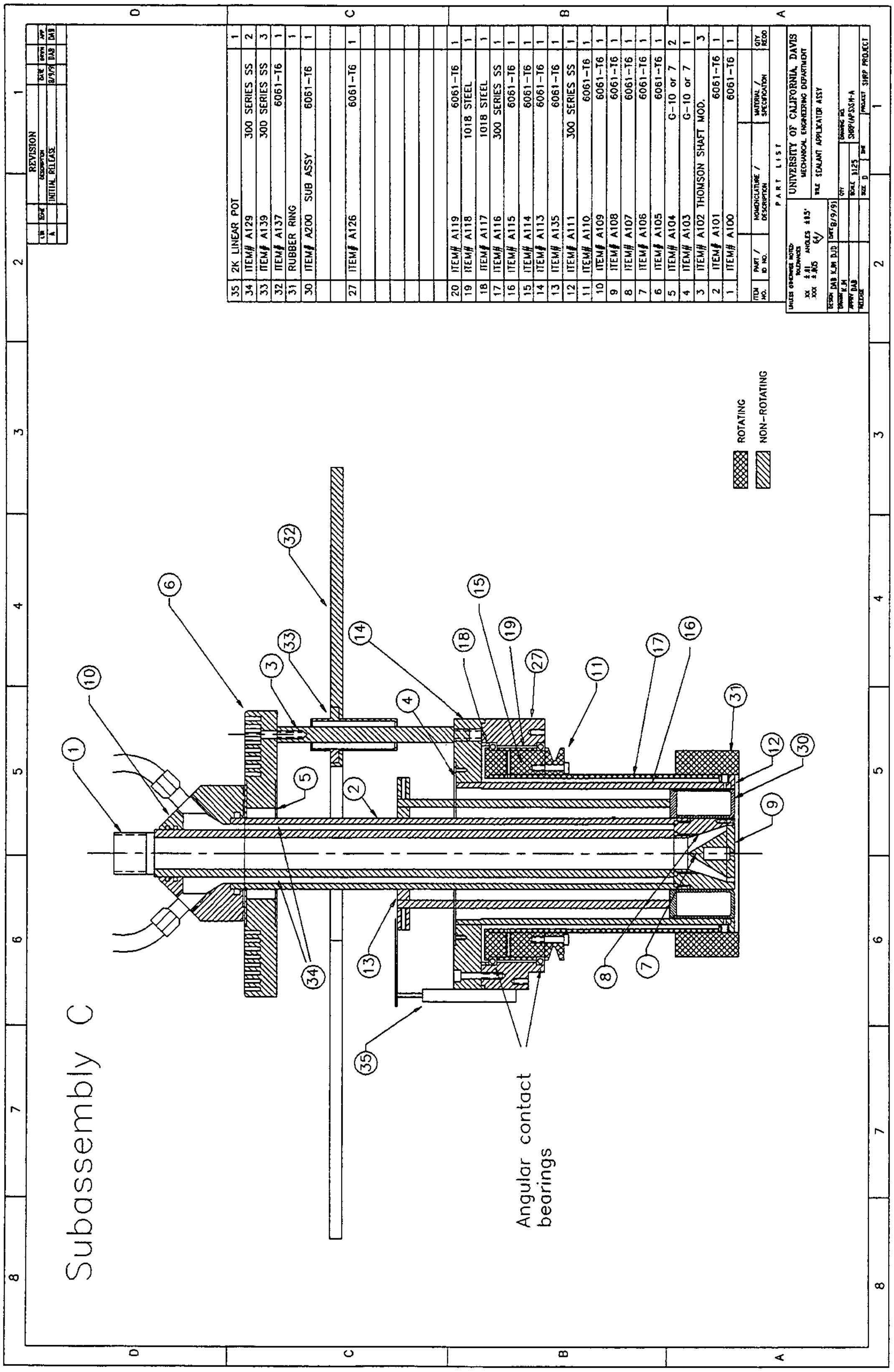


Figure 4.5.14 - Sealant Supply Tube With Rotating Components

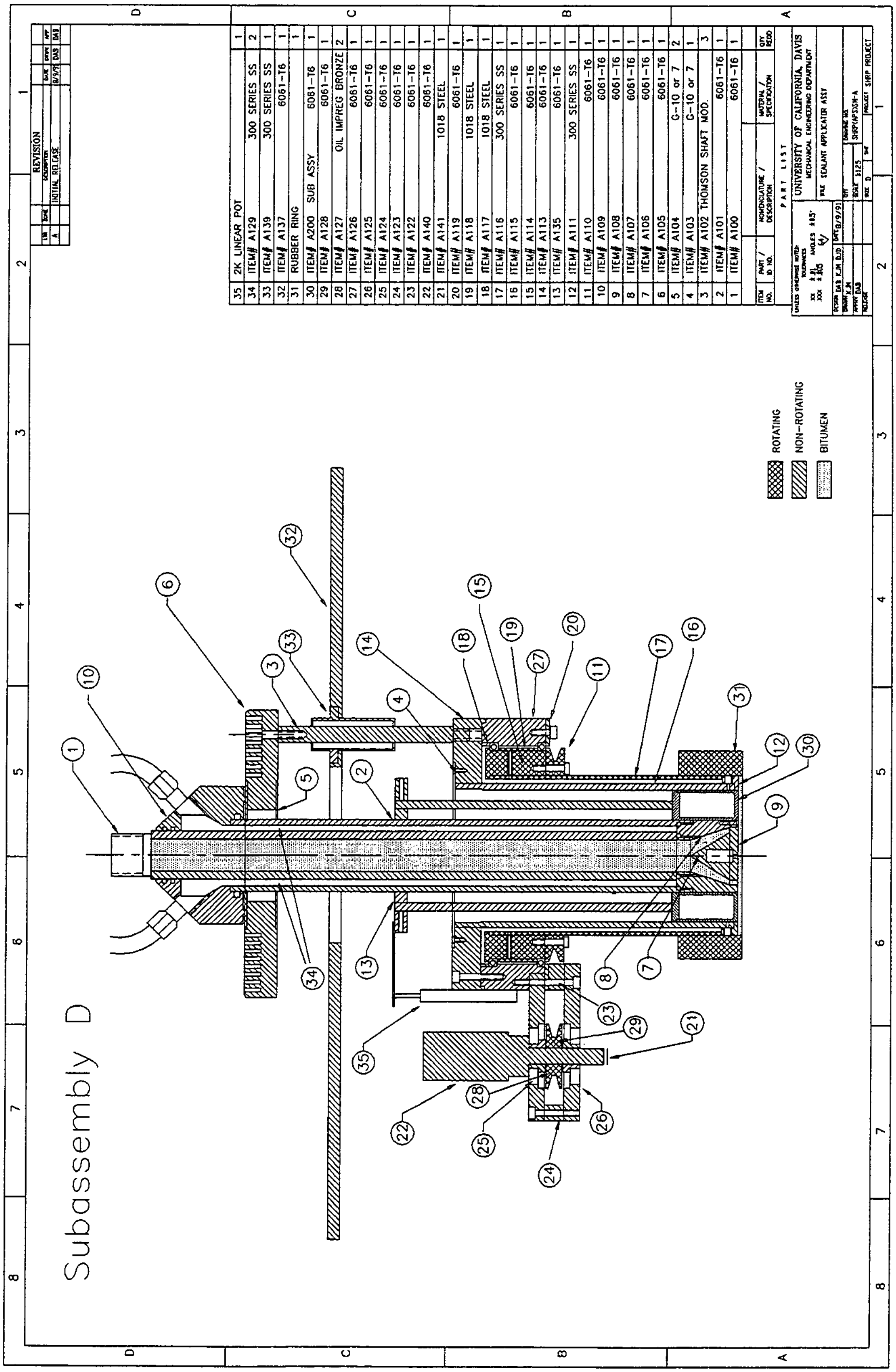


Figure 4.5.15 - Cross-Sectional View Of Sealant Applicator

4.6 - Vehicle Orientation And Control System (VOC)

4.6.1 - System Description

The Vehicle Orientation and Control (VOC) system tracks the position of cracks on the road surface with respect to a fixed point (e.g. the robot base) located on the truck. This system is required so that the position of road cracks identified by the Vision Sensing System (VSS) at the front of the crack sealing truck can be tracked continuously as the truck moves forward, and until the cracks enter the work space of the robot arm at the rear of the truck. At that point, the crack position data will be sent to the controller on the robot arm (RPS) via the ICU. The robot controller will then send signals to position the end effector of the robot arm over the cracks. Once positioned, the end effector will rout, clean, heat, and finally seal the cracks. It is our intent that ultimately the entire process of identifying the cracks, tracking their positions, positioning the robot end effector, and performing the crack repair operation will be done in a continuous fashion with the truck moving ahead at a slow forward speed. A schematic illustration of the crack sealing truck and the integrated VOC, VSS, RPS, and ICU is given in Figure 4.6.1.

The task of tracking points on a crack would be simple if the truck were moving straight ahead or if it were turning a corner of constant radius. However, this is usually not the case. To illustrate this point, it is noted here that after a particular point on a crack is identified by the VSS, the truck must move ahead approximately 35 feet before that same point on the crack moves into the work space of a robot arm. Throughout this distance it is unlikely that the truck will maintain a straight heading or even a turn of constant radius. Instead it is very likely that the truck will be moving with many combinations of left and right turns (of various radii) and straight ahead motion. The heading variations may be small but they will be significant enough to have a large impact on the accurate positioning of the robot end effector.

4.6.2 - Principles of Operation

The entire VOC system uses digital communication. Two (2) optical, rotary, incremental encoders are each mounted on separate "fifth wheel" assemblies. The fifth wheel assemblies are mounted on

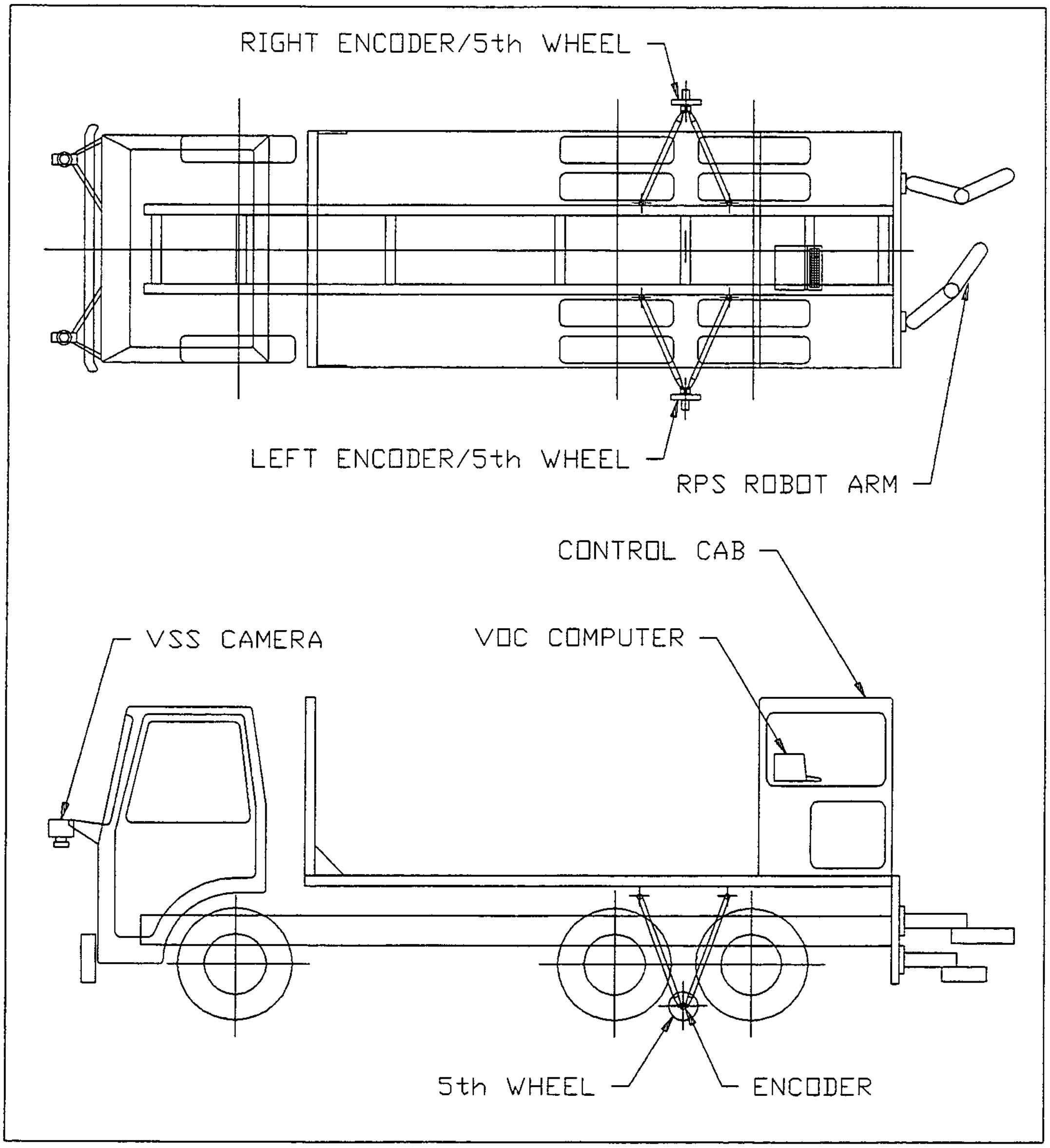


Figure 4.6.1 - Crack Sealing Truck Showing Integrated VOC, VSS, RPS, and ICU (conceptual illustration only).

either side of the truck outside of the rear wheels and midway between the two rear axles of the truck so that the center line of the encoders passes through the center of rotation of the truck (see Figure 4.6.2). The fifth wheel assemblies will be located approximately 10 feet apart. The fifth wheel assemblies are continuously monitor the change in position of each side of the truck. From position data obtained from the encoders, the translation of the truck (laterally with respect to the

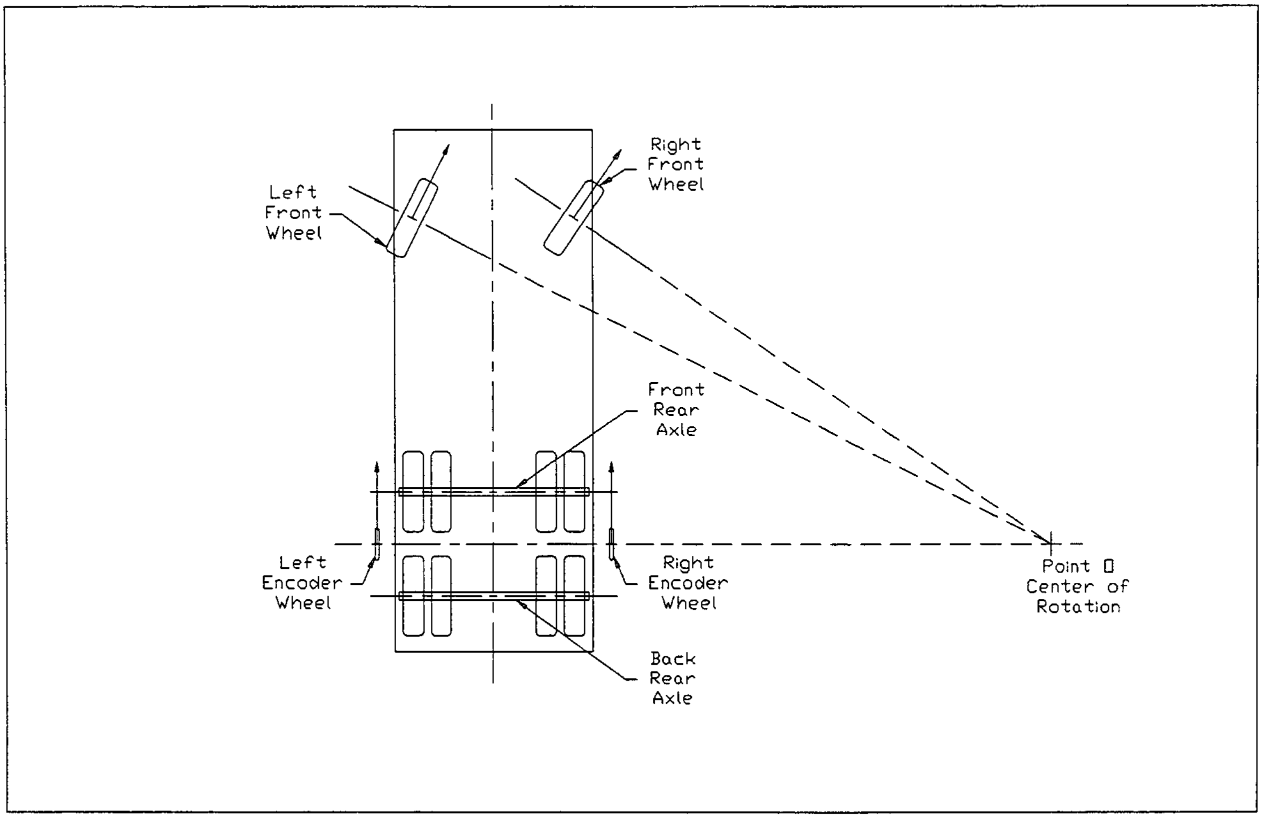


Figure 4.6.2 - Placement Of Encoders On Crack Sealing Truck.

road surface) and rotation of the truck (yaw - about a vertical axis with respect to the road surface) is continuously calculated.

An on-board computer is also part of the VOC. This computer serves several functions. In general, crack position data sent to the VOC computer from the VSS and truck position data will be gathered from the encoders on the fifth wheels. Calculations of truck position and orientation and crack position (with respect to the truck) are performed by the VOC computer. This information is shared with the ICU. The VOC computer also updates the path planning module in the ICU. Finally, the VOC computer sends current crack position data to the RPS for immediate crack sealing.

More specifically, the VOC computer performs as follows. The Cartesian reference frame used by the computer program is fixed on the truck near the center of the rear bumper. This reference frame moves (in position and orientation with respect to the road surface) as the truck moves. The VOC computer receives (from the VSS) the position, perpendicular to the direction of travel of the truck (with respect to the truck), of points on cracks as they are identified by the VSS camera at the front of the truck. The VOC computer notes the time instant when this data is received. Then the VOC begins tracking the change in position and orientation of the truck with respect to the time instant when the data was received from the VSS by sampling data (at a set time frequency) from the right and left encoders. When the crack moves into the work space of the RPS and is immediately ready to be sealed, the VSS performs a final calculation of points on the crack with respect to the truck, and transforms the coordinates into the RPS frame of reference. This information is sent immediately to the RPS so that the RPS end effector can clean, heat, and seal the crack. Once the crack repair operation is completed on that particular portion of crack, that crack segment is no longer tracked by the VOC computer. Refer to Figure 4.6.3 for a flow chart of the integration of the VOC with the VSS, RPS, and ICU.

4.6.3 - The Use of Fifth Wheels

One design consideration that merits some discussion is the decision to mount the position encoders on fifth wheels rather than attaching them directly to the tires of the crack sealing truck. There are several advantages to the fifth wheel design. These advantages follow.

- All drive train noise that is transmitted through the truck wheels is not transmitted to the encoders.
- The wheel base distance can be increased if necessary to allow greater accuracy in computing the vehicle position and orientation.
- Noise coming from the truck and various systems can be dampened through the fifth wheel connection (to the truck) so that the noise is minimized by the time it reaches the encoders.
- The truck tires are subject to fluctuations in radius caused by tires of low stiffness and changes in tire pressure, vehicle weight, consumable materials fluctuations, number and weights of persons riding the truck, vibrations, etc. Nearly all problems caused by changes in tire diameter can be eliminated through the use of a relatively high stiffness wheel attached to a fifth wheel assembly. This allows for greater accuracy in the encoder data since fluctuations in wheel radius are minimized.
- For a tandem axle truck that is turning any sort of corner, the tires of one of the rear axles must always "scrub" sideways slightly. If more of the vehicle weight is resting on

the front rear axle, the back rear axle tires will do the majority of scrubbing. Conversely, if more of the vehicle weight is resting on the back rear axle, the front rear axle tires will do the majority of scrubbing. This phenomenon effectively changes the distance between the front of the truck (where the VSS cameras are located) and the rear axle that is in contact with the road surface. This change causes a slight error in the results of the kinematics equations used for the VOC system. This error can be minimized by centering the encoders midway between the rear axles of the truck. As an added benefit, the scrub on the encoder wheels is minimized. The fifth wheel is an effective design feature for mounting the encoders midway between the rear axles of the truck

- The fifth wheels can be designed to be more sensitive to the road surface than truck tires by optimizing design characteristics such as damping, wheel stiffness, road/wheel contact force, natural frequencies of fifth wheel components, etc.

4.6.4 - VOC Computer Program and System Interface

The VOC system consists of two optical encoders, a computer interface card, and software. The encoders output a square wave pulse as the vehicle moves, and the computer interface card records the number of pulses.

The software performs three functions: 1) reads the number of recorded pulses on the computer interface card, 2) calculates the vehicle's new position and heading based on the number of recorded pulses, and 3) provides the RPS crack locations upon request. The new position and heading are calculated in the program using kinematics schemes similar to those described in Appendix C. When the RPS requests new crack locations, the program executes a matrix transformation routine that provides an updated crack location based on the current vehicle location and the old crack locations provided by the VSS.

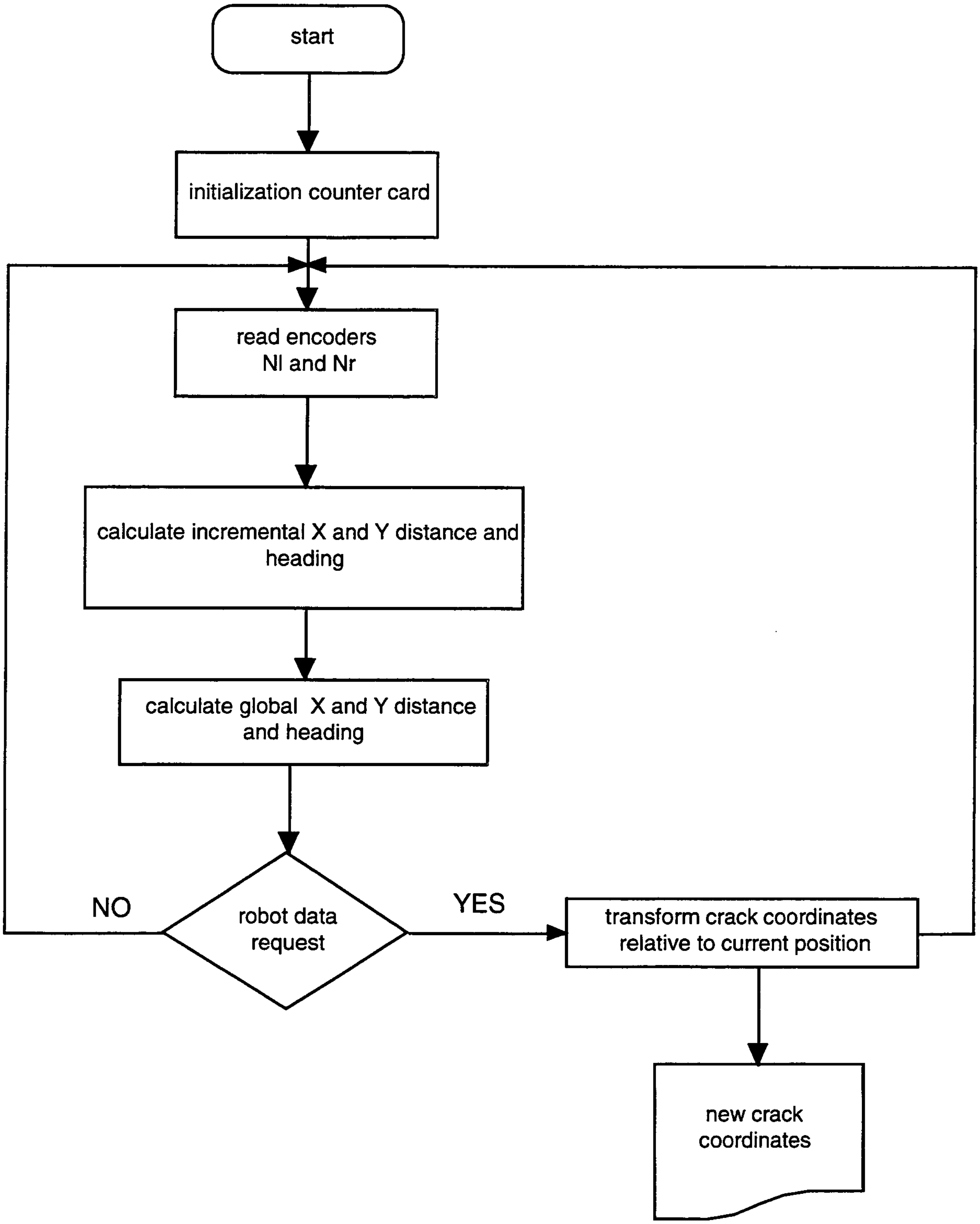


Figure 4.6.3 - Flow Chart of VOC System And Interface.

4.6.5 - Cart Test of Integrated Prototype

The integrated prototype of the VOC system was tested and debugged on a specially designed test cart (see Figure 4.6.4). The test cart was used as the VOC system platform for prototype testing in place of the crack sealing truck. The test cart provided a convenient, scaled-down test platform on which the VOC system could be easily tested and debugged. In Phase III, the fifth wheels were tested and calibrated.

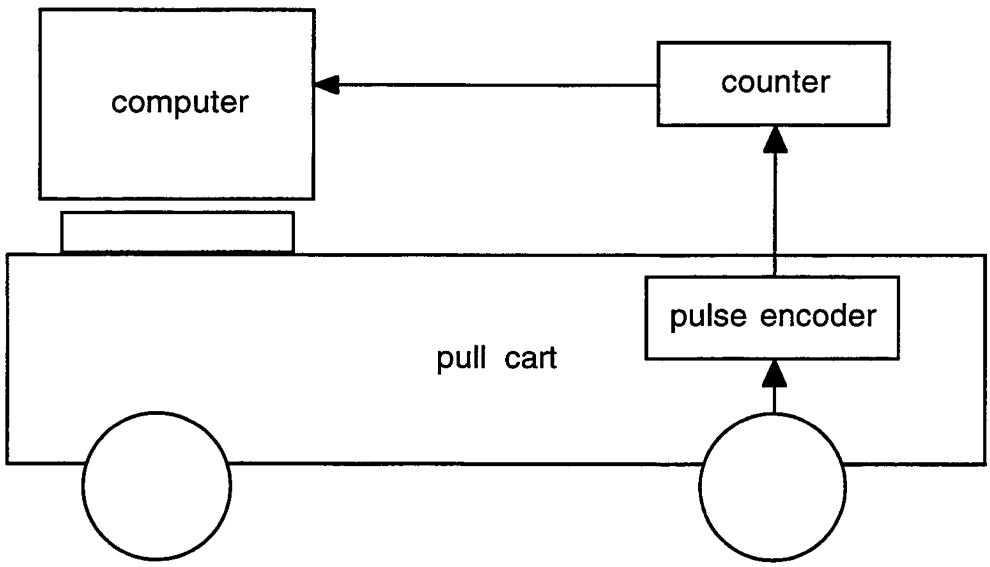


Figure 4.6.4 - Schematic Illustration of VOC Test Cart.

Once the system was tested and debugged on the test cart, it was transferred to the Caltrans Mobile Imaging Lab (MIL) and integrated with the other subsystems. Testing and troubleshooting is currently underway in preparation of installing all subsystems on the crack sealing truck.

4.6.6 - Component Descriptions

4.6.6.1 - Fifth wheel

The fifth wheel subassembly is used to provide data to the VOC computer program for the purpose of tracking the position and orientation of the crack sealing truck. The fifth wheel subassembly consists of the following components:

- a wheel that rolls on the road surface and is attached to each encoder,
- an encoder to convert the rotary wheel motion to digital outputs, and
- all linkage, fastening components, and electrical cables necessary for attaching the wheel and encoder to the crack sealing truck and VOC computer.

Refer to Figure 4.6.1 for a schematic illustration of the integration of the two fifth wheel subassemblies on the crack sealing truck. Complete detailed lists of parts and components necessary to build the second generation 5th wheel subassemblies are provided in Appendix A, drawings SHRP(VOC)M-A100, SHRP(VOC)M-A200, and SHRP(VOC)M-B100.

4.6.6.2 - Encoders

A simplified optical, rotary encoder consists of three major parts. These include:

- a disk with radial line slits (see Figure 4.6.5),
- a light source, and
- a light detector.

As the disk rotates, light is transmitted between radial line slits to the light detector which generates a triangular-wave voltage output. This output is fed to a comparator that transforms it to a square-wave voltage. The square wave is then fed to a counter which is triggered by the leading edge of the square wave.

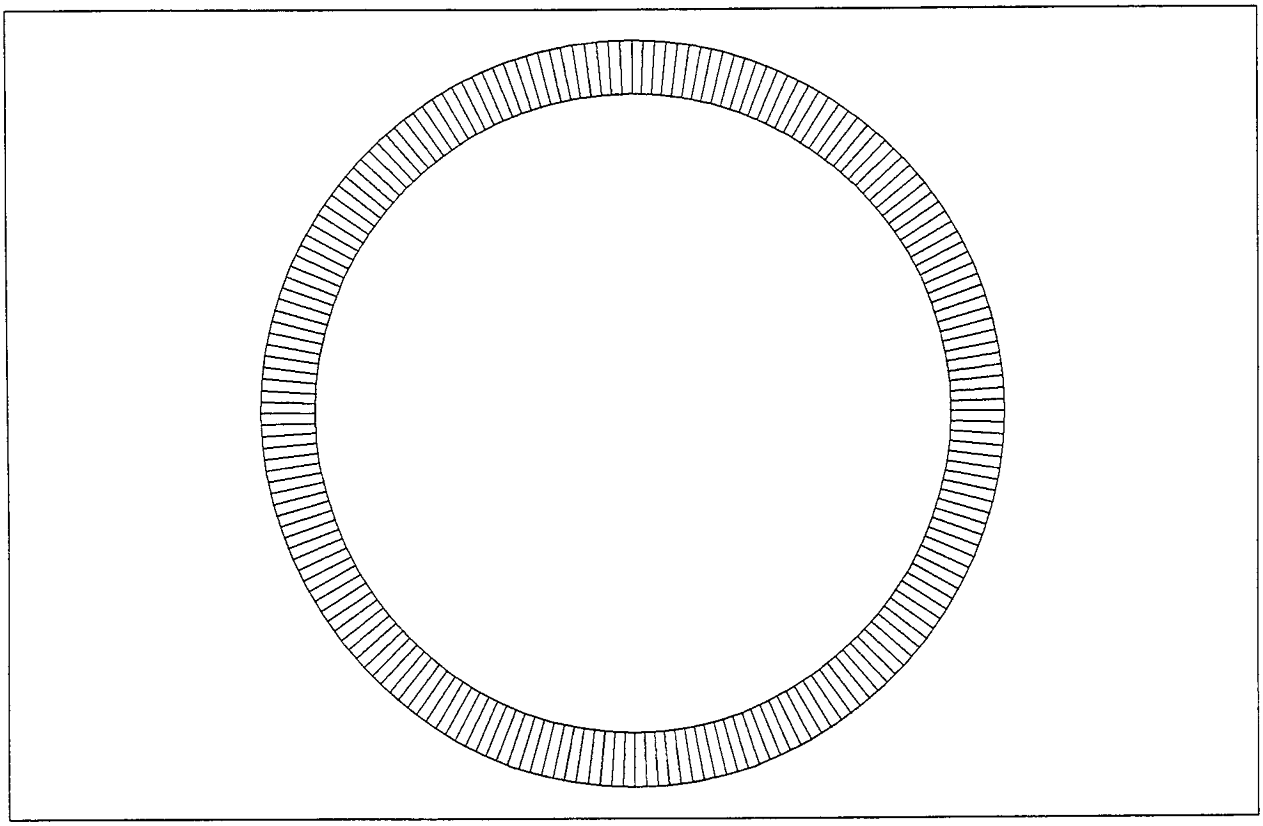


Figure 4.6.5 - Schematic Illustration of Encoder Disk with Radial Line Slits

Two incremental pulse encoders are used as the position transducers, and provide information on the vehicle's incremental position and heading. To meet the encoder requirements shown in Table 4.6.1, two BEI encoders were purchased. The encoders have a resolution of 2500 pulses per revolution. This results in a position error of 0.02 inches and a heading error of 0.14 degrees per pulse.

ENCODER RESOLUTION (LINES PER REVOLUTION)	2500
MINIMUM DISTANCE RESOLUTION	0.0625" (1.588 mm)
ENCODER OUTPUT	5V
ENCODER SUPPLY VOLTAGE	5Vdc
ENCODER OUTPUT FORMAT	channels A , B and Z
ENCODER CABLES	shield, twisted pair
FIFTH WHEEL RADIUS	8" (203 mm)
TEMPERATURE	0-70 C
HUMIDITY	100% RH
VIBRATION	5-2000 Hz
SHOCK	20G

Table 4.6.1 - Encoder Requirements.

4.6.6.3 - Counter Card

A counter card is installed on the backplane of the computer and records the counter outputs of the encoders. The A and B channels of each encoder output the same frequency pulse with a 90 degree phase shift, and enable the counter card to detect if the vehicle is moving forward or backward. The Z signal enables the counter card to track the number of revolutions the wheels have turned. To meet the counter card requirements specified below, a Xycom 230 Intelligent Counter Module was purchased and installed on the VME computer backplane. The Xycom counter card has eight thirty-two bit counters.

MINIMUM NUMBER OF COUNTING CHANNELS	6 up and down channels
BUS COMPLIANCE	VME compatible bus
COMPUTER	Heurikon HK68/VE3
MINIMUM INPUT FREQUENCY	2kHz
POWER REQUIREMENTS	5V
TEMPERATURE	0-65 C
HUMIDITY	95% RH
VIBRATION	2.5 G peak acceleration
SHOCK	30G peak acceleration

Table 4.6.2 - Counter Card Requirements.

4.6.7 - Second Generation 5th Wheel Assembly Design Drawings

The second generation 5th wheel assemblies are quite complex. From experience gained during the development, testing, and troubleshooting of the first generation prototype, it was apparent that substantial redesign of the second generation prototype was necessary to meet the functional specifications of the VOC system. The second generation 5th wheel assemblies were delivered from the vendor, tested and mounted on the crack sealing truck.

All assembly and detail drawings for the second generation 5th wheel assemblies are provided in Appendix A.

4.7 - Component Performance Specifications

4.7.1 - Introduction

This section presents the performance requirements of the four primary system components on the automated sealing machine. These components are:

1. Crack sensing system.
2. Router.
3. Hot air lance.
4. Sealant applicator (and finishing tool).

Each of these system components interacts directly with cracks in the pavement. The net result of all components operating sequentially is the preparation of cracks and installation of sealant material into the prepared crack. This sequence closely follows the sequence of operations associated with conventional sealing methods.

1. Crack routing or sawing (optional).
2. Crack cleaning and drying.
3. Sealant application.
4. Sealant finishing.

The obvious differences are that, in conventional operations, crack sensing (locating the cracks in the pavement) is done by the equipment operators and sealant finishing is usually a separate operation that is performed after sealant application.

The performance requirements of each of the four system components are presented in the following sections. Most of the requirements pertain to operational effectiveness (i.e., how well the system accomplishes its objective). However, production rate and equipment durability requirements are also included.

4.7.2 - Crack Sensing System

The objective of the sensing system is to locate and store crack positions, and accurately measure crack widths so that automated crack preparation and sealant installation can be properly performed. Any errors incurred in sensing the position of the crack will likely create problems in subsequent operations. Hence, the crack sensing system is perhaps the most critical system in the automated operation.

The sensing system consists of two components that work in conjunction with one another. The Vision Sensing System (VSS) uses a video camera and an image processor to locate the approximate position of a possible crack. The Local Sensing System (LSS) uses a laser vision sensor to scan the area around the potential crack location identified by the VSS and confirm or reject the presence of the crack. In addition, the LSS provides more precise crack position information to compensate for inherent inaccuracies in the VSS.

There are many performance requirements that are placed on the automated sensing system. Table 4.7.1 lists the specific requirements related to operational effectiveness. In general, the system must be able to detect unsealed transverse cracks and define their position and dimensions to an accuracy of 0.2 in (5.1 mm). The cracks that are identified should meet the agency's criteria for crack sealing in terms of width, length, and density. This complex sensing process must operate rapidly enough to allow the automated sealing unit to move continuously down the roadway at a rate of at least 2 mph (3.2 km/hr). From a durability standpoint, the functioning equipment must not be adversely affected by prevailing conditions (i.e., temperature, dust, and flying debris).

Performance Indicator	Requirement
Resolution Along Scan	0.063 in (1.59 mm)
Vertical Resolution	0.063 in (1.59 mm)
Accuracy of Crack Position	0.2 in (5.1 mm)
Field of View	4 in (102 mm)
Humidity	0 to 85 percent
Operating Temperature	32 to 160 ^{o}F (0 to 71 ^{o}C)
Sensor Must Function Properly When Exposed To:	Wind and Sunlight Dusty Environment Surface Color Variations Moisture on Pavement Debris in Cracks Road Surface Height Variations Temperature Variations Electromagnetic Interference
Sensor Must Distinguish Between Actual Cracks and:	Previously-Sealed Cracks Oil Spots Shadows

Table 4.7.1 - LSS requirements.

4.7.3 - Router

The objective of the router component is to create a widened channel along the crack surface. This channel permits the sealant to be placed in a uniform shape and also helps to ensure that sufficient quantities of the sealant material are applied to the crack. Both result in increased performance potential; with penetration improving adhesion and shape uniformity enhancing flexibility.

There are four essential performance requirements for the automated rotary-impact router, in addition to equipment durability. These requirements are:

1. Must accurately follow cracks.
2. Must not inflict significant damage to the pavement surround.
3. Must form channel of consistent depth (and width) along same crack and among individual cracks.
4. Must maintain sufficient cutting rate.

When a router does not accurately follow a crack, the result is two adjacent channels (one formed by the router and the other the existing crack) and a weakened pavement segment in between. In the case of conventional impact routers, missed cracks are usually due to operator error. Cracks missed by the automated impact router, however, will likely be the result of either inadequate maneuverability, inaccurate crack position information, or jostling of the router component during operation. In any case, it is important that the router accurately follow cracks over at least 97 percent of the total crack length.

While rotary-impact routers generally satisfy the above objective, they have a tendency to inflict additional damage to the pavement in the form of spalls or fractures. This is because the impact action of the router bits tears rather than cuts material away from the pavement. Hence, serious pavement surround damage is more likely to occur when router bits are dull, pavement temperatures are low, or the AC surface course contains large coarse aggregate. For the automated impact router, such damage must be kept to less than 3 percent of the crack length.

Routed crack channels are generally created for the purpose of injecting sufficient sealant material into the crack. However, the dimensions, or shape, of the channel are often selected to provide optimal flexibility of the sealant material. Where the shape of the channel varies from the optimal shape, the potential performance of the sealant material is reduced. Thus, it is important that the cutting dimensions (primarily depth) are consistently maintained to an accuracy of $\pm$ 0.2 in (5.1 mm).

The range in cutting dimensions of the automated router component were selected based on conventional and innovative rout profiles. These include 0.5 x 0.5-in (12.7 x 12.7-mm), 0.75 x 0.75-in (19.1 x 19.1-mm), and 0.2 x 1.5-in (5.1 x 38.1-mm) channels. The prototype router must be capable of producing channels up to 2.25 in (57.2 mm) wide and 0.85 in (21.6 mm) deep.

Finally, while meeting all of the above requirements, the router must also maintain a production rate that is consistent with the forward rate of the automated sealing unit. For longitudinal operations, the router has already been demonstrated to work effectively at 2 mph (3.2 km/hr).

4.7.4 - Pavement Heating System

The pavement heater is the main component in the heating, cleaning and debris removal (HCD) system. It is an important component of the crack preparation process because it is responsible for the instantaneous drying of any moisture in the crack and heating the crack immediately prior to the application of sealant. Both actions greatly improve the bonding potential of the sealant to the sidewalls of the crack channel.

The pavement heater provided on the Automated Crack Sealing Machine is capable of sustained production rates up to 11 ft/sec (3.4 m/sec). This extraordinary heat transfer rate is attributed to the unconventional approach of impinging larger quantities of heated air on the road surface. The burner heats the exhaust air in a three foot long nozzle up to 1600° F (870° C). The heated air is then exhausted at flow rates in the vicinity of 400 ft^3/min. (11.34m^3/min.) at a pressure equal to approximately 90 lb/in^2 (621 kPa).

Since the automated pavement heater is designed to only dry and heat the crack channel, and not clean it, there are three main performance requirements for this device. First, it must adequately remove any moisture that might exist in the crack channel. Successful application of the automated pavement heater will result in a channel that is dry to the touch and hot-applied sealant that does not bubble shortly after installation.

Second, the automated pavement heater must not overheat the AC surface. Overheating not only results in brittle asphalt concrete along the crack periphery, but also produces an oxidized grit that can adversely affect adhesion by the sealant material.

Finally, while satisfying the first two requirements, the automated pavement heater must operate along the crack at a speed that is consistent with the forward rate of the automated sealing unit. For longitudinal operations, the automated pavement heater has already been demonstrated to work effectively at 7 mph (11.3 km/hr). In conventional sealing operations, production is occasionally constrained by the heat lance operation. However, this is primarily because the heat lance is also used for cleaning.

4.7.5 - Sealant Applicator and Squeegee

The final step in the automated sealing process is sealant application and finishing. The system component devised for performing this step is a combination sealant dispenser and squeegee, capable of rapidly applying and shaping sealant in various configurations (e.g., band-aids of varying widths).

From a performance standpoint, the applicator unit must be able to accomplish four tasks. First, in order to produce the desire sealant configuration, an adequate amount of material must be applied to the crack and the proper strike-off must be made. The finished surface should, for all practical purposes, be within 0.0625 in (1.6 mm) of the desired level.

Second, the crack channel must be filled from the bottom up to prevent air from being trapped under the material. Signs of entrapped air include immediate bubbling of the sealant and localized sagging of the material.

Third, and perhaps most importantly, the hot-applied sealant material must be applied to the crack at the manufacturer's recommended application temperature. The actual application temperature should be within $\pm$ 5 ^{o}F (2.8 ^{o}C) of the recommended application temperature in order to achieve optimal performance.

Finally, to stay in stride with the forward rate of the automated sealing unit, the applicator must operate individually at a rate at a speed that is consistent with the forward rate of the automated sealing unit. For longitudinal operations, the sealant applicator has already been demonstrated to work effectively at 15 mph (24 km/hr).

4.7.6 - Summary

It is apparent that in order for the automated sealing machine to achieve its objective, each system component will have to execute its portion of the overall sealing operation precisely and at a relatively high speed. Thus far, prototype component testing has indicated good potential for doing so.

Performance of both the overall and individual operations will be evaluated in a field demonstration trial. Various sections of highway will be used to study the operation effectiveness, production, and durability of each component under various conditions. Each test will be closely monitored and documented, and the results will be analyzed to see if performance requirements were met. Further details about the field demonstration trial are provided in Chapter 5.

5

Machine Testing

5.1 - Introduction

The original intent of the SHRP H-107A team was to perform a detailed field-testing program during the course of this project with the intent of quantifying the ACSM's operational performance. Generally, the project has progressed satisfactorily despite a number of delays that have occurred; e.g., at the beginning of each new funding phase progress was significantly hindered due to administrative contractual delays. However, the one delay that the research team could not overcome has been the unusually harsh weather experienced in Northern California during winter and early spring of 1993. This harsh weather significantly delayed the testing of component subsystems which in turn prevented the final testing of the integrated ACSM machine. Rather than completing a detailed quantitative test program, the group has only been able to qualitatively examine the operation of numerous components and the integrated longitudinal portion of the machine. Accordingly, a clear area for future work is the detailed testing and evaluation of the integrated ACSM. As such, the purpose of this chapter is to establish the test plan which will be utilized as the development of the machine continues. It should also be noted that numerous sections in Chapter 4 present quantitative results from detailed individual component testing.

5.2 - Detailed Test Plan

In order to fully evaluate the operational performance of the automated sealing machine as a complete unit, it must be field-tested on an appropriate section of pavement. Since the H-107A research effort has focused heavily on automating the most difficult sealing operation, AC transverse crack sealing, the test pavement section must be asphalt-surfaced and must contain a sufficient number of transverse cracks for a variety of tests.

Designing and arranging a field-demonstration trial can be a long and difficult process. The first step is to identify the goals and objectives of the experiment. In general terms, the objective of the test plan is to evaluate the ability of the individual components as well as the system as a whole to seal cracks. Thus, the testing must consist of:

- Microtesting (of the individual components).
- Macrotesting (of the overall system).

There are generally many factors that must be considered for each type of testing. Decisions must be made as to which factors will be evaluated in the field trial given the constraints of cost, time, personnel availability, weather, and so on.

Once a field testing plan has been formulated, the search can begin for potential sites that accommodate the specific features in the test plan, as well as any other desired characteristics. In the event that multiple potential sites are located, they may be ranked in order of suitability. Permission to use the most suitable site will be sought from the agency having jurisdiction over the pavement facility. Sites both on and near UC Davis and the Caltrans Transportation Laboratory have already been utilized extensively in the demonstration and testing to date.

Prior to conducting the field trial, an evaluation plan must be developed in order to assess the performance of the various tests. Field documentation forms and equipment must be prepared for collecting the performance data.

As the automated crack sealing equipment has developed, different components of the overall system are farther advanced than others. Based on the timeline of this project, SHRP's imminent closure, and the delays discussed above, it has not been possible to complete the development of equipment with full functionality. At this point, the technology associated with longitudinal crack sealing is the most mature. The hardware and software to perform transverse crack sealing in AC pavements are in prototype condition, but require additional integration effort at this time.

To address this uneven development, it is believed that an appropriate test plan consists of a process which takes into consideration the current maturity of the various systems. The test plan described below accomplishes this.

The following sections discuss the important aspects associated with designing and arranging the field demonstration trial for the Automated Crack Sealing Machine.

5.2.1 - Longitudinal Crack Sealing System

The prototype of the longitudinal crack sealing system is further advanced than that of the transverse crack sealing system and therefore, in the near term, it can be subjected to a more rigorous and comprehensive field test. This is a result of the fact that the longitudinal crack sealing system can operate independently of both the Vision Sensing System (VSS) and the Integration and Control Unit (ICU). Furthermore, the operation, which progresses along a straight, uninterrupted longitudinal path, is the least challenging to the system's two major components.

Qualitative longitudinal crack sealing system testing has been performed on several sections of road both on and within close proximity to the UC Davis campus. Qualitatively, the components perform well. The router provides relatively smooth and consistent reservoirs of the desired depth. Based on the up-milling cutting approach used by the router, it does not show any tendency to walk out of the crack. The pavement heating system provides a large volume of heated air to effectively blow away debris, and the pavement surface is heated thoroughly without scorching. The sealant applicator has worked extremely effectively throughout the project, with minor modifications occurring regularly to provide better robustness to road irregularities, etc. The resultant seal is extremely uniform, and, for sealing only, the operation is effective at speeds as high as 15 mph (24 km/hr). The longitudinal positioning system was exercised by operator joystick control, and again, effective end-effector placement occurred at speeds as high as 15 mph (24 km/hr).

Qualitatively, the longitudinal crack sealing system performs well. However, more detailed and quantitative field testing of the longitudinal crack sealing system should take place to test the following operations and subsystems:

- Speed of sealing.
- Long-term performance comparison with conventionally performed sealing.
- Sealing alone.
- Routing and sealing.

- Routing, vacuuming, and sealing.
- Pavement heating system.

Additional detailed component testing is now discussed.

Router

The field test of the router component must consider both the interaction between the router and the pavement, as well as the way in which the various components and the router perform together. The test must evaluate whether the router creates the desired size and shape of reservoir, if the routing process causes additional damage to the pavement, and if the reservoir is left clean enough to be sealed. Additionally, it should be determined if there are crack paths that the equipment cannot follow.

Considering the current stage in the development of the equipment, it is recommended that this test be performed in a semi-controlled environment. The purpose of the test is not to evaluate the overall robustness of the equipment, but rather to assess its current abilities and highlight what future work is needed to proceed beyond the prototype stage.

Sealant Applicator and Peripherals

This subsystem consists of the sealant applicator and the storage and heating reservoir. For the sealant storage and heating reservoir, the following capabilities must be evaluated:

- Are the properties of the sealant left stored in the reservoir essentially unchanged after being subjected to the heat of the sealant reservoir?
- How much time is required to bring the sealant to the manufacturer's recommended application temperature?
- Is the sealant maintained at sub-critical temperatures as the volume of the storage reservoir changes?
- How is the heat monitored? How accurate are the readings?

For the sealant applicator, the following capabilities are of interest:

- Does the applicator apply sealant in the cracks that are selected for sealing?
- Is the sealant applied according to the desired configuration?
- Is sufficient sealant applied?
- What is the effect of sealing the pavement on the overall ride (in other words, does the sealant cause increased roughness)?
- What is the long-term performance of the sealed pavement?

5.2.2 - Transverse Crack Sealing

The general portion of the ACSM, which addresses transverse type of cracking, has had limited demonstration. Based on delays in the development process, this system has been exercised in an off-line manner only. This demonstration has shown the capability of the RPS to adequately follow and seal a transverse crack. Mechanically, the system is ready for integration with the VSS, ICU and VOC. However, these subsystems are still being integrated with the use of the Caltrans Mobile Imaging Lab (MIL). When integration is complete, the test of the prototype transverse crack sealing operation will be conducted in a semi-controlled environment in recognition of the current status of the equipment. The purpose of the test will be to document and demonstrate the capabilities of the prototype equipment, rather than to show that the equipment is ready for commercialization. The test will include both component-by-component and overall system checks.

5.2.3 - Ideal Test Plan

Ultimately, the transverse crack sealing system will need to be subjected to a field test on an actual pavement. Such a test is better able to assess the system's robustness, operating speed, consistency, productivity, safety concerns, and so on. This section addresses the test plan to be performed when the system is ready for complete testing.

To satisfy testing of the most essential performance attributes, the following features are desired in the test site:

- Close proximity to development facility.

- Asphalt surfaced pavement (AC flexible or AC/PCC composite) section at least 1 mile (1.61 km) in length.
- Four-lane facility with moderate traffic (7500 to 20,000 Average Daily Traffic (ADT)) levels and 5 to 10 percent trucks.
- 12-ft (3.7-m) lane widths.
- Working, transverse thermal or reflection cracks.
  - Average crack width between 0.188 and 0.5 in (4.76 and 12.7 mm).
  - Average full-width crack spacing between 25 and 75 ft (7.6 and 22.9 m).
  - Some deteriorated cracks (i.e., secondary cracks, cupping, lipping) present.
- Flat and moderate grades (0 to 4 percent).
- Moderate quantities of additional distress.
- Adequate safety features (i.e., full outside shoulders, good sight distance).

Additional features may become necessary should other performance considerations be desired.

Identification of Proposed Test Site

As a means of locating potential test sites, a 1- or 2-day pavement inspection trip will be made around California. Various pavement facilities will be examined to see how they meet the criteria presented in the previous section. Those facilities identified as having conformed to most or all of the requirements will be rated for overall appropriateness using a quantitative analysis procedure. This is done by assigning different weights to each of the desired characteristics, rating the individual characteristics of each potential test site, and computing a mean overall rating for each site. The highest rated test site would be the prime candidate for conducting the field demonstration trial. Permission would then be sought from the appropriate agency to use the site.

Controlled Conditions and Factors

Thorough examination of the performance capabilities of the Automated Crack Sealing Machine necessitates the use of several trial sections within the test site. The exact number of trial sections depends on:

- The perceived importance of the various performance factors.
- How efficiently a testing matrix can be formulated.
- Time and financial constraints.
- Limitations presented by test site length.

In order to evaluate the effectiveness of each system component, test trials will be conducted whereby different sets of components are operated. Table 5.1 lists the component combinations to be operated for evaluating the effectiveness of each component.

In addition to these standard tests, the effects of several weather- and pavement-related factors on effectiveness will be studied, as shown in Table 5.2.

System To Be Evaluated	Components To Be Operated
Sensing System	1. Sensor, or 2. Sensor, Router, and Vacuum
Router	1. Sensor, Router, and Vacuum
Debris Removal (Vacuum)	1. Sensor, Router, and Vacuum
Heating System	1. Sensor and Heating System, or 2. Sensor, Router, Vacuum, and Heating System
Sealant Applicator	1. Sensor, Heating System, and Applicator, or 2. Sensor, Router, Vacuum, and Applicator, or 3. Sensor, Router, Vacuum, Heating System, and Applicator

Table 5.1 - Evaluation of system components.

Effectiveness of Operation	
Factor	System Evaluated
Air Temperature	Sensor, Router
Wind	Sensor
Intensity of Light	Sensor
Crack Width	Sensor, Router
Crack Deterioration Level	Sensor, Router
Pavement Moisture	Sensor, Vacuum, Heating System

Table 5.2 - Weather- and pavement-related factors affecting system performance.

Evaluation Procedures

Performance evaluation techniques should, for the most part, be straightforward. Simple inspections and various types of measurements will usually be sufficient in assessing the effectiveness of the individual operations. In addition, production will be timed over established distances to determine rates for both the system components and the entire automated sealing unit. Table 5.3 lists suggested evaluation procedures for the various system components. In controlled condition sections (i.e., sections where weather- and pavement-related factors are investigated), effectiveness will be measured using the same procedures shown in Table 5.3.

5.3 - Test Results

The information collected from the field demonstration trial will be analyzed primarily during the trial so that any minor equipment adjustments can be made for prompt retesting. The overall results of the test will be analyzed and compared with conventional sealing operations in order to determine the practicality of the machine as a maintenance tool. Additional factors that will be considered as part of the analysis include costs, short-term effectiveness, and long-term performance.

System Component	Performance Item	How Evaluated
Sensing System	Accuracy in Defining Crack Position	Compare to Results of Manual Identification
	Accuracy in Determining Crack Dimensions	Compare Selected Cracks to Those Selected Manually
	Surface Distinctions	Visual Inspection
	Speed	Time
Router	Accuracy in Following Crack	Measure Percent of Missed Crack
	Inflicted Damage to Pavement Surround	Measure Percent of Fractured or Spalled Pavement
	Consistent Channel Dimensions	Measure
	Speed	Time
Heating System	Drying Effectiveness	Visual/Touch Inspection
	Proper Heating	Visual/Touch Inspection
	Speed	Time
Sealant Applicator	Desired Seal Produced	Measure
	Proper Filling Procedures Followed	Visual Inspection
	Sealant Dispensed at Recommended Application Temperature	Measure with Thermometer Probe
	Speed	Time

Table 5.3 - Evaluation procedures for system components.

5.4 - Machine Performance Specifications

5.4.1 - Introduction

The current prototype sealing machine is designed to seal transverse and longitudinal cracks in AC pavements. Critical to its acceptance and integration into highway maintenance operations are the rate at which the machine can operate, the quality of the results of the sealing operation, and the capabilities and limitations of the system. The impact of the costs of the equipment on its acceptance is addressed elsewhere.

5.4.2 - Production Rates

The production rate for the prototype sealing machine is related to the speed of the Vision and Local Sensing Systems, the rate of each preparation and installation attachment, the distance between transverse cracks, and factors that relate to the individual characteristics of the system components. As noted previously, current test results indicate that the slowest of the operations is the rotary impact routing which has been demonstrated during longitudinal operations at 2 mph (3.2 km/hr). The tested or estimated speeds of each component of the prototype crack sealing machine are listed in Table 5.4. These rates are based on the assumptions that the cracks are routed, cleaned and heated, and sealed with hot-applied sealant. The table also contains estimates of sealing rates using the above preparation procedures and current conventional manual methods. It should be noted that the crack sealing policies of highway agencies differ considerably, and those agencies that omit one or more of these steps will experience a faster production rate; e.g., longitudinal seal only operations have been performed with the ACSM at speeds as high as 15 mph (24 km/hr). Secondly, due to the lack of integrated system testing, the rate of transverse operations could not be estimated.

Rates and Requirements [2]	Transverse Cracks		Longitudinal Cracks	
	Current Methods	Prototype Equipment	Current Methods	Prototype Equipment
Sealing Rate, ft/min	12 to 15	176	12 to 18	176
Travel Rate, mph [3]	0.25 to 0.45	TBD	0.14 to 0.21	2.0
Workers Required	6	2	5	2

Table 5.4 - Comparison of sealing rates and requirements.

As the table indicates, the sealing rate of the prototype equipment is significantly faster than that of current sealing practice. In addition, the number of workers required to complete the sealing operation, apart from traffic control workers, is reduced from 6 to 2 when the prototype equipment is used in transverse operations and from 5 to 2 for longitudinal operations. The great improvements in production rates, labor requirements, and worker safety are readily apparent.

[2] 1 ft = 0.3048 m; 1 mi = 1.609 km

[3] Distances between transverse cracks are assumed to range from 25 ft (7.6 m) to 50 ft (15.2 m).

5.4.3 - Quality of Performance

The quality of sealant installation can be rated on the basis of several factors. These factors, listed below, are related to the routing, the cleaning, and the installation operations.

- Accuracy of the router positioning.
- Conformance of the routed reservoir depth.
- Pavement damage caused by the routing operation.
- Cleanliness of the reservoir prior to sealant installation.
- Damage to the pavement from the heating system.
- Consistency of the sealant surface level.

A good quality, manually controlled routing operation can follow a meandering crack quite effectively, but if travel speeds are high, the router tends to ride out of a crack, resulting in inconsistent reservoir depths. The prototype router should follow meandering cracks as effectively as manually controlled operations, but due to the up-milling cutting process employed, the SHRP H-107A router will not ride out of a crack. Dull router blades, blades rotating at low speeds, low pavement temperatures, or large coarse surface aggregate can result in cracking and spalling of the crack edges. An experienced router operator using a router that has sharp blades can typically keep spalling to a minimum, and the prototype router is expected to perform at least as well, with potential to improve upon manual results again attributable to the superior cutting process employed.

The cleanliness of the crack reservoir and the surrounding pavement can significantly affect the performance of crack sealants. Good quality manual sealing operations allow more than one minute delay between hot airblasting and sealant installation. This permits the pavement surface to cool, possibly allowing moisture to condense on the crack sidewalls. It also allows time for dirt and debris from the surrounding pavement to return to the sealant reservoir. The automated sealing machine must completely remove dirt, dust, and oxidized asphalt grit from the crack sidewalls. With the automated sealer, the time delay between cleaning and sealant installation is on the order of one second which will promote greatly improved sealant adhesion.

Overheating an AC surface with hot, compressed air can scorch the asphalt binder, resulting in brittle asphalt concrete that is less compatible with hot-applied sealants. Indicators of overheating are a darkened AC surface and an oxidized asphalt grit that forms on the pavement surface. The automated heating system, when performing properly, should maintain the desired temperature without damaging the AC pavement due to high or prolonged heating through the use of a road surface pyrometer in combination with closed-loop burner control, and the high volume of heated air used.

When sealant material does not completely fill a sealant reservoir or has settled, sand and debris can collect in the reservoir and the sealant can oxidize more quickly. Underfilled reservoirs can result from an insufficient amount of sealant being placed in the reservoir or from sealant sinking into the underlying crack. Overfilling the reservoir can result in unsightly sealant remaining on the pavement surface. The automated sealant applicator should maintain the surface of the sealant even with the pavement surface without underfilling or overfilling the reservoir.

Of course, overall performance is measured by long-term monitoring of the sealed pavement. It is expected that the use of automated systems of crack and joint sealing will result in a significantly longer lasting sealant system than the best crack sealing jobs done manually. This is due to better routing, more thorough heating without scorching, dispensing of sealant with little time delay from pavement heating, and proper sealant filling. Additionally, the resultant seal will have a much higher level of consistency.

5.4.4 - Capabilities

The prototype Automated Crack Sealing Machine is capable of sealing longitudinal and transverse cracks in AC pavements. It is not designed to seal fatigue cracks, which is indicative of a major structural distress requiring rehabilitation. Neither is the automated crack sealing equipment designed to be able to seal random block cracking that is closely spaced.

The vision and local sensors are able to detect longitudinal and transverse cracks in AC pavements that have widths greater than 0.2 in (5 mm). When a secondary crack or branch is encountered, the longitudinal machine continues sealing the crack that is closest to the direction of the current crack. In a similar situation, the general (transverse) crack sealing machine uses pre-planned path information to resolve the branching decision.

The specially designed router is capable of producing a sealant reservoir up to 1.0 in (25 mm) deep and up to 1.5 in (38 mm) wide. It can cut in any direction. This allows the routing operation to proceed more rapidly.

Currently, the sealing machine is designed to install hot-applied sealant material with a variable width band-aid. The sealant heating chamber is capable of holding 200 gal (757 l) of sealant, heating a full container of sealant to application temperature within 1 hr at an ambient temperature of 50 ^{o}F (10 ^{o}C). It can maintain sealant at an application temperature of 380 ^{o}F (193 ^{o}C) while dispensing at a rate of 10 gal/min (38 l/min).

6

Commercialization Issues

6.1 - Introduction

A basic summary of the current research team findings as they relate to the issues associated with commercialization is provided in Chapter 6. This chapter includes a preliminary market study, ACSM machine cost projections, cost benefit analysis, and discussion of future commercialization efforts. In addition, suggested modifications that will allow the ACSM to address the full range of crack/joint sealing and filling operations are presented.

In order to address commercialization issues adequately, the UC Davis/Caltrans Advanced Highway Maintenance and Construction Technology (AHMCT) Research Program has contracted the Technology Development Center (TDC), a Davis CA based business incubator. TDC's investigation includes market research to (1) estimate market size for the automatic crack sealing machine (ACSM), (2) identify prototype and final manufacturing candidates, (3) estimate production costs, and (4) develop commercialization strategies for the device. In order to help understand the potential range of points of view on the ACSM, TDC held two focus group meetings. The findings based on the focus groups will be discussed in detail later in the chapter, and along the way their opinions will be alluded to numerous times. Several sections in this chapter are derived directly from TDC's report to AHMCT.

Machine costs have additionally been projected by Bechtel using a different approach than TDC's, and interestingly, each group has arrived at virtually the same general unit cost. Based on the analysis herein, the ACSM is anticipated to be a good value, excellent investment, and sound technology to be pursued in trying to meet the increasing demands on the State DOTs for maintenance and refurbishment of the highway systems in this country.

6.2 - The Market

6.2.1 - Customer Segments

Federal

The federal government purchases less than 5% of the total crack sealing equipment sold in the United States. Generally, it does not purchase road maintenance equipment directly; but rather spends money to regulate the transportation activities of the states. Its small portion of the market is comprised of purchases of equipment for use at Air Force and other military bases.

Since approximately 1986, the federal "Four R" program (rehabilitation, restoration, resurfacing, reconstruction) allows states to be reimbursed up to 95% for crack filling before an "overlay" or total resurfacing of a road. But industry contacts estimate that a very minimal amount of federal crack sealing expenditure arises from this provision. The federal government is not a direct customer for crack sealing equipment when it reimburses states under the Four R provision, since the states use their own equipment or contract the work.

State

All states have state transportation departments (SDOT's), which collectively maintain 26% of the total 3,081,799 United States' road miles. According to industry contacts, SDOT's purchase 30% of all crack sealing equipment sold, making them the largest single segment. Furthermore, state Departments of Transportation (SDOT's) are the largest individual customers for crack and joint sealing equipment, as each maintains an average of 16,000 miles of roadway and spends an average of $139,900,000 on road maintenance[4].

States maintain the roads they construct and seal cracks in federal interstate highways.[5] Variation in miles of roadway maintained by SDOT's is large; Texas' SDOT maintains over 76,612, while Hawaii's SDOT maintains only 1,072 miles.[6] States also vary greatly in total maintenance expenditures and in maintenance expenditures between urban and rural areas. An example inter-

4 U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, pp. 90-92 1990.
5 Joe Massucco, Federal Highway Administration, San Francisco.
6 U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, p. 125, 1990.

state variation, North Dakota's 1990 maintenance expenditure for urban areas alone was only $388,000, whereas Pennsylvania's was $304,613,000.[7]

Crack sealing is a minor expenditure for state transportation agencies. In 1992, 26 states spent less than 1% of their maintenance budget on crack sealing, while only 8 spend more than 6%.[8] States seal cracks both with agency personnel and under contract to private firms.

Cities, Counties, Towns, Toll & Turnpike Authorities

Like SDOT's, these local government agencies also perform road maintenance. Although local agencies control 74.8% of the national roads,[9] industry contacts estimate that they collectively purchase only 40% of the total crack sealing equipment sold (individual breakdowns were not available). Initial feedback from focus groups indicates that typical local agencies spend less than $50,000 (1% of their maintenance budgets) on crack sealing, which includes labor, materials, fuel, maintenance on equipment, insurance, etc., in addition to purchase of new equipment.

Private Contractors

According to industry contacts, 25% of sealing equipment is sold to private contractors, who service both private sector customers (airports, privately-owned roads, and parking lots for business establishments), and the public agencies already mentioned. The best estimate available is that there are approximately 7,000 such contractors in the United States.[10]

The profile of these contractors is as follows. Most are small businesses: only 16% earn revenues over $1,000,000, 4% in excess of $5,000,000. Eight percent have more than 21 employees. Not all contractors perform work on all surface types: 95% work on parking lots; 35% streets; 22% recreational surfaces; and 16% airport runways.[11] A variety of services are offered, including asphalt patching, asphalt paving, sweeping, striping and marking, snow removal.

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7 U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, p. 90, 1990.
8 Deng, Pearce, McNeil, "Economic Analysis of Automated Pavement Crack Sealing", p. 2, 1992.
9 U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, p. 125, 1990.
10 Anonymous industry source.
11 Research conducted by the Aberdeen Group, Pavement Maintenance Research Magazine.

6.2.2 - Mileage

Of the United States' 3,880,151 miles of roadway, 80% are rural, 20% urban. There are three times as many locally-controlled miles as state controlled miles in the United States. Twelve percent are of rigid, PCC (Portland concrete cement) construction; the rest are flexible or composite surfaces, including asphalt.[12]

Mileage is a poor indicator of crack sealing expenditure, however, as public agencies vary greatly in the emphasis they place upon crack sealing--some agencies maintain many miles but seal no cracks, and vice versa. Instead, maintenance budgets and belief in crack sealing effectiveness drive expenditure.

6.2.3 - The Purchase Process

State and local transportation departments normally employ a bidding process to procure equipment. We will describe the Caltrans process, with the understanding that thus far, little variation has been observed between Caltrans' purchase process and those of other state and local agencies.[13]

At Caltrans, equipment supply needs are developed in the field by regional managers and supervisors in the 12 transportation districts. These individuals determine materials, quantities, target locations for the new equipment, etc. Regional managers and supervisors are authorized to make purchases of up to $10,000 by an informal bidding process, usually handled by telephone. Caltrans' rules state that at least two potential suppliers must be contacted and provided with identical specifications. And the lowest bid must be accepted, regardless of any preferences about different companies and products on the basis of quality, reputation for maintenance, and other attributes. Almost all states use the lowest bidder procedure according to industry contacts.

For orders exceeding $10,000, a district manager or supervisor must submit a "purchase estimate" to the equipment office. The request is reviewed at several levels, and is eventually approved by the Department of General Services at the State Office of Procurement. The entire process takes 4 to 6 weeks.

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12 U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, p. 131, 1990.
13 Using data from two state and ten local agencies.

With difficulty, both Caltrans and the Nevada State Department of Transportation can perform "sole source" (only 1 bid is accepted) purchases of equipment, but receive pressure not to do so. A Caltrans sole source purchase is accomplished as follows. The Office of Equipment writes a justification to sole source a specific piece of equipment, and a division chief or deputy director must subsequently authorize the request. Afterward, the equipment office writes a purchase estimate and sends it to the Office of Procurement, as described above.

It is also possible within Caltrans to negotiate an "equipment rental agreement" through the Caltrans Office of Contracts. A rental is done either (1) to buttress up equipment supplies during an emergency, or (2) to allow Caltrans to trial a new machine and see if it works well for them. A new 100-gallon boiler kettle with oil convection heating was apparently tested in this fashion before purchase.

6.3 - The Industry

6.3.1 - Size And Growth

State highway agencies, municipalities, counties, and townships collectively spend approximately 18 billion dollars on road maintenance annually, which includes labor, material, equipment and overhead.[14] Maintenance equipment cost grew by an average of 5.3% per year from 1985 to 1990, and by the same amount from 1989 to 1990.[15] Among the maintenance activities performed are crack and joint sealing, fog seals, sand seals, slurry seals, grinding and surfacing, dig out, pot holing and hand patching, slab removal, chip sealing, and spall repair.

In 1992, the entire national crack sealing expenditure (including equipment, labor, materials and overhead) was estimated at $187.5 million, a very minor portion of highway and road maintenance.[16] Furthermore, the crack sealing equipment industry is a minor portion of total crack sealing expenditure, at approximately $15 million dollars per year (80% sales of new kettles and boiler systems, and 20% sales of accessories--lances, applicators, squeegees, and hoses), according to industry contacts, who also estimate its current annual growth rate at 10% to 15% per year.

14 U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, pp. 92,108,111, 1990.
15 U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, p. 130, 1990.
16 Deng, Pearce, McNeil, "Economic Analysis of Automated Pavement Crack Sealing", p. 3, 1992.

The largest manufacturer of crack and joint sealing equipment is Crafco of Chandler, Arizona, whose equipment comprises approximately 65% of the market. Trailing with 10% market share each are Cimline and Aeroil of Minneapolis, Minnesota and Hackensack, New Jersey, respectively. The following smaller companies, BearCat (Wickenburg, Arizona), Berry (Lexington, Kentucky), Stepp Corporation (North Branch, Minnesota), Buckeye (Sandusky, Ohio), Bergkamp (location unknown), collectively account for the remaining 15% market share.

Companies which supply sealant material typically do not also supply equipment; Crafco is an exception, supplying both.

Within Caltrans, 66% of crack sealing cost is labor; 22% equipment (including maintenance of existing equipment, fuel and insurance, as well as purchase of new equipment); and 12% materials. Minor deviation among agencies in these percentages has been observed thus far, but is insignificant for our purposes.

6.3.2 - Intensity Of Competition

Focus groups and manufacturers of crack sealing equipment describe the intensity of competition as high. The intensity of competition is a function of the following 5 factors.

Barriers To Entry

Barriers to entry into this market are reported to be low. To be eligible to bid for Caltrans' business, for example, companies must have been in business at least 1 year and must have an in-state maintenance facility. Industry contacts suggest that it is equally easy to sell to other local and state agencies. Low barriers to entry contribute to the intensity of competition.

Product Differentiation

The intensity of competition in an industry negatively correlates with the extent to which competitors can differentiate themselves and their products from one another. Product differentiation between manufacturers of double-boiler kettles is moderate, though every manufacturer does have a unique blend of features and characteristics, spanning oil convection heating, gallons of sealant capacity, flow rates, agitating paddles, pump design, temperature gauges, hoses, hydraulic equipment, etc. One focus group participant said he would choose equipment based upon the average height of his workers--based on the need to keep workers comfortable.

Overall, since the low bidder is chosen automatically in state agencies, a great deal of poor quality equipment is reportedly purchased and subsequently parked in "the yard" when it breaks. The state of Ohio has allegedly made several such purchases, selecting the lowest bidder, and has not corrected the tendency for their purchasing process to procure low quality equipment.

Bargaining Power Of Customers

Bargaining power of customers positively correlates with the intensity of competition in an industry. State Departments of Transportation (DOT's) have ample bargaining power, since they buy large volume and always require bidding. Selling to state level and local public sector customers as a result is highly competitive.

Reportedly, contractors have little bargaining power, since they usually do not purchase in high volume. Amidst ample variation in features and prices of crack and joint sealing equipment, industry contacts say that contractors tend to select the equipment that best fits their needs and pay the quoted price, unable to influence price. Competition in selling to low-volume-purchasing contractors is less competitive than selling to state transportation departments.

Bargaining Power Of Suppliers

The suppliers of kettles and other crack sealing equipment are a diverse group with little power to influence price, contributing to the intensity of competition.

However, the low bargaining power of suppliers is offset slightly because a large supplier (Crafco) dominates the industry--academically, a market with one or two very large-market-share firms tends to be less competitive than one with many small market-share companies of approximately equal size.[17] Thus, the market is slightly less competitive than it would be if many equal sized competitors were pursuing market share.

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17 Aaker, David A., Strategic Market Management, p.99, 1988.

Threat of Substitute Products

Another factor moderating the intensity of competition in this industry is the fact that, aside from marginal innovations in boiler kettles and other equipment currently used to seal cracks, there appear to be no substitutes for current crack sealing equipment. Focus group participants note, however, that there may be two alternative procedures available in the near future.

Slurry seal (also known as a chip seal) is a thin overlay with emulsified asphalt instead of hot asphalt. A slurry seal is not structural repair as it does not strengthen the roadway. However, it is reportedly adequate for residential streets where the weather (rather than the traffic) has damaged the streets. It was described in the focus group as "a face lift . . . not strong," and was said to be an effective measure in lieu of crack sealing in select applications where high strength was not necessary.

Another possible indirect competitor is "micropaving," a new procedure (developed in Europe) which resembles a "slurry seal" in application. It can allegedly be performed on streets with rutting as high as two and a half inches to smooth out the pavement, and allows cars back on the road in ten minutes. Although the cost is high (equal or slightly less than an overlay), the resulting seal is said to last for many years. There appears to be a great deal of disagreement in the industry regarding the value of micropaving and its ability to substitute for crack sealing in the future. Some focus group participants had the very positive view that crack and joint sealing will be replaced by micropaving. Other industry contacts do not concur, however. One cited an example of pavement near his location where micropaving was a "complete failure."

The ACSM appears to have no direct competitors.

6.3.3 - Key Success Factors In Selling Crack Sealing Equipment

In selling crack sealing equipment to the public sector, the most important success factor appears to be the ability to bid at lowest cost, since public agencies are usually required to choose the lowest cost bidder who meets the specifications. Efficient, automated production to control costs is imperative according to contacts.

A second key success factor derives from the first--the ability of manufacturers to convince agencies to write "proprietor specifications" which very closely resemble the specifications of the manufacturer's products. It is much easier for a manufacturer to bid lowest on specifications which closely resemble the specifications of its own products. An example is Crafco (the largest equipment supplier), which sells mostly through distributors who pursue a strategy of selling state mechanical engineers on Crafco's product specifications.

Private contractors reportedly impute more importance to service, reliability, durability, and quality of product (rather than price) in comparison to public agencies. When selling to this segment, according to contacts, it is imperative to have a product that "works" and the service to support it.

Value-Added Stages

Often in an industry, it is crucial that manufacturers excel in a particular value-added stage of the production or marketing process. When selling to public agencies, the crucial stage appears to be the production process, which must be streamlined and efficient in order to bid at lowest cost. R&D, and quality control are the crucial stages when selling to private contractors, who value a quality product that "works."

Channels Of Distribution

Crack sealing equipment companies sell 50-60% of their products through an estimated 500 distributors, and employ direct sales to sell the remaining units.

Industry contacts say that Crafco, the largest manufacturer, selects channels of distribution in relation to the geographic market served. For competitive states, like California and Pennsylvania, they sell directly to buyers. In other states, they distribute through independently-owned distributors who handle the products of several manufacturers.

Trends In Crack And Joint Sealing Technology

According to industry contacts, double-boiler kettles have experienced several design changes during the past 10 years, motivated by safety concerns and environmental regulations. Specifically, workers occasionally received burns from splashed material, and the open pots sometimes caught fire, requiring time to burn out. When a new environmental regulation prohibited roadside dumping of unused sealant from cleaning operations, a reversing pump was incorporated into the machines to draw excess sealant from the hoses back into the kettles.

6.3.4 - Factors Which May Favorably Impact Crack And Joint Sealing Equipment Sales In The Future

Federal Highway Administration and SHRP

The FHWA is committed to promoting the use of the equipment developed under the SHRP program.

Increasing Traffic Levels

Miles of vehicle travel increased 41% from 1983 to 1990.[18] If this trend continues, wear and tear on roadways will increase, augmenting the amount of crack and joint sealing (assuming the proportion of maintenance expenditure allocated to this maintenance activity remains constant).

SHRP Pavement Research Program

If the SHRP study of pavement surface repair materials produces favorable findings regarding crack sealing with particular materials, there may be a trend toward increased crack sealing in agencies which already crack seal, as well as adoption of the procedure by agencies currently averse to crack sealing due to doubts about its value/effectiveness.

6.3.5 - Factors Which May Impede Crack And Joint Sealing Equipment Sales In The Future

Sophistication of Pavement Management

According to the California focus group, the quality of California pavement is steadily improving, requiring less crack and joint sealing relative to other maintenance activities.

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18 U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, p. 219, 1990.

Micropaving

If as effective as one focus groups said it is, it could partially replace or substitute for crack sealing.

Budget Cuts And Recession

Current crack sealing and general maintenance budgets are reported to be fairly consistent, despite the recession (focus groups); should maintenance budgets be downsized, a proportional reduction in crack sealing expenditure is expected.

6.4 - Pricing Analysis

6.4.1 - TDC's Cost Development

The Advanced Highway Maintenance and Construction Technology Program, Department of Mechanical Engineering, University of California, Davis, supplied TDC with a complete set of working drawings (detail drawings, assembly drawings, and the information to develop a bill of materials) for each of the subsystems of the ACSM. They also supplied a list of vendors that they used to develop the prototype machine, and the price they paid for each of the purchased parts. Additionally, they supplied their estimate of labor hours necessary to assemble each of the subsystems of the ACSM.

Because of time restrictions, it was decided to utilize the purchased-parts prices experienced during the development of the prototype machine. This approach has merit, we believe, because any small price escalation that may have occurred due to inflation over the last one or two years, would be balanced by a decrease in price that we would expect when professional purchasing agents were utilized. No reduction in the price of purchased parts due to quantity discounts was taken.

The estimated aggregate cost of purchased parts for the total ACSM is $433,322.

Selling Price Development

In the development of the selling price for the ACSM the following assumptions were made:

1. The ACSM would be manufactured by a company involved in the manufacture of similar type equipment.
2. The manufacturing company would have the following rates, which are reasonable for companies in this type business.
   - a. Manufacturing Overhead as a % of D/L 100%
   - b. Selling Expense as % of Selling Price 10%
   - c. G & A as % of Selling Price 10%
   - d. Royalty as % of Selling Price 6%
   - e. Profit as % of Selling Price 15%
   - f. Direct Labor (D/L) @ 20.00/hour

Calculating the Selling Price using these assumptions a selling price of $799,145 is obtained. note that this price is based on a single ACSM with identical components and configuration. The development of a production ACSM would incorporate numerous modifications such as the elimination of redundant computer abilities, etc. Furthermore, a first generation machine often over specifies components based on uncertainties. We feel that later units costs would be reduced considerably as discussed later.

Since this number is so large, it was decided to make several calculations, allowing the overhead and the selling expenses to vary. The results are shown in Table 6.4.1.

	O/H=50%	O/H=75%	O/H=100%	O/H=150%
S =0.08P	$ 757,299	$ 765,121	$ 772,944	$ 788,589
S =0.1P	$ 782,970	$ 791,058	$ 799,145	$ 815,321
S =0.15P	$ 855,467	$ 864,304	$ 873,140	$ 890,814
S =0.2P	$ 942,760	$ 952,498	$ 962,236	$ 981,713

Where: S is the selling Expense
P is the selling Price
O/H is manufacturing overhead as % of direct labor

Table 6.4.1 - Selling prices for ACSM.

In addition to developing the selling price for the ACSM, it was decided to develop the selling price for the "Applicator and Peripherals Subsystem" (APS) of the ACSM. This subsystem is the only one in which most of the potential customers had an interest. These prices, shown in Table 6.4.2, were developed using, (1) the same assumptions as above, and (2) the same assumptions as above, with the added assumption that if a professional purchasing agent is utilized, there will be a savings of 15% on the purchase of parts and materials.

	100% Material Cost	85% Material Cost
Sealant Applicator	$18,556	$15,849
Debris Removal	$11,983	$10,273
Router	$ 9,643	$ 9,173
Burner	$23,389	$ 20,267
Hydraulics	$38,067	$32,571
Generator System	$25,856	$22,994
Sealant Melter	$44,762	$38,292

Table 6.4.2 - Selling prices for subsystems.

Appendix D additionally presents the cost breakdown of all of the ACSM's subsystems. Table 6.4.3 presents cost estimates for a variety of possible machine/component configurations. These are listed according to the hierarchy of possible machine/component configurations. That is, the sealing operation could potentially be incrementally automated due to the modularity of the ACSM and the stand alone components. The crack sealing operation could be automated at the lowest level by addressing first the simpler longitudinal types of cracks and only dispensing sealant, and ultimately incorporating automation until the full spectrum of preparations, etc. are employed in general sealing operations with the use of the ACSM. To follow, configurations of Table 6.4.3 are concisely listed:

Longitudinal sealing operations

a. Sealing only with owners own vehicle and with their own linkage to hold the custom sealant applicator. Applicator will need to be positioned by the driver steering the support vehicle. User will need their own sealant tank, hosing, support vehicle, etc.

b. a. with the ACSM longitudinal positioning system linkage assembly. This will allow for stowing of the longitudinal system. User will need their own flatbed truck in addition to melter, etc. Positioning of sealant applicator will still be done by driver.

c. b. with hydraulic actuator and controller. This will allow for joystick positioning of the sealant applicator over the crack by an additional operator. The driver will merely drive down the road and allow for less than one foot from the crack. In addition to b., the user will need a source of

	APS $149,419						
	Sealant App.	Debris Removal	Router	Burner	Hydraulics	Generator System	Sealant Melter
Unit Price 100% Mtl.	$18,556	$11,983	$9,643	$23,389	$38,067	$25,856	$44,762
Unit Price 85% Mtl.	$15,849	$10,273	$9,173	$20,267	$32,571	$22,994	$38,292
Configuration							
a) Sealing Only	$15,849						
b) a.,with longitudinal positioning system linkage assembly	$15,849						
c) b., with hydraulic actuator & controller	$15,849				$32,571		
d) c., with the local sensing system	$15,849				$32,571		
e) d., with the option of routing	$15,849		$9,173		$32,571		
f) e., with the option of heating and blowing	$15,849	$10,273	$9,173	$20,267	$32,571		
g) Complete ACSM	$15,849	$10,273	$9,173	$20,267	$32,571	$22,994	$38,292

NOTE: other configurations are possible

RPS $143,927	LRPS $32,748		ICU $92,854	VSS	LSS	VOC	TRUCK $179,781	
Robotics	Linkage	Control System	Computer					Config. Price
$143,927	$13,371	$19,376	$92,854	$142,128	$41,550	$16,739	$179,781	
								$15,849
	$13,371							$29,220
	$13,371	$19,376						$81,167
	$13,371	$19,376			$41,550			$122,717
	$13,371	$19,376			$41,550			$131,890
	$13,371	$19,376			$41,550			$162,430
$143,927	$13,371	$19,376	$92,854	$142,128	$41,550	$16,739	$179,781	$799,145

Table 6.4.3 - ACSM Configuration Pricing.

hydraulic power to supply the actuator (can come from a separate power supply of the the power take-off of the truck).

d. c. with the Local Sensing System. This will allow for the automated positioning of the sealant applicator over the crack eliminating the operator (i.e., driver only operation like a. and b.).

e. d. with the option of routing. This will allow for routing of the pavement prior to sealing. Hydraulic power source is required with sufficient power to accomplish both routing and positioning.

f. e. with the option of heating and blowing. This will allow for removing debris and additionally preheating the pavement prior to sealing. Need the user to provide propane supply for heater and adequate hydraulic power for blower, router, and positioning.

General sealing operations

g. Complete ACSM.

6.4.2 - Bechtel's Cost Development

Estimates were made to ascertain the cost of a commercial version of both the complete ACSM and the longitudinal portion of the machine alone. The cost of the prototype was benchmarked against the issues received as feedback in those elements of the research marketing plan that have been executed, as well as being based upon the input we get from various manufacturing firms of large or heavy construction and roadwork equipment. An additional projection was performed using standard cost projection models as practiced in the one-off design manufacturing market sector. These projections take into account standard percentage projections for Non Recurrent Engineering (NRE) and the subsequent cost of additional units produced.

In addition, an analysis and comparison was made to existing heavy highway equipment that address one or more of the elements of crack recognition and/or repair. These systems were used for cost comparison of "standard" highways equipment.

Complete ACSM Cost Analysis

The hard equipment cost of the prototype complete ACSM was estimated to be $422,450. This can be broken down into the following subsystem costs (rounded off to the nearest $10.00 value):

Truck Platform	$84,900
ICU	$29,800
VSS	$65,170
LSS	$26,700
VOC	$ 8,790
RPS	$92,430
APS	$29,990
LRPS	$20,320
Electrical Integration	$18,880
Mechanical Integration	$72,470
	$422,450

(Modular) Longitudinal Machine Cost Analysis

From the above cost summary, the hard equipment cost of the Longitudinal machine (LRPS) would appear to be $20,320. The true cost of the Longitudinal machine is estimated at $137,280 (for a fully automated version) due to the cost of several support systems required to allow its operation as a dedicated unit on a vehicle of opportunity or dedicated (smaller) maintenance vehicle. These additional system costs are:

APS	$29,990
LSS	$26,700
VIDEO SYSTEM	$ 3,500
Hydraulic Power Supply	$19,620
MELTER	$25,450
MISC. SUPPORT EQUIPMENT	$ 1,550
Electrical Integration	$ 4,650
Mechanical Integration	$ 5,500
	$116,960*

NRE Cost Model Analysis

NRE (Non Recurrent Engineering) cost analysis models were developed from an evaluation of several quotes for advanced system hardware development from a variety of market sectors. These included robotic equipment manufacturers, heavy industry (automated logging and forestry equipment) manufacturers, heavy roadway equipment manufacturers, and advanced recycling equipment vendors/manufacturers for the petroleum industries. In the analysis, engineering man hour costs were valued at $50.00 per hour.

In general it was found that NRE for the first unit produced accounted for approximately 45 - 65 percent of the quoted value/cost of the unit. Each subsequent unit cost approximately 35 - 55 percent of the first unit cost -- the difference being the NRE. These NRE activities/costs were typically associated with Electrical, Mechanical, and software engineering activities needed to make the new systems function within the given operating environments. These activities would be analogous to many of the current R&D functions being executed in the development of the current automated crack sealing equipment prototypes. In addition, it was found that fair market value was equal to hard equipment cost marked up by approximately 35 - 50 percent for manufacturers gross margin. This markup was consistent throughout the evaluated cases for equipment produced with a total expected market of less than 100 units. Within the traditional manufacturing sector where the market is estimated in thousands of units (or more) this type of markup is considered exorbitant and would typically be in the 5 - 15 percent range. This being noted, it was felt that the <100 unit markup values would be more representative of the potential market for this equipment within the U.S. Transportation (Infrastructure Maintenance) industry.

With these values in mind, we then find that the cost projections for the complete ACSM would most likely be on the order of $824,000 for the first 1 to 5 units, then a probable cost of $550,000 for each additional unit. The cost projections for the longitudinal machine would most likely be on the order of $228,000 for the first 1 - 5 units, then a probable unit cost of $152,000. It should be noted that the cost projected here for the longitudinal machine represents what one could consider a maximum. The value given represents a fully automated machine with routing, debris removal, and pavement pre-heat capabilities in addition to sealant application. Due to the modular nature of the LRPS design, the simplest version that has no automatic tracking capabilities and only lays down sealant (using an existing sealant melter system) could be as low as the $35,000 to $55,000 range. It should also be noted that this is still a preliminary or order-of-magnitude cost estimate for the ACSM, due to its current state of development (being a concept prototype verse a commercial prototype).

6.5.3 - Comparative Cost Analysis

In an effort to determine if the order-of-magnitude cost projections for the prototype equipment were significantly out of line with other heavy roadwork equipment, a comparison was made. Existing and standard equipment for AC work and PCC work were included in this analysis. The AC equipment consisted of crawler-pavers, course rollers, and finish rollers. The PCC equipment based upon RCC (roller-compacted cement) application technologies and was evaluated for a single class of equipment, the "paver". The full range of asphalt equipment costs were obtained from the most recent Caterpillar Equipment Selection Guide, and were provided by a large corporate equipment leasing firm. The PCC equipment quote was gotten from Rexroth, a specialty equipment manufacturer. An additional piece of equipment, the hot in place "Pyropaver", was also evaluated on a cost basis in order to complete the comparative analysis by looking at the cost of competitive technology. The price for the Pyropaver was based on discussions with a contractor that owns 4 of these pieces of equipment. Equipment costs ranges were found to be as listed below:

Model #		Minimum $	Maximum $
Crawler Paver	std. AP1000	232,750	266,000
	hvy. AP1050	271,250	310,000
	Attachments for AP1050	22,500	55,000
Course Roller	CS563	97,750	115,000
Finish Roller	sm. CB434	83,125	95,000
	med. CB534	103,250	118,000
	lg. CB614	122,500	140,000
PCC Paver	Rexworks T&C	220,000	245,000
Pyropaver	300E	1.3 million	1.8 million

From this cost chart we can see that the projected costs of the general machine, at $550,000 to $824,000 are in line with the higher end or typical and specialty roadwork equipment. The projected cost of $35,000 to $228,000 for the longitudinal machine is also in line with not only the low to mid end of equipment costs, but also consistent with attachment costs (for the high end equipment) at the lower end of its configuration/price combination.

6.6 - Cost Benefit Analysis

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

The cost of congestion alone to lost productivity in this country is estimated to be about $100 billion annually, and this estimate does not include the costs of wasted fuel and environmental damage. Caltrans estimates the cost of congestion as $7.25 per vehicle per hour. The maximum throughput at highway speeds in the Los Angeles metropolitan area is approximately 1400 vehicles per lane per hour. As such, the congestion costs of a lane closure in the Los Angeles area is approximately $10,000 per hour. It is apparent that maintenance equipment that reduces traffic disruptions can have significant economic benefits with respect to congestion costs alone.

Each year, about 40,000 people are killed on the nation's highways and another 5 million are injured in traffic accidents. These fatalities and injuries are estimated to cost the nation's economy over $100 million, and a large percentage of the accidents are caused by traffic congestion. Again, reduction of traffic congestion through more optimal maintenance operations has the potential to reduce the occurrence of maintenance based & congestion oriented traffic accidents and is accordingly of economic value.

Concerning the cost benefits of safety, Caltrans estimates the cost of a highway worker's fatality to be $1 million to the state. Injuries to workers in general are quite costly to the state as well. As such, the removal of maintenance workers from the highway can also result in considerable cost savings.

In analyzing the system's cost and benefits, one may be concerned with two important questions: how long will it take the system to pay for itself, and how much benefits can one realize from this investment? The following analysis seeks to answer these questions in terms of the investment recovery period and net present value. While above we have noted the extreme costs of congestion, injury, and deaths on the highways, simple incorporation of these costs into the analysis to follow was not possible; e.g., it would be quite difficult to extract the anticipated numbers of individuals injured due to the added congestion of crack sealing. As such, the analysis is quite conservative as the reduced costs due to less congestion and injuries could be substantial.

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

The major cost to implement the automated crack sealing system is the cost of the equipment. The platform for the new system may cost up to $250,000 based on the price of a similar platform used in current operation plus supporting equipment such as an air compressor, a heater, and an on-board computer system. Additionally, special devices are required to perform specific functions such as preparing the pavement, heating and applying bitumen. These may cost an average of $300,000, bringing the total system cost to $550,000. Note that this is the NRE based cost estimate for the ACSM.

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

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

In the first scenario, the analysis takes into account the reduction in the crew size alone. Currently, an average Caltrans crack sealing crew consists of 8 persons. Supporting tasks, such as lane closure and signing, are provided by a separate crew which will not be affected by the new system. An automated system will require a crew of 4 persons, one to operate the platform vehicle, one to monitor the system performance and two to operate a supply vehicle. If necessary, the supply vehicle team may also perform touch-up tasks and other duties as required. Assuming an average cost of $50,000 per person-year, the annual labor cost savings as a result of the crew size reduction alone would amount to $200,000. At this rate, the cost of investing in the new system may be recovered within 3 years and the system's net present value is over $400,000 (see summary case 1).

In the second scenario, the analysis takes into account the speed improvement over the existing system. Assuming that the new system may operate at up to 4 miles per day, the reduction in labor cost, allowing for overhead, may be reduced by an additional 30%. The annual labor cost savings would amount to an additional $60,000. Coupled with the savings from case 1, the recovery period is slightly more than 2 years and the system's net present value is over $700,000 (see summary case 2). This is a rather conservative estimate given that the system will be designed to operate at an average speed of 2 miles per hour. Nonetheless, this estimate should be accurate early in the implementation stage due to the learning curve and logistical problems.

In the last scenario, the analysis assumes that a better sealing process performed by the new system will prolong the maintenance cycle from an average of once every two years to once every three years. This assumption is based on Caltrans data. This cycle change will not significantly affect the labor and operational costs but will decrease the annual cost of materials by 16.67%, an additional savings of $15,000. The annual savings resulting from the crew size reduction, the speed advantage, and the prolonged maintenance cycle now totals $275,000. The recovery period is reduced to under 2 years whereas the net present value increases to over $800,000 (see summary case 3).

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

The cost savings analysis clearly shows that the automated crack sealing system is an excellent investment for it offers a recovery period of less than 2 years and a net present value of up to $800,000. This is quite an attractive proposition even without considering the monetary value of the intangible benefits (improved safety and reduced congestion), which may be quite substantial. The automated crack sealing system will reduce or eliminate hazardous elements on the job as well as improving the crew's working environment, thereby allowing them to focus on the quality of work. The indirect savings from increased safety to the work crew alone may exceed the cost of the system.

Based on this analysis, the ACSM is anticipated to be a good value, excellent investment, and sound technology to be pursued in trying to meet the increasing demands on the State DOTs for maintenance and refurbishment of the highway systems in this country. However, in an effort to provide a comparison with other emerging technologies (which could be construed to be competitors to this method), a common means of evaluation needs to be developed. We believe that one aspect of this comparison method needs to be the cost per lane mile of the remediation method. Such a cost model will allow comparison of this approach to roadway remediation and maintenance to other forms of the same, as they are often bid on a square yard or meter basis, which is translated into cost per lane mile. For example, current manual crack sealing in California costs approximately $1800 per lane mile with 66% for labor, 22% for equipment and 12% for materials, whereas Hot-In-Place (HIP) Recycling costs $24,650 per lane mile. To best compare other approaches, including the ACSM, it is necessary to establish the lane mile cost and the comparison method would additionally need to incorporate numerous other aspects such as time and type of next required remediation, etc. All of the cost per lane mile estimates would certainly be subject to variables such as degree of severity of road degradation, cause for road distress/failure, and in the case of HIP, the cost of materials to either refurbish the pavement to design specification or the cost of material required to change to a new design mix. It should also be noted that each of these methods are really a tool in a tool kit and that no one method is a panacea.

6.7 - Focus Groups

As part of its primary research effort, TDC arranged and conducted two focus groups; one group elicited the points of view of Nevada public agencies with individuals representing Nevada DOT and select city transportation departments, while the other queried representatives of California city and county agencies.

A focus group is a moderated discussion with five to twelve individuals who are selected to represent the range of points of view possible in the market for a new product or service. However, despite the attempt to cover all points of view, the small number of reactions obtainable limits the findings to qualitative, rather than quantitative significance. Hence, the views presented may not accurately reflect the views of the entire market.

The goal of a focus group is to obtain an exhaustive list and description of the issues which govern marketability. This ensures that all important issues to be included for quantitative inquiry when a survey is used to obtain accurate inferences about the entire market. That is, focus groups are used early in a marketing analysis, and only are used to serve as a guide in developing the actual marketing survey.

In this section, the complete list of focus group comments is presented. It must be stressed that this is an unedited list presented herein for the purposes of raising as many issues as possible as they relate to future ACSM marketability. The SHRP H-107A team feels that some of the focus group members' comments are not well founded, are in mathematical error, or are a result of the limitations of TDC personnel in the explanation of the ACSM's operation. However, this is expected from initial focus group based marketing analysis, and overall the focus groups have provided valuable input.

The focus group findings are listed to follow.

6.7.1 - Obstacles To Sale Of ACSM

Participants are not convinced that ACSM will be a net safety improvement to an entire maintenance operation

The total crack sealing team will only be reduced by one to two people, leaving approximately (it varies by agency):

- 2 to 3 persons for traffic control
- 1 person driving a vehicle to supply the truck with the crack-filler material
- 1 person to maintain the boiler pot
- 1 nurse truck or attenuator vehicle driver behind
- 1 driver for the ACSM

In Nevada, traffic control can not be reduced unless ACSM can travel at least 15 mph. Other states may have similar restrictions, limiting ACSM's ability to reduce team size any further.

Participants concede that crack sealing teams themselves will be safer, (1) because they will be one to two workers smaller with ACSM, (2) because the workers who keep the melting pot going will be up on the vehicle, off of the ground, and (3) because lance and applicator operators will not be on the ground.

However, these focus group participants feel that workers eliminated from the sealing team will simply be transferred to another roadside maintenance activity, as maintenance budgets will remain constant. Thus, no net reduction in agencies' worker exposure to traffic is expected.

Additionally, participants are concerned that ACSM will be a hazard to passing traffic. There concern is manifest in specific fears that bicyclists or motorists will misjudge the berth necessary to avoid contact with the longitudinal sealing apparatus protruding from the side of ACSM.

Participants doubt their agencies would impute a significant dollar value to the intangibility of improved safety if they purchased ACSM.

Concern about losing workers from their crews

Somewhat contradictory to the previous section, other focus group participants feel that individual managers may be concerned that they will lose workers from their particular teams permanently if they use an automated crack-sealing system. The workers would not be fired, just transferred to another team or activity, but managers could not afford to lose workers permanently from their particular teams to automate or streamline an activity that they ". . . only spend a week or two on each year."

Insufficient boiler capacity

Although the Nevada focus group realizes the devise presented to them was a prototype, they comment that the Nevada State DOT would not consider purchasing a machine with a 150 gallon capacity. Their current, manual application speed already outruns the capacity of their 400-gallon pots, so having faster application speed with a smaller pot would not help them. "Speed is a factor of our material . . . at 400 gallon capacity, we must re-fill every 1.5 hrs . . . since we can lay 222 pounds of material per crew hour."

Aversion to purchasing from a sole source

The agencies which are allowed to do this apparently get a great deal of pressure from their attorneys not to do so. This problem could probably be overcome, however, by licensing a second party to produce ACSM.

Concern about training and set-up costs

Participants are not concerned about training to operate machine when it is working correctly, but rather about training to fix the system when it "goes down" and to handle all of its peculiarities. This is where all the time is lost with high tech products, according to the focus groups--handling all the problems which arise when a machine like ACSM is used, regardless of how well it performs when it is working correctly. Maintenance people allegedly require a great deal of experience with a new piece of equipment of this complexity before learning to trouble-shoot and minimize downtime. They report that they always have to "tweak something high-tech before it works our way, with our methods, in our state."

Participants are also concerned about the level of software expertise necessary to operate ACSM. "You have to match the computer to the mechanics . . . (in their experience with computerized, complex machinery) . . . you must revisit the mechanics and software repeatedly to make something like this work."

Participants also have a general aversion to high-tech, first generation, computer intensive equipment like this, "We have had $180,000 pieces of high tech equipment driven by software, and not one of them performed at anywhere near what was expected. Your personnel have to be trained to determine what goes wrong."

Skeptical of a "one-pass" seal all claim

Members in the groups say that they often have to do more than one longitudinal crack at once, meaning ACSM would have to make a second sweep to seal all cracks on a typical section of roadway.

The general system must be able to seal the entire lane width and reach under bushes on the side of the road, in order to achieve a one pass sweep. We assume the lateral reach of the general system would be increased for the final product, but the focus group participants who were able to look at the ACSM immediately identified this as a necessity.

Belief that performance claims will only hold for longitudinal cracks

Very seldom do the participants seal "nice straight cracks;" most are irregular, such as alligator cracks, with sharp bends and high density per lane foot. Estimates of the percentage of total crack filling performed on straight cracks range from 5% to 25%, which means that an average agency seals curved or general cracks more than 75% of the time. These potential customers are skeptical that ACSM can fill random cracks with an average speed of 2 mph, even though this would be a vast improvement over the one mile per day efficiencies frequently experienced under current practice.

Participants are not influenced by lane mile performance claims

Nevada State DOT and the California cities and counties interviewed so far require data from studies which measured pounds of sealant put down per unit of time or man hour, or, as a second choice, linear crack filling speed. Contacts say that most states measure by pounds of material, whereas Caltrans measures by lane mile. The objection to the lane mile criteria is that results are mitigated by the density and type of cracking in certain areas. Focus group participants are not convinced that an improvement in lane mile performance for Caltrans would have any relevance to their crack filling jurisdictions.

The possibility of developing a specialized crew for ACSM

Crack sealing is the "most hated task" in highway/road maintenance, according to Nevada State Department of Transportation--it causes the highest absentee rate of any of their activities. There was mixed reaction among participants about whether or not agencies will be willing to (1) devote extra time to train a specialized crack sealing crew, and (2) whether they could assign such a specialized crew to crack sealing for much longer than the current two to three weeks per year that a typical crew spends on the activity.

$800,000 + is perceived as too high by cities, counties, town, and even the Nevada DOT

Initial feedback indicates that it is rare for city or county to spend even as much as $50,000 in one year on crack sealing, which includes labor, equipment, and material. The seller of ACSM would be asking a city, town or county to spend 10 to 15 times its entire crack filling budget on crack filling equipment alone. Even if the machine works three times as well as their current method, focus group participants say "this is never going to happen . . . $800,000 [price] is half the entire equipment budget for a typical size county."

Nevada State DOT participants' unanimously judged ACSM too expensive, though they had not had the opportunity to do a detailed analysis--"We could instead buy 10 dump trucks ($50,000 to $75,000 each) for $800,000, which we can use for all other maintenance activities, or 2 avalanche control devices . . . We won't even spend $250,000 for a new rotary snowplow, and we really need those."

Weather window and logistics

Regions vary widely in their length of time and season given for crack sealing. Nevada State DOT crack seals intermittently during December-April. Weather has limited their 1992-93 crack sealing to 3-6 weeks. At this level of usage, the amortization or lease expenditures on ACSM ($800,000) would be prohibitive. "You would be spending over half a million dollars for a machine that you could only use for a few months out of the year."

In 1992, Nevada State DOT spent $1.5 million on crack sealing, with $393,000 for crack sealing equipment. Thus, they would greatly exceed their crack sealing equipment budget to purchase even one ACSM. They laid approximately 1,500,000 pounds of material during 1992, and required over 700 crew days, spread among 38 different crews and 23 boiler kettles. An average of 7 crews were sealing every day during their last season (700 crew days divided by 100 workdays; 5 months at 20 weekdays each).

The weather varies in any given season, so ACSM could not be used on as many crew days as is currently possible with crews in different locations. In other words, when weather permits sealing in specific areas, Nevada State DOT can currently use several of their 38 crews during one rain-free day--during 1992, they put an average of 7 to work in rain-free areas simultaneously each day. This flexibility would not be possible with one ACSM. And when it was not possible to deploy ACSM to a rain free area, the user would incur the amortization or lease expense, as well as the opportunity cost of not being able to seal during each day the machine was idle. Finally, they could not rotate one ACSM through their 6 districts within the rain free days available each season.

Amidst these concerns, Nevada State DOT doubts that ACSM could seal fast enough to offset its acquisition cost (whether leased or purchased) in less than three years, which they say it would have to do to be considered under current financing practices. They will require a beta test and trial of ACSM in their state before they believe it can improve the efficiency of their current sealing operation through increased speed and labor savings, or through higher quality seals.

Use of crack sealing as a rainy day activity to make workers productive

Several participants in the California focus group said they crack seal to make labor productive when the threat of rain prevents beginning an overlay or another activity with a large cost of interruption. With ACSM they could not approach crack sealing in this fashion, and would incur the large costs explained earlier each time rain began in the area to which ACSM had been deployed.

6.7.2 - Technical And Other Concerns

Too many moving parts

Participants say that these kind of machines have meant trouble in the past. "Too many moving parts. Street sweepers are the biggest maintenance problem because they have so many moving parts." This machine scares them for this reason.

Replacing router blades

According to the participants, maximum router life is attained through water cooling the blade, and failure to do so is very expensive. Participants wanted to know if the router was water cooled. The Nevada State DOT often routes a day prior to filling or sealing; either they rely on wet ground from rain to keep the router blades cool, or they spray water on the blades. In either case, they must wait a day to seal, until the ground is dry. They are skeptical that the system will be able to wet router blades for sufficient life AND dry the ground sufficiently for a quality seal in a one pass route and seal operation. If the equipment can accomplish this, they will need to see a beta test or trial it themselves to be convinced.

Emissions

Is there a recovery system ("closed system") for suspended particulates ("PN10's") included? The Nevada State DOT says this is necessary due to regulations.

Durability of robotics and computer

Participants are concerned about robotics breaking down and requiring expensive repairs. ". . . they [robotics] do not seem to hold up after continued use . . . they do not just break off either, they cause problems you can not spot."

Several comments have surfaced expressing doubt that a computer system can tolerate the harsh conditions under which ACSM will operate. "Can the computer handle the harsh temperature, dust, etc. of the conditions under which it will be operating?" This concern would be mitigated by incorporating embedded systems into the design.

Can ACSM adhere to their preferred sealing or filling configuration?

Participants wanted to know "Would the new applicator actually get filling material down in the crack?" Agencies will either have to be convinced that a particular seal configuration is optimal, or be supplied with a sealant application system that mimics their preferred seal configuration.

Anxiety about new, high-tech equipment in general

Nevada State department of transportation says it is not easily sold on claims about new equipment. "Asphalt binder equipment was made available to the states by FHWA, and the stuff did not work, even though it was supposed to be 'up and running equipment.'"

6.7.3 - Opportunities For Sale Of ACSM Technology

Crack sealing budgets are strong

All participants estimate that their crack and joint sealing expenditures would either remain constant or actually increase (not decrease) if they had a more efficient crack sealing system.

Crack sealing, specifically, will be safer

Agencies believe that the crack sealing operation specifically will be safer--"You will not have people on the ground running lances and applicators." Though, as mentioned before, agencies are not convinced that there will be a net reduction in worker exposure to traffic if workers eliminated from crack sealing are transferred elsewhere. Therefore, it is unclear as to whether agencies will pay to make crack sealing safer.

6.7.4 - Other Findings Pertinent To The Sale Of ACSM

Threshold payback period & purchase criteria

The Nevada State DOT says that ACSM would have to break even (recoup the initial cash outlay with cost savings) within three years, to be considered under their current financing practices. They also offered the following criteria for purchasing a machine like ACSM:

1. Improved productivity (in pounds of sealant laid down per hour and/or linear feet of particular types of crack sealed per hour).
2. Better quality seal
3. Safety, though it is not clear the intangibility of safety will be materially factored into the purchase price

Unlike the Nevada State DOT, California city and county participants were unwilling to specify a threshold payback period for a machine like ACSM. They said that they do not think about time to get back initial investment when they buy something like this, although that criteria would be a powerful argument for purchasing if ACSM excelled on that dimension. Their purchase criteria are as follows:

1. Will it benefit the public by an amount equal to its cost?
2. Will the quality of the work be better--longer lasting seal, etc.?
3. Could we do something else productive with laborers displaced by a new machine?
4. How fast does it do the work compared to our current method?
5. What are all the ways it will benefit us?

One participant succinctly stated, "We are in the business of spending money. We try to find the best way to spend whatever amount of money that we have been given." Others concurred. The five criteria provide insight into designing performance claims which will be meaningful to agencies.

Maintenance

Participants from both focus groups will require the supplier of ACSM to warrantee for and perform maintenance. Furthermore, some states will require an in-state maintenance facility for ACSM.

State-to-state variation in severity of crack problems

California roads are very sophisticated--they have almost eliminated reflection cracking according to the focus group. They are steadily improving, and less and less cracks are occurring. The groups felt that other states with less sophisticated paving methods and more damaging weather would be a better market for ACSM. Arizona, for example, has a larger freeze/thaw problem than California and hence more crack problems, all else equal.

6.7.5 - Findings On The Possibility Of A Stand-Alone Sealant Applicator

Participants are averse to purchasing a sealant applicator which is limited to longitudinal sealing, no matter how fast it can seal. Only a beta test could convince them that such a device could make their current crack sealing process more efficient. If the longitudinal-only applicator outran the rest of the team, for example, they would need two sets of traffic control for one sealing team. Furthermore, most of the cracks that must be filled are random, rather than longitudinal cracks.

A stand-alone applicator capable of general/random crack sealing

Nevada State Department of Transportation said that if a sealant applicator that worked on general cracks and was as fast as their current system was available, they might pay as much $20,000 per unit for it, provided it was easier for the workers to use. Worker comfort and acceptance is crucial for them.

If such an innovation was developed, Nevada State DOT says that a favorable demonstration (in which they could use the sealant applicator for the day) could convince them to trial the device.

6.7.6 - General Recommendations Arising From Focus Groups

1. Design a general sealant applicator (either manual or controlled by joystick) that fills random cracks and can be added to current crack sealing configurations without purchasing the entire ACSM.
2. Perform beta tests on any equipment to be offered, which document performance in pounds of material laid down and/or linear feet of crack filled per unit of time.
3. Perform a "coring study" to document the improved seal performance with the ACSM. Nevada State DOT's seals currently last only one year, necessitating annual resealing. Since their seals fail annually, they say that a study showing longer seal life with ACSM could be accomplished in only one year, and would increase their chance of purchase.
4. Leverage the findings of the SHRP program regarding seal performance with different materials and techniques, etc., to validate the effectiveness of crack sealing.
5. Conduct a regional trial of ACSM with multiple state participation. The Western Association of State Highway Transportation Officials (WASHTO) can pool funds from several states to test new maintenance equipment. Federal funds may also be available.

6.8 - Preliminary Market Report Conclusions

6.8.1 - Relevance Of The Industry Information

The relevance of the current crack sealing industry information provides limited insight with respect to the sale of the ACSM concept machine because ACSM is not a direct competitor to existing equipment, and because ACSM's price greatly exceeds the prices of existing crack sealing equipment.

If ACSM is feasible, it will require direct selling--a machine which costs $800,000 and replaces $20,000 machines used for the same purpose will require extensive direct selling, demonstrations, and trials.

Double boiler kettles cost about $20,000, requiring district approval at Caltrans because they exceed the $10,000 threshold mentioned earlier. ACSM, at $800,000, will require an override of the standard purchasing policies of most, if not all agencies.

Sole sourcing policies will have to be circumscribed because of ACSM's technical sophistication in relation to current crack sealing equipment. A state agency could not circulate specifications for the entire ACSM and obtain several (if any) bidders, let alone economical bids.

The smaller modules of the technology, such as the sealant applicator with or without further upgrades, could fit into the current purchasing procedures if they could be sold for $20,000, and if the benefits can be quantified with a beta test.

6.8.2 - Feasibility Of ACSM At The Local Agency Level

At the city, county and town level, the $800,000 cost of ACSM is more than the entire equipment budget for a county, and between fifteen and twenty times the entire crack sealing budget for a year (including labor and materials as well). Even if ACSM could be leased for 10 years, the yearly payment would be $50,000. $50,000 per year is still far above the current crack sealing equipment budget for cities, towns and counties, which is usually only slightly above $10,000. Our conclusion is that the ACSM is not feasible for purchase or lease by public agencies below the state level, regardless of efficiency, because it transcends their emphasis on crack sealing.

6.8.3 - Sealant Applicator Limited To A Longitudinal Application, For All Market Segments

Sealant applicator alone or with linkage and hydraulic upgrades will not be feasible if limited to a longitudinal capacity, unless it proves that it can enhance current crack sealing configurations through a beta test. The price will need to be fairly close to $20,000, however, according to focus groups. This result applies to both cities, counties and towns.

6.8.4 - Sealant Applicator Adapted For General Sealing

Sealant applicator adapted for use on general cracks as well as longitudinal cracks shows promise of feasibility in all segments of the market if it materially improves any of the following:

1. Sealing efficiency
2. Worker comfort
3. Seal quality and performance
4. Worker safety in the crack sealing operation

If the ACSM team feels it can develop a sealant applicator package that seals general cracks and is compatible with the current crack sealing team configurations, and which could sell for $20,000 (or $30,000 at the most).

6.9 - Suggested Modifications for Commercial Machine

6.9.1 - Introduction

There are two major issues that must be addressed as the prototype equipment evolves into a working, marketable product. The existing prototype is being developed with capabilities somewhat short of those which would be desired in transverse crack sealing equipment. For example, the final prototype will only seal transverse cracks within an 8-ft (2.4 m) wide swath, while ideally it is desired to be able to seal cracks a full lane width. Also, the prototype and its components are currently being developed to address transverse and longitudinal cracks in AC. A complete sealing machine needs to address several other types of cracks and joints.

This section identifies operations for which the automated sealing equipment could be adapted. Also included are discussions of the preparation methods and materials that are currently required for completing these operations, as well as a summary of the additional equipment that would be required. Not covered in this section are the additional modifications that are required to move the prototype equipment to a fully functioning, marketable product.

6.9.2 - Additional System Applications

The technology developed in producing the prototype crack identification and sealing machine can be applied to other types of sealing projects, resulting in faster, safer, and more consistent sealing operations. Among the sealing operations for which the automated sealing machine could be modified are the sealing of the following:

- Transverse contraction joints in PCC pavements.
- Longitudinal joints in PCC pavements.
- Longitudinal PCC/AC shoulder joints.
- Transverse cracks in PCC pavements.
- Longitudinal cracks in PCC pavements.

Each of these operations has a slightly different set of recommended preparations and procedures that require the modification of the current design or the development of new system components.

With the possible exception of transverse cracks in PCC pavements, each of these cases is a simpler test of the system's vision sensing capability and the algorithms that are currently used to identify sealable cracks and joints. This is true because transverse joints occur at regular intervals. They are either uniformly spaced or follow a repeated pattern (e.g., 12-13-17-16 ft) and are oriented either perpendicular to or at an 80 degree angle to the pavement edge. Longitudinal joints (either lane-lane or lane-shoulder) present even less difficulty in locating the joint position. Once the longitudinal or transverse joints are located, it will be fairly simple for the Local Sensing System to follow the joints for the preparation and sealing steps, since these joints are relatively straight and continuous.

6.9.3 - Transverse Contraction Joints in PCC Pavements

Transverse contraction joints in PCC pavements are located in the traffic lanes and PCC shoulders. Their purpose is to allow for shrinkage contraction and slight expansion of the concrete without compromising structural integrity. Movement of these joints is typically horizontal and can be quite large. In new construction, transverse joints are typically formed by sawing a 3/8 to 1/2-in (9.5 to 13 mm) wide by about 1.5 in (38 mm) deep channel in the cured concrete. These joints are typically spaced at a distance between 15 ft (4.9 m) and 60 ft (19.7 m) and are positioned either perpendicular to the lane edge or slightly skewed (usually 1:6) from perpendicular. The recommended practice for resealing these joints includes:

1. Removing the old sealant from the joint reservoir.
2. Sawing about 1/16 in (1.6 mm) from both faces of the reservoir.
3. Removing all wet-sawing slurry from the reservoir and allowing the reservoir to dry.
4. Sandblasting each side of the reservoir.
5. Airblasting the sand, dust, and dirt from the reservoir and surrounding pavement.
6. Inserting properly-sized backer rod or backer tape into the reservoir.
7. Installing the sealant material in the joint over the backer rod.
8. Tooling the surface of the sealant as required to achieve good adhesion.

Removing the sealant with a plow blade is necessary if the sealant "gums-up" a concrete saw blade. Sawing the joint faces is usually accomplished with a water-cooled, diamond-bladed concrete saw. The sawing operation leaves a slurry of cement dust, old sealant, and water in the joint reservoir. If the slurry is allowed to dry in the joint, it is very difficult to remove. Sawing residue is typically removed by water washing and airblasting the reservoir. After the plowing, sawing, and slurry removal operations are completed, the concrete is allowed to dry, typically for more than 24 hours. Then the sandblasting, airblasting, backer rod insertion, and sealant installation operations are completed in as rapid succession as possible.

The sandblaster must clean each joint face, and the sand and dust must be completely removed by airblasting and/or vacuuming. Spalling and variations in joint width can precipitate the need for using different sizes of backer rod, since the rod must fit tightly to the reservoir walls and to all adjacent backer rod. Recently developed "soft-type" backer rod is more forgiving of joint width variations, and may be used with cold-applied sealants. Backer tape has also been used, although its effectiveness has not yet been established.

6.9.4 - Longitudinal Joints in PCC Pavements

Longitudinal joints in PCC pavements are located at either the lane-lane or the lane-shoulder interface of full-width concrete pavements. In new construction they are typically sawed 0.25 to 0.5 in (6.4 to 13 mm) wide and about 1 in (25 mm) deep. Movement at these joints is generally small, especially if the joints are tied. The same methods listed above for preparing transverse joints are recommended for resealing longitudinal joints in PCC pavements.

6.9.5 - Longitudinal PCC/AC Shoulder Joints

Asphalt concrete shoulders are frequently used in conjunction with concrete traffic lanes. The longitudinal joint between the shoulder and the traffic lane should be sealed. Movement in these joints is typically vertical and can be large, particularly when the underlying soils are frost susceptible. There can also be horizontal movement due to separation. In most projects, the following methods are used to seal these shoulder joints.

1. Use an impact router or a dry saw to cut a reservoir in the asphalt concrete next to the concrete to a width of at least 1/2 in (13 mm) and the desired depth. A typical reservoir is 1 by 1 in (25 by 25 mm).
2. Sandblast the face of the concrete.
3. Airblast the reservoir and surrounding areas to remove all debris.
4. Insert backer rod into the reservoir to the proper depth.
5. Install the sealant in the reservoir over the backer rod.
6. Tool or screed the sealant surface as required.

In many cases, the AC shoulder surface is either above or below the concrete pavement surface. To keep the sealant at the proper level, the sawing and sealing equipment must adjust the cutting and sealant surface depth to the level of the lower AC or PCC surface. Failure to make this adjustment could result in an improper shape factor or an overfilled joint.

6.9.6 - Transverse Cracks in PCC Pavements

Transverse cracks in PCC pavements typically meander across a pavement perpendicular to the lane edge and range in width from less than 1/16 in (1.6 mm) to more than 1 in (25 mm). They can be "working" or "nonworking" cracks, and appropriate load transfer restoration or replacement options should be considered if the cracks are "working" cracks. It is suggested that cracks between 0.125 in (3 mm) and 0.75 in (19 mm) wide be sealed.[19] The recommended method for sealing these cracks include the following steps.

1. Use a small-diameter diamond-bladed saw or a vertical spindle router to create a 0.375 to 0.5 in (9.5 to 12.7 mm) wide and 1.25 in (31.8 mm) deep reservoir above the crack.
2. Sandblast the walls of the reservoir.
3. Airblast the reservoir and the surrounding pavement.

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19 Rigid Pavement Design for Airports, Chapter 7 – Standard Practices for Sealing Joints and Cracks in Airfield Pavements," Air Force Manual 88-6, January 1983.

4. Insert backer rod into the reservoir to the proper depth.
5. Install the chosen sealant material, tooling as required.

Steps 2 through 4 must be completed in rapid succession to achieve optimum seal performance. Saws with small diameter diamond blades cut faster than vertical spindle routers, but they are not as maneuverable. Vertical spindle routers can be used to follow irregular cracks more easily, but they are slow and have a tendency to spall the concrete edges. Rotary impact routers will spall or crack the joint edges and should not be used.

6.9.7 - Longitudinal Cracks in PCC Pavements

Longitudinal cracks in PCC pavements are typically the result of ineffective methods of forming the longitudinal joint, improper longitudinal sawing, or poor pavement support. The method recommended for sealing these cracks is the same as that described above for transverse cracks. In some cases, these cracks divide in a "Y" pattern, forcing the automated equipment operator to make two passes or to seal the adjacent crack by hand.

6.9.8 - Desired Additional Material Handling

For automated resealing equipment to be useful in this extended set of applications, it must be able to install the sealant materials that have performed well and are currently in use. Current research indicates that some hot-applied, polymer-modified asphalt sealants are performing well in sealing cracks in AC pavements.[20] In addition, two other sealants are performing well for filling non-working longitudinal cracks in AC pavements.

- Polymer modified emulsion.
- Fiberized asphalt sealant.

The following materials are generally used for resealing joints and sealing cracks in concrete pavements.

- Nonself-leveling silicone.

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20 Evans, L. D., C. G. Mojab, A. J. Patel, D. G. Peshkin, A. R. Romine, K. L. Smith, T. P. Wilson, "Innovative Materials and Equipment for Pavement Surface Repairs – Initial Draft Report on Performance of Materials and Methods," Strategic Highway Research Program, SHRP-89-H-106, April 1992.

- Self-leveling silicone.
- Certain polymer-modified, asphalt sealants (modified ASTM D-3405).

Hot-applied sealants (ASTM D 1190) are typically used for sealing the joint between PCC pavement and an AC shoulder. However, lower-modulus silicone sealants have recently been developed that may also perform well.

Preformed seals have been used to seal joints in new concrete pavement, but less success has been reported when resealing older joints. Performance is especially reduced when the joint edges are spalled and not perfectly smooth. Therefore, it is not believed that the use of automated sealing equipment to install preformed seals is appropriate or desirable at this time.

To meet the demands of resealing joints and cracks in AC and PCC pavements, the automated sealing equipment should be capable of installing polymerized emulsion sealants, fiberized asphalt sealants, and silicone sealants, in addition to its current ability to install hot-applied sealants. Since most sealant manufacturers recommend that sealant be recessed about 1/4 in (6.4 mm) below the pavement surface, the automated equipment must be able to accomplish this without spilling or wiping sealant on the adjacent pavement surface.

6.9.9 - Required Modifications and Component Development

Adapting the automated sealing machine to meet these additional applications and sealant materials requires that several additional pieces preparation, installation, and monitoring equipment be developed, installed, and tested.

6.9.10 - Accessory Joint or Crack Preparation Equipment

For preparation and cleaning of PCC joints or cracks, the following accessory equipment could be developed:

- Joint plow for removing old sealant from PCC joints.
- Diamond-bladed saw for refacing joint sidewalls in PCC.
- Waterwashing equipment and vacuum for removing sawing slurry.

- Vertical spindle router for widening cracks in PCC.
- Small-diameter, diamond-bladed saw for widening cracks in PCC.
- Sandblast apparatus for cleaning joint sidewalls.
- Vacuum for removing sand and debris.
- Airblasting equipment for cleaning joints and cracks.

A joint plow attachment must be able to remove enough sealant from the joint so that the sealant does not "gum-up" the concrete saw blades. The plow must not spall or crack the adjacent joint edges. Bits for the plow must be straight sided, not tapered. The best cleaning is accomplished by forcing the side of the blade against one side of the joint to literally scrape off the old sealant and debris. The process is then repeated for the other side of the joint.

A diamond-bladed saw attachment must follow the joint reservoir very closely, removing only 1/16 in (1.6 mm) from each sidewall. To maintain the position of the blade in the center of the joint, a centering guide is very useful. It is much easier to achieve consistency in joint width when "ganged" or full-width saw blades are used. Sawing is generally completed using a downward cut on the leading edge of the saw blade. More potential for cracking and spalling of the joint edge arises when the leading saw edge is cutting upward.

Waterwashing and/or airblasting should immediately follow the sawing operation. This attachment must be able to remove the sawing slurry from the joint reservoir, and should be accompanied by a vacuum attachment that removes the slurry and debris from the reservoir and pavement surface.

For creating a sealant reservoir above cracks in concrete pavement, a vertical spindle router or a small-diameter, diamond-bladed sawing attachment is required. Both attachments must be able to follow the cracks closely, developing a reservoir without cracking or spalling the joint walls.

A sandblasting attachment is necessary to remove the remaining slurry dust and small amounts of sealant from the joint sidewalls. The attachment must direct a stream of air and sand at each individual joint face, exposing clean, fresh concrete surfaces on both sidewalls to which the sealant can bond well. An effective vacuum attachment must be used in conjunction with the sandblasting operation.

To remove any remaining sand, dust, and dirt from the joint reservoir, an airblasting attachment may be necessary. The stream of air should be directed in such a way that it does not recontaminate previously cleaned joints.

6.9.11 - Accessory Sealant Installation Equipment

Immediately following joint or crack preparation, backer rod and sealant should be installed. Accessory installation attachments that must be developed to allow sealant installation in PCC joints and cracks include the following:

- Backer rod or backer tape insertion equipment.
- Applicator for installing silicone sealant and recessed hot-applied sealant.
- Tooling apparatus for nonsag silicone sealants.

Backer rod insertion equipment must be able to insert backer rod of various sizes into a joint to the design depth without tearing or stretching the rod. No gaps can remain between the rod and the sidewalls or at intersections of backer rod. Achieving a tight fit can be especially difficult when the joint edge contains spalls, and methods for addressing this problem must be developed.

A sealant applicator attachment must fill the joint from the bottom up, maintaining the sealant surface between 0.25 (6 mm)and 0.125 in (3 mm) below the pavement surface for most projects. Good performance of the sealing equipment is extremely important to the long-term performance of a seal. In order to obtain the desired consistent surface level, the sealing equipment must be able to deliver a highly controllable amount of sealant. The sealing equipment should be able to install silicone sealants, emulsions, and fiberized asphalt sealants without over- or under-filling the joints or cracks. Nonself-leveling silicone sealants and fiberized asphalt sealants require different tooling operations to produce the desired profile. If these types of sealants are used, the sealant applicator must be able to form the sealant to the proper shape.

6.9.12 - Accessory Performance Monitoring Equipment

To ensure that the quality of preparation and installation is adequate, several accessory monitors may need to be developed.

- Depth sensing equipment for controlling router or saw height.
- System to monitor sandblaster operation.
- System to judge removal and cleaning effectiveness.

Feedback systems would also need to be developed to initiate the recleaning process as the monitors dictate. Commonly the surface of an AC shoulder is not level with the concrete pavement surface. If the depth of the sawcut and sealant surface level are controlled by the concrete pavement surface level, the sawcut may not form an adequate reservoir in the asphalt, and excess sealant may placed in the reservoir, spilling over onto the shoulder. The level of the saw blade and the installation attachment must be controlled by the height of the lowest pavement (AC shoulder or PCC pavement) so that a good sealant shape factor is maintained. This can be accomplished by using electronic depth sensing equipment or simply by using a foot or roller connected to the saw and sealant installation attachments that follows the lowest pavement surface.

It is sometimes difficult to maintain consistent sand and air flow from sandblasting equipment. If the sand is wet or the humidity is high, the moist sand can clog the nozzle. Likewise, if a small stone or other debris enters the blasting line, the nozzle can become clogged, and the sandblaster becomes ineffective. To prevent this situation from happening, the sandblasting attachment should be monitored for sand and air flow, and a feedback system should notify the operator of any problem.

The effectiveness of the cleaning equipment has a large impact on the performance of a joint seal, making it essential that the results of the sawing, sandblasting, and airblasting operations be satisfactory. An inspector is present at most major resealing projects to ensure that proper cleaning and installation results are achieved. To maintain high seal quality, the automated sealing equipment must have a method of ensuring that each apparatus is performing adequately. These sensors may be visual or based on other criteria, and an accompanying feedback network should be developed to initiate repetition of the process of a deficiency is noted.

6.10 - Summary and Conclusions

This chapter has addressed the commercialization issues related to the ACSM. A preliminary market study has produced a better understanding of the potential purchasers and users of the developed machinery. Two independent estimates using different analysis methods have arrived at virtually identical costs for producing a small number of machines identical to the first generation prototype ACSM, that being approximately $800,000. Through the use of a Non Recurrent Engineering (NRE) based model, a commercial version of the ACSM has been predicted to cost approximately $550,000. Additionally, the cost of a modular longitudinal machine should cost between $35,000 and $152,000 depending upon the functions required by the purchaser. These costs are consistent with numerous other current roadwork equipment. A conservative cost benefit analysis contained herein has shown that a $550,000 ACSM is an excellent investment and its cost will be recovered in approximately 2 to 3 years. The cost benefit analysis did not quantify the additional and potentially large cost savings of reduced congestion and improved safety. Suggested modifications and developments that will allow the ACSM to address the spectrum of crack and joint sealing/filling operations have also been presented. Finally, the preliminary market analysis has included two focus group meetings which have provided a wide set of points of view concerning the ACSM, and these issues will help develop the actual market analysis.

Initial inquiries to large heavy equipment manufacturers (Caterpillar and Case), were met with interest in the program. In general the issues of cost of production quickly set in. It was determined that in order for a major manufacturer to get involved, they had to have a projection of sales of at least 100 - 120 units over a relatively short period of time (2 - 3 years). They felt that the overall approach was sound and had potential merit, but they also pointed out that they would probably take an additional 8 - 12 months to re-design several of the sub-systems to fit their "standard" component inventory. They also, pointed out that before they would be interested in getting involved with a project such as this, that they would need to see some sort of study that would support a projected market of this size.

Upon receiving this feedback, an effort was made to determine if there were some smaller or low volume manufacturers/vendors, of roadwork equipment, that might be candidates for the production of this type of equipment. It was found that several firms existed (e.g.: Rexroth and Barber-Green). The AHMCT Research program is also in the process of assessing commercialization potential of several highway maintenance devices. Additionally, TDC has initiated contact with several small companies with interests in possibly manufacturing specific ACSM components. A more detailed analysis, points of contact, and feedback program should be instituted to determine the level of interest and what the controlling factors and parameters might be.

In the final analysis, several issues remain to be addressed. These include operating costs; maintenance factors/costs; reliability and productivity analysis; additional standardization studies done in conjunction with industry - the manufacturers - in order to optimize cost of production; and additional technology transfer to take best advantage of other research work.

The longitudinal machine, by being modular in design and operation, and by being relatively simple while taking advantage of improved process, is commercially viable today. Most likely a certain amount of additional NRE would be incurred in attempting to make the system capable of being mounted on a wider range of vehicles of opportunity. Also, depending upon a specific district's needs or operational practices, one or more of those items in section 6.9, identified as desirable enhancements, would be candidate for rapid prototyping and inclusion into the LRPS design. This machine should be able to be produced not only by a (large) volume manufacturer, but also by local fabrication shops and/or county, state, and federal maintenance facilities.

While the feasibility of the complete ACSM has been demonstrated, the machine would appear to have at lease one more generation of development to go through before being a marketable system. Again, those elements identified in sections 6.9 need to be specifically addressed before the machine would be as readily accepted as the LRPS was (by Caltrans maintenance personnel). Specifically, due to the complexity of the ACSM, an additional iteration in the development process needs to take place to make this machine more reliable and simpler to use.

In both cases a formalized and operationally intensive field trial period needs to be executed. This program would be of significant value to FHWA as well as any researchers/manufacturers involved, since it will not only provide both qualitative but also quantitative feedback on machine performance, but also bring out the programmatic differences (due to widely varying work practices in the transportation districts) that need to be normalized or accommodated by additional machine modules.

The research program has been a success with regards to the development of commercially viable maintenance equipment with the potential of improving performance/cost ratios as well as improving personnel safety and productivity.

7

Maintenance Program With Automated Machinery

7.1 - Introduction

The integration of the automated sealing system into a highway agency's maintenance program is a multi-step process. The agency must first identify a need for the maintenance that the system performs. Decision criteria are then outlined to determine if the system meets the agency's needs. If the system does meet the agency's decision criteria, the equipment will most likely be tested in a contracted project. Then, if the system performs well and its cost-effectiveness can be demonstrated, the agency may regularly contract for the use of the equipment and its operator. The agency may also decide to pursue the possibility of joint ownership of the system with other agencies in its region. Finally, a fully- or partially-equipped system may be purchased, with the option to add capabilities at a later date. Each of these steps in the integration process are detailed in the following sections.

7.2 - Decision Criteria

There are two fundamental decisions that need to be made as part of the automated equipment implementation process. The first decision is whether or not to acquire and/or use such equipment at all. Many agencies have rigorous procedures for procuring equipment and competing for available funding. This has a direct impact on decisions to acquire new equipment, because when budgets are cut, equipment purchases often have the lowest priority. Therefore, it is critical that the benefits and cost-effectiveness of the new equipment be clearly determined at the beginning of the procurement process.

The decision criteria used by a highway agency must be clearly defined before the potential for integration of a system into its maintenance program can be determined. Some important decision criteria include:

- The maintenance operation that the equipment performs must improve pavement performance enough to justify the expenditure for the equipment.
- The equipment must be durable, so that down-time and maintenance expenses are minimized.
- The technical difficulty and cost of repairs to the equipment must be manageable, as it is desirable to perform most repairs in-house.
- The speed and quality of work must be superior, especially when compared to already existent, satisfactory methods.
- Traffic control must be acceptable and user delays within a tolerable range.
- The equipment must be professionally manufactured, aesthetically built, and have proven performance.

If the equipment satisfies these criteria, highway agencies are likely to be willing to expend funding to integrate the system into their maintenance programs.

The second decision follows once an agency has determined that it is worthwhile to acquire the automated sealing equipment. That decision is, given access to, or even ownership of, the equipment, on what types of projects should it be used? The simple answer is that automated sealing equipment should be used on projects on which its use is cost-effective. If it is assumed that once the pavement is sealed, the repair placed by manual methods will last as long as that placed by automated methods, then it is only necessary to consider the actual installation costs in performing this analysis of cost-effectiveness.

Some of the costs associated with sealing operations are easily measurable. These include equipment costs, labor costs for the number of people required, and material costs, if the rate of use is different. However, two of the largest costs, user costs and safety costs, are not easily quantifiable. The use of an automated sealing system will reduce the direct exposure of highway workers to traffic. It will also reduce the exposure of traffic to both visual and physical disruptions in the roadway. As the operation approaches the speeds that are targeted for the final working equipment, it will also reduce lane occupancy time. Taken together, these will have a direct and positive, albeit non-quantifiable, effect on costs that must be considered.

Perhaps there exists a third decision that in some cases takes precedence over the normal decision-making process. The original objectives of SHRP in the automated maintenance equipment project area were to create new equipment system prototypes to:

- allow surface repairs or crack filling operations from a position off the roadway, and
- reduce personnel requirements.

In the decision-making process it is also necessary to consider maintenance operations associated with both high and low-volume traffic streams and urban and rural pavement networks.

These requirements suggest that even over 5 years ago, there existed agencies for which the decision to adopt the use of automated equipment was driven by factors that are not readily quantifiable, including user costs and safety costs. It is those agencies that will approach the use of automated equipment in a different manner from the majority of agencies that perform sealing. Where these other costs are valid concerns, it is likely that there will be strong incentives to use automated sealing equipment even when such use can not be supported by a strict cost-benefit analysis.

7.3 - Integration

Because of its high cost, it is unlikely that individual agencies primarily responsible for low-volume and rural pavement networks would be able to purchase this system. Nor is it likely that their needs would lead them to be interested in an automated system. Rather, interested agencies are likely to be those responsible for high-volume roadways in an urban environment. For such agencies, integration of automated sealing technology into a maintenance program would likely be accomplished in one of two ways:

1. Several highway agencies may share ownership of the equipment.
2. The highway agency may contract for use of the equipment and its operator.

7.3.1 - Shared Ownership

If the equipment is shared among highway agencies within a given state or region, the agencies' own crews will have to use and maintain the equipment. The agencies will have to develop a training program to provide the crews with the high level of technical training necessary to operate and maintain the equipment.

7.3.2 - Contracting for the Service

It is more likely, however, that the majority of equipment use will be from maintenance contracting. In this case, two types of contracts may be used: 1) a contract for final hourly cost for use of the equipment with a specified minimum number of hours to be used on each contract period, or 2) the highway agency may take bids for work on a specific project. In order to make the use of the equipment cost-effective, contracts should provide for a long-term commitment (2 years or more, if possible under the agency's contract laws).

7.4 - Gradual Integration

The most likely initial use of this machine by highway agency maintenance crews is for longitudinal crack sealing. This is an application for which the technology is already competitive with existing alternatives. The modules that perform this function are well advanced in their development, and their cost is comparatively low. There are several applications in which longitudinal crack sealing is the predominant activity, and this equipment could be used to address that need immediately. These cases include reflective cracking of a lane-shoulder joint on an AC widening project, some longitudinal joint reflective cracking, and cold joints on AC paving projects.

Later, the transverse crack sealing equipment could be integrated, as its capabilities develop from a prototype to a fully functioning version. Even at this stage, it is envisioned that a gradual integration of the machine would be desirable. For example, there are several components that individually carry out specific tasks in crack sealing program. These include the router, the heat lance, the vacuum, and the sealant applicator. Since not all agencies use all of these components in their crack sealing programs, an appropriate gradual integration might include the use of the applicator only, followed by the router and the applicator, and then the full system. It is also suggested that appropriate tests of the system on actual highways would actually start with the easiest application, on low volume roads, and then later be introduced in more demanding applications.

Highway agencies will probably test the usefulness and cost-effectiveness of the equipment through contracted projects before considering purchasing the equipment themselves. If several agencies decide to share ownership of the equipment, it is likely that the equipment would initially be purchased with the crack sealing and filling features. It is highly probable that highway agencies would continue to contract for joint resealing. However, agencies that share ownership of this equipment, initially rigged for crack sealing and filling, may add joint resealing capabilities to the equipment at a later time.

8

Conclusions and Recommendations

This document reports on the development of an automated machine for the sealing of cracks and joints in highway pavement. This machine is comprised of two independent machine systems: one for longitudinal cracks and joints that exist at the edge of the lane (e.g., construction joints), and the other for general (random or transverse) cracks/joints that may extend across a lane. The important features and the coordinated activities of the numerous components of both the integrated longitudinal and general crack sealing systems are discussed. Detailed descriptions and discussions on the principles of operation of each of the machine components and subsystems are presented. A critical feature of the machine development plan is the use of as many commercially available components as possible to improve component reliability and expedite machine development. Accordingly, manufacturer and model number information for much of the purchased equipment is included in Appendix B. To facilitate the significantly higher speed of the automated operations relative to manual operations, several custom components were developed, including the router and sealant applicator. Detailed engineering drawings of these components have been included in addition to layout drawings of each component subsystem and the support vehicle. Performance specifications of the components are also discussed.

The ACSM has been developed in a modular manner. The component subsystems are stand alone; they can operate independently. This has allowed for rapid prototyping of the machine. Of equally import, this implies that the end users can tailor the set of components to best meet their crack and joint sealing methods. This is quite significant in light of the variety of preferred highway agency methods.

The incorporation of technological advances into the normal work environment is often a difficult problem. Since the ACSM is a significant departure from the standard manual approach, ideas as to how the automated machinery can be integrated into the maintenance programs of highway agencies are presented in this report. Additionally, recommended machine modifications that will allow the machinery to address all types of crack and joint sealing/filling operations thus increasing the applicability of the ACSM are included.

Unanticipated severe weather persisted through winter and early spring of 1993 in Northern California which delayed the total ACSM integration effort. Thus, testing was limited to qualitative testing of the integrated longitudinal crack sealing system and the components of which it is comprised. Since the general crack sealing system shares the same components, their successful implementation in that machine is evident. A test plan has been outlined herein that should provide significant additional information on the viability of the ACSM.

Based upon the testing performed, estimates of machine production have been made. For the simplest longitudinal operation, sealing only, the ACSM can effectively seal at speeds as high as 15 mph (24 km/hr). At such speeds, an operator can effectively follow cracks by employing joystick control of the longitudinal positioning system. With the incorporation of the pavement heating system, the machine can effectively preheat and seal at speeds as high as 8 - 10 mph (13 - 16 km/hr). Finally, the complete operation, routing, blowing, debris removal, heating and sealing, can be performed effectively for longitudinal cracks at 2 mph (3.2 km/hr). This significant speed increase over manual operations comes with the additional benefit of about a three man crew reduction.

Numerous commercialization issues of the integrated machine are discussed. A preliminary market analysis presents the results of machine cost projections, cost benefit analysis, and focus group discussions. The machine cost projections have been performed by two independent groups employing different analysis methods. They have arrived at virtually the same result – that a single identical ACSM could be produced for approximately $800,000. Based on a Non-Recurrent Engineering based cost analysis, a commercial ACSM produced in quantities of more than five units would be sold at approximately $550,000. A conservative cost benefit analysis contained for a $550,000 ACSM shows that it is an excellent investment and its cost will be recovered in approximately 2 to 3 years. The cost benefit analysis does not quantify the additional and potentially large cost savings of reduced congestion and improved safety.

The cost projections for the longitudinal machine are on the order of $228,000 for the first 1 - 5 units, then a probable subsequent unit cost of $152,000. It should be noted that the cost projected here for the longitudinal machine represents the fully automated machine with routing, debris removal, pavement heating, and sealant application. Due to the modular nature of the LRPS design, the simplest version that has no automatic tracking capabilities and only lays down sealant (using an existing sealant melter system) could be as low as in the $35,000 to $55,000 range.

Based on an assessment of comparative equipment, the projected costs of the general machine, at $550,000 to $824,000, are in line with the higher end or typical and specialty roadwork equipment. The projected cost of $35,000 to $228,000 for the longitudinal machine is also in line with not only the low to mid end of equipment costs, but it is also consistent with attachment costs (for the high end equipment) at the lower end of its configuration/price combination.

The longitudinal machine is commercially viable today. While the feasibility of the complete ACSM has been demonstrated, the machine would appear to have at lease one more generation of development to go through before being a marketable system in order to improve system reliability and reduce system complexity. However, the prototypes have demonstrated their potential for vast improvement in personnel safety and productivity while concurrently improving the quality and uniformity of the resultant seal.

The California Department of Transportation has been an active participant in this entire project providing direct cost share in addition to personnel, equipment, and numerous other resources. The continued integration of the general crack sealing system of the ACSM is on-going as this report is being produced through Caltrans additional support. The SHRP H-107A is committed to completing this development effort. The following is a summary of recommendations for continued effort aimed at the final development and commercialization of the ACSM.

- Following final integration of the general crack sealing system, a detailed test program based on the plan provided in Chapter 5 should be performed. This will allow for a more accurate assessment of the expected machine performance for both the general and longitudinal systems.

- A complete analysis should be performed to assess the marketability of the integrated ACSM systems as well as the individual components. Secondly, the market analysis will help guide the further development of the machine. Third, this analysis should lead to identifying a vendor or a series of vendors to commercialize individual components as well as the integrated machine.

- Based on the test results and the market analysis, the second generation general crack sealing system prototype with less complexity and higher reliability should be developed.

- Detailed field trials of the ACSM should take place. This will provide invaluable information concerning machine usability, robustness, and reliability. Field trials by Caltrans of the sealant applicator and non-automated longitudinal machine are already set for Spring, 1993 with subsequent field trials of the automated LRPS to follow.

- Based on the field trials, modifications to the ACSM should take place to best meet user needs.

- A series of machine demonstrations should be performed throughout the U.S. to promote the use of the ACSM to a the wide variety of highway agencies in addition to potential machine and component manufacturer/vendors.

In summary, the primary objectives of this project were to design machinery for the sealing and filling of joints and cracks in pavement in order to:

- Increase the cost-effectiveness of these operations,

- Increase the quality, consistency, and life of the resultant seals and fills,

- Increase the safety of workers and highway users, and

- Increase the use of remote operation and control of equipment to attain the above.

The developed Automated Crack Sealing Machine has the potential to satisfy each of these objectives, and accordingly, it will be a valuable addition to the highway maintenance field.

9

Abbreviations and Glossary

9.1 - Abbreviations

A/D:	Analog-to-Digital.
AASHTO:	American Association of State Highway and Transportation Officials.
AC:	(1) Asphalt Concrete. (2) Alternating Current.
ACSM:	Automated Crack Sealing Machine.
ADT:	Average Daily Traffic.
APS:	Applicator and Peripherals System.
ASCII:	American Standard Code for Information Interchange.
ASME:	American Society of Mechanical Engineers.
BTU:	British Thermal Units.
Caltrans:	California Department of Transportation.
CCD:	Charge Coupled Device.
COGS:	Cost of Goods and Services.
CPU:	Central Processing Unit.
D/A:	Digital-to-Analog.
dB:	decibel.
DC:	Direct Current.
° C:	Degrees Celsius.
° F:	Degrees Fahrenheit.
DFT:	Discrete Fourier Transform.
D/L:	Direct Labor.
DOD:	Department of Defense.
DOE:	Department of Energy.

DOF:	Degrees-of-Freedom.
DOS:	Disk Operating System.
DOT:	Department of Transportation.
EIA:	Electronics Industry Association.
FHWA:	Federal Highway Administration.
Four R:	Rehabilitation, Restoration, Resurfacing, and Reconstruction
FPM:	Feet Per Minute.
ft:	Feet.
G&A:	General and Administrative.
gal:	Gallons.
GUI:	Graphical User Interface.
HCA:	Hot Compressed Air.
HCD:	Heating, Cleaning, and Debris removal system.
HIP:	Hot-in-place.
HP:	Horsepower.
hr:	Hours.
Hz:	Hertz.
I/O:	Input/Output.
IBM PC:	International Business Machines Personal Computer.
ICU:	Integration and Control Unit.
IEEE:	Institute of Electrical and Electronics Engineers.
km:	kilometer
kPa:	kiloPascals.
kW:	Kilowatt.
l:	Liters.
Laser:	Light Amplification by Stimulated Emission of Radiation.
lb:	Pound.
LP:	Liquid Propane.
LRPS:	Longitudinal Robot Positioning System.
LSS:	Local Sensing System.
m:	Meters.
mA:	milliamps.
MAP:	Manufacturing Automation and Productivity
MB:	Megabyte.
MHz:	Megahertz.
mi:	Miles.

MIL:	Mobile Imaging Lab.
min:	Minute.
mm:	Millimeters.
MP:	Mile Post.
MPH:	Miles Per Hour.
MSDOS:	Microsoft Disk Operating System.
mtl:	Material.
N:	Newton.
NBS:	National Bureau of Standards.
NDOT:	Nevada Department of Transportation.
NEMA:	National Electrical Manufacturer's Association.
NIST:	National Institute of Standards and Technology.
NRE:	Non-recurrent Engineering.
O/H:	Manufacturing Overhead.
OSHA:	Occupational Safety and Health Administration.
P:	Selling Price.
Pa:	Pascals.
PC:	Personal Computer.
PCC:	Portland Cement Concrete.
PID:	Proportional-Integral-Derivative.
PSD:	Photosensitive Device.
PSI:	Pounds per Square Inch.
PSU:	Power Supply Unit.
PVC:	Polyvinyl Chloride.
QA/QC:	Quality Assessment / Quality Control.
R&D:	Research and Development.
RAM:	Random Access Memory.
RAVE:	Real-time Audio Visual Environment.
RCC:	Roller-Compacted Cement.
ROI:	Region Of Interest.
ROM:	Read Only Memory.
RPM:	Revolutions Per Minute.
RPS:	Robot Positioning System.
RTOS:	Real-Time Operating System.
S:	Selling Expense.
SCARA:	Selective Compliance Architecture for Robotic Assembly.

SCFM:	Standard Cubic Feet per Minute.
SCSI:	Small Computer Systems Interface.
SDOT:	State Department of Transportation.
SDU:	System Display Unit.
SHRP:	Strategic Highway Research Program.
TDC:	Technology Development Center.
TRB:	Transportation Research Board.
TTL:	Transistor-Transistor Logic.
UCD:	University of California at Davis.
UPS:	Uninterruptible Power System.
US:	United States.
VOC:	Vehicle Orientation and Control System.
VSB:	VME Subsystem Bus.
VSS:	Vision Sensing System.
WASHTO:	Western Association of State Highway Transportation Officials.

9.2 - Glossary

Accuracy:	Precision. For a mechanism such as a robot, accuracy refers to the precision with which the mechanism can be placed at a specified point. For a sensor, accuracy refers to the precision with which the measurement can be made.
Actuator:	A mechanism to activate process control equipment by use of pneumatic, hydraulic, or electronic signals; e.g. a valve actuator for opening or closing a valve to control the rate of fluid flow.
Adhesion:	Being or becoming attached to.
Aggregate:	The natural sand, gravel, and crushed stone used for mixing with cementing material in making mortar and concrete.
Algorithm:	A set of well-defined rules for the solution of a problem in a finite number of steps.
Alligator Cracking:	An advanced state of cracking caused by car and truck wheel loads that appears as an interconnected or interlaced set of cracks both inside and outside of the wheel path. Polygons formed by alligator cracking are usually less than 1 foot on a side.
Ammeter:	An instrument for measuring the magnitude of electric current flow.

Analog Data: Data represented in a continuos form, as contrasted with digital data having discrete values.

Array: A collection of data or variables organized in a row or column. In a computer program, an array consists of a collection of data items with each identified by a subscript or key and arranged in such a way that the computer can examine the collection and retrieve data from these items associated with a particular subscript or key.

Asphalt Emulsion: See emulsified asphalt.

Aspect Ratio: The ratio of the width to height of an image.

Asynchronous: Not synchronized, i.e. not occurring at predetermined or regular intervals. Often used to describe communications in which data can be transmitted intermittently rather than in a steady stream.

Ball Bearing: An antifriction bearing permitting free motion between moving and fixed parts by means of balls confined between outer and inner rings; also one of the balls in such a bearing.

Baud Rate: The number of electrical oscillations that occur each second in a communications channel. In most serial communications, only one bit of information is encoded in each electrical oscillation, so that the baud rate corresponds to the number of bits per second (bps) that are transmitted. At higher speeds, it is possible to encode more than one bit in each electrical change, so that the number of bps may be actually higher than the baud rate. For example, if four bits of data are encoded in each electrical change, a 2400 baud modem can actually transmit 9600 bits per second.

Bearing (Linear): See Linear Bearing.

Bearing: A machine part that supports another part which rotates, slides, or oscillates in or on it.

Binary Image: An image in which each element, or pixel, is either on or off. Each pixel is generally represented by a zero (off) or a one (on).

Bit: Either of the digits 0 or 1 as used in the binary notation. Bits are the basic unit of information in a computer system. A unit of information content equal to one binary decision or the designation of one of two possible and equally likely values or states of anything used to store or convey information.

Bit Map: A representation, consisting of rows and columns of dots or pixels, of a graphics image in computer memory. The value of each pixel is stored in one or more bits of data. For a monochrome image, one bit is sufficient for each pixel. For a gray scale image, each pixel requires multiple bits to represent the gray levels.

Bitumen: Any of various mixtures of hydrocarbons, such as asphalt or tar. Naturally occurring or pyrolytically obtained substances of dark to black color consisting almost entirely of carbon and hydrogen, with very little oxygen, nitrogen, or sulfur.

Block Cracking: Interconnected cracks which form a series of large polygons (generally greater than 1 foot but less than 5 feet on a side) usually with sharp corners or angles.

Bus: A collection of electrical connections through which data is transmitted from any of several sources to any of several destinations in a computer.

Bus Transfer Rate: The rate at which data can be transferred on a computer bus.

Byte: A sequence of adjacent binary digits operated upon as a unit in a computer and usually shorter than a word. Typically, a collection of eight bits.

Calibration: The act of determining, by measurement or comparison with a standard, the correct value of each scale reading on a meter or other device, or the correct value for each setting of a control knob. The action of correcting a measurement device. Also, the process of determining the relationship between systems, for example the relation between the frames of reference for the VOC, VSS, and RPS on the ACSM.

Cartesian Coordinates: A system used in analytical geometry to locate a point with reference to two or three mutually perpendicular axes.

Cartesian Reference Frame: A Cartesian frame of reference attached to a body, and used to define points relative to that body.

CCD Camera: Charge Coupled Device Camera. A camera that uses a charge coupled device to digitize the image that is focused on it by the lens of the camera.

Center of Rotation: The point about which a body rotates.

Chain Coding: A method for representing curves and boundaries where the direction vectors between successive boundary or curve pixels are encoded in a string.

Chip Seal: A sealing method using an asphalt emulsion and gravel chips applied over an existing AC base to seal fine cracks.

Clevis: A U-shaped metal fitting with holes in the open ends to receive a bolt or pin; used for attaching or suspending parts.

Closed-Loop Control System: A system in which the value of some output quantity is controlled by feeding back the value of the controlled quantity and using it to manipulate an input quantity so as to bring the value of the controlled quantity closer to a desired value.

Comparator: An electric circuit used to compare its input signal to a reference signal (usually zero). If the input signal is higher than the reference, the comparator outputs a high value, and if the input signal is lower than the reference, the comparator outputs a low value.

Compliant Motion Control: A method of control of a device in which the device is commanded to follow a nominal trajectory, while the trajectory is modified based on a measurement from an external sensor. Compliant control is most often used in conjunction with a force sensor as the external sensor, but compliant control can also be used in conjunction with a camera, a laser range finder, or a proximity sensor as the external sensor. In the ACSM, the LSS (laser range finder) is used for compliant control of the GMF A-510 manipulator during the crack sealing operation.

Concurrent Processes: Processes on a computer that are able to run simultaneously. See also multitasking.

Continuity Level: A parameter in the VSS crack detection algorithm. This parameter determines the minimum length of crack that will be detected by the system.

Control System: A system designed to control a process or a piece of machine. In general, a desired response will be specified for the process or machinery, and the control system is designed to achieve or approximate this desired response. See also closed-loop control and open-loop control.

Convection Heating: A process by which heat is transferred from one part of a fluid to another by movement of the fluid itself.

Damping: A decrease in the amplitude of an oscillation as a result of energy being drained from the oscillating system to overcome frictional or other resistive forces.

Data Module: See Shared Memory.

Data Structure: A collection of data components that are constructed in a regular and characteristic way. Examples include lists, arrays, records, trees, tables, and graphs.

Degrees-of-Freedom: The number of independent parameters required to specify the configuration of a system.

Demographics: The study of the statistics of populations, including birth, age, mortality, sex, and other social, ethnic, and economic factors. Here, demographics are used in the process of marketing and commercialization to determine the viability of a given product.

Diffuse Reflection: Reflection of a light source (sunlight, laser, etc.) from a surface which causes the light to spread out or diffuse.

Digital: Describes any system or signal based on discontinuous data or events.

Digitize: To convert analog data into a digital form. For example, the VSS uses its CCD cameras to translate the analog image of the road into a bit-mapped image which can then be processed by the computer.

Down-Milling: Milling method in which the teeth of a cutting tool advance into the work in the same direction as the feed.

Duplex: Refers to the transmission of data in two directions simultaneously.

Dynamics: The branch of mechanics concerned with the motion of bodies under the action of forces.

Embedded Application: A computer program or operating system that has been written or burnt into a ROM. Embedded applications can be found in many devices, from computers to televisions to automobiles.

Empirical: Based on observation or experiment, rather than on theory.

Emulsified Asphalt: A dispersion of asphalt particles in water with the presence of an emulsifying agent, such as soap.

Encoder: A device for measuring angular displacement. It consists of a disk with radial line slits, a light source, and a light detector. As the disk rotates, light is transmitted between the radial line slits to the light detector which generates an output signal (usually sinusoidal or triangular) which is then fed to a comparator which transforms the signal to a square wave. This square wave is then fed to a counter, which is triggered by the leading edge of the square wave. The counter value can then be used to determine the angular displacement.

End-effector: The tool attached to the end of a robot. Depending on the application, the end-effector could be a gripper, welding torch, electromagnet, or other device. In the ACSM, the sealant applicator can be thought of as the end-effector of the robot.

Error Feedback Signal: The difference between the desired quantity and the measured quantity in a closed-loop feedback system. Used to correct the alignment between the controlling and the controlled elements of the system.

Ethernet: A local-area network protocol developed by Xerox Corp. in conjunction with DEC and Intel. It uses a bus topology and supports data transfer rates of 10 megabits per second.

Ethernet Backbone: The Ethernet wire that connects the various computers on a given local-area network.

Ethernet Transceiver: A device which converts one form of Ethernet connection to another. For example, a Thin Net to AUI transceiver will allow the connection of a thin net cable to an AUI port on a computer.

Fatigue Cracking: Cracking resulting from repeated or cyclic stress.

Feedback Control System: See closed-loop control.

Fiberized Asphalt Sealant: Hot asphalt cement modified by the addition of high tensile-strength fibers.

Field of View: The area or solid angle that can be viewed using an optical sensor or instrument. For example, in the LSS, the field of view is the width of pavement that the LSS is able to sense from its normal operating height.

Fifth Wheel Assembly: A horizontal wheel on a vehicle serving as a coupling and support. Here, the fifth wheel is attached to the truck and in contact with the ground, and is used to monitor the position of the vehicle by driving an encoder.

Filter: A circuit used to remove noise from a signal, used in the selective enhancement of a given class of input signals.

Foot-Candle: A unit of illumination.

Fork: See process fork.

Four-Bar Linkage: A plane linkage consisting of four links pinned tail to head in a closed loop with lower, or closed, joints.

Frequency: The rate of repetition of a regular (periodic) event. The number of cycles completed by a periodic quantity in a unit time.

Full Duplex: See duplex.

Gimbal: A type of joint or mount in which rotation is allowed about two perpendicular axes. A device with two mutually perpendicular and intersecting axes of rotation, thus giving free angular movement in two directions, on which a device can be mounted.

Global Data: A planned path for the RPS using the data from the VSS and the VOC, without any local feedback from the LSS.

Gray Level: Discrete values used to represent shades of gray in an image.

Gray Scale Image: An image consisting of many shades of gray. Continuous tone images can be converted into gray scale images by quantizing the range of gray levels into discrete values, called gray levels.

Heading: The direction in which the longitudinal axis of a vehicle (e.g. the truck) points.

Heat Exchanger: A device for transferring heat from one body or fluid to another or to the environment.

Heuristic: A method of solving a problem for which no algorithm exists. It typically involves trial-and-error, iteration, or physical insight into the problem.

Histogram: An ordering of pixel values based on intensities. A representation of a distribution function by means of rectangles whose widths represent intervals into which the range of observed values is divided, and whose heights represent the number of observations occurring in each interval.

Homogeneous Transformation: A mathematical construction used to transform position vectors between different reference frames. It combines changes in position and orientation into a single matrix. The matrix can also be used as a representation for position and orientation in a given frame.

Hot-Applied Sealant: Sealant which becomes soft upon heating and hardens on cooling, usually without a change in chemical composition.

Hydraulic: Operated or effected by the action of water or other fluid of low viscosity.

Hz: hertz. Cycles per second. The unit of frequency; a periodic oscillation has a frequency of n Hz if in 1 second it goes through n cycle.

Image Processing: The processing of a two-dimensional picture by a digital computer. A technique in which the data from an image is digitized and various mathematical operations are applied to the data with a digital computer in order to create an enhanced image that is more useful or pleasing to a human observer, or to perform some of the interpretation and recognition tasks usually performed by humans.

Image Segmentation: The process of separating the extracted features of an image into components. For example, the separation of different objects by extracting their boundaries.

Infrastructure: Subordinate parts, installations, etc., that form the basis of a system, organization, or enterprise. The stock of fixed capital equipment in a country, e.g. roads.

Internet: The world's largest computer network. The Internet connects computers worldwide for communication by way of e-mail, file transfer, etc.

Interrupt: See prioritized interrupt.

Joint Rotation: The relative angle between two linkages connected by a rotary or revolute joint.

Joint Stroke: The relative position between two linkages connected by a sliding or prismatic joint. Also known as the joint offset.

Joystick: A computer input device consisting of a lever which moves in all directions and controls the movement of a pointer or other display symbol. A joystick contains potentiometers that give a reading proportional to the displacement of the stick, and is thus well suited for the positioning of mechanical devices, such as the LRPS. A typical joystick will also contain two buttons which can be used to turn a device on or off.

Karel: The programming language for the GMF A-510 robot manipulator.

Kinematics: The branch of mechanics concerned with the motions of objects without being concerned with the forces that cause the motion. The kinematics of a mechanism refer to the relationship between internal positions and velocities of linkages and the external position and velocity of the active portion of the mechanism.

Laser: Light Amplification by Stimulated Emission of Radiation. An active electron device that converts input power into a very narrow, intense beam of coherent visible or infrared light. The input power excites the atoms of an optical resonator to a higher energy level, and the resonator forces the excited atoms to radiate in phase. Here, the laser is used to project a structured light.

Line Scan Camera: Camera that has a CCD sensor consisting of a linear array of sensors. These cameras yield only one line of an input image. The motion of an object past the line scan camera produces a two-dimensional image.

Linear Bearing: A machine part over which another part slides in a linear, or straight, fashion.

Linear Slide: A straight track that a robot can be mounted to. The slide typically has an actuator to move the robot back and forth on the slide, thus increasing the range of motion, or workspace, of the manipulator.

Linkage: A mechanism that transfers motion in a desired manner by using some combination of bar links, slides, pivots, and rotating members.

Longitudinal Crack: A crack which is oriented in the direction of vehicle travel on a roadway.

Low-Pass Filter: A filter designed to pass signal components below a specified cutoff frequency and substantially attenuates signal components above the cutoff frequency.

Lumen: The SI unit of luminous flux equal to the flux emitted by a uniform point source of 1 candela in a solid angle of 1 steradian.

Machine Vision: The process of extracting, characterizing, and interpreting information from images of a three-dimensional world using a computer. Machine or computer vision can be divided into six principal areas, in order of increasing sophistication: sensing, preprocessing, segmentation, description, recognition, and interpretation.

Manipulator: A robot.

Matrix Transformation: See homogeneous transformation.

Matrix: A set of quantities in a rectangular array, used in certain mathematical operations. The matrix is usually enclosed in large parentheses or in square brackets.

Mean: The mean is the sum of all measurements divided by the number of measurements. The mean corresponds to the standard notion of an average.

Micropaving: A new procedure developed in Europe which resembles a slurry seal in application. It can allegedly be performed on streets with rutting as high as two and a half inches to smooth out the pavement, and allows cars back on the road in ten minutes.

Mode: In a set of measurements or numbers, the mode is the most frequently occurring value.

Moment: See statistical moment.

Multiprocessing: Refers to the utilization of multiple CPUs in a single computer system. This is also known as parallel processing.

Multitasking: Refers to a computer system's ability to support more than one process (program) at the same time. Multitasking operating systems enable several programs to run concurrently. Unix is a well-known multitasking operating system. OS-9 is a multitasking operating system, and is used in the integrated general ACSM.

Natural Frequency: The frequency at which resonance occurs in a system. The frequency with which a system oscillates in the absence of external forces.

Noise: Any undesired signal or unwanted disturbance.

Normal: A line drawn at right angles to a surface.

Nyquist Sampling Frequency: The theoretical minimum frequency at which data must be sampled so that the original signal is completely specified by the sampled signal.

Open-Loop Control: A control system in which the system outputs are controlled by system inputs only, and the actual system output is not fed back as a part of the control.

Optical Encoder: See Encoder.

O-ring: A circular shaped seal, usually made of rubber.

OS-9: A multitasking multiuser real-time operating system.

Overbanded Sealant: A specific seal configuration in which the crack is covered with a crown of sealant projecting slightly above the road surface and the sealant is additionally dispersed adjacent to the crack on the road surface.

Overlay: A repair topping of asphalt or concrete placed on a worn roadway.

Palletize: To package material for convenient handling on a pallet or lift truck. Palletizing is a typical application of a robot in industry.

Parity: The use of a self-checking code in a computer employing binary digits in which the total number of 1's or 0's in each permissible code expression is always even or always odd.

Pascal: The SI unit of pressure equal to one Newton per square meter. Abbreviated as Pa.

Perpendicular: At an angle of 90° to another surface or line.

Phase Shift: A shift in time between two signals of the same frequency or period. The phase angle between the input and output signals of a system.

Photosensitive Device: Any device that when exposed to electromagnetic radiation produces a photoconductive, photoelectric, or photovoltaic effect.

PID Control: A method of feedback control in which the actuator signal is a combination of a term proportional to the error signal (P), its integral (I), and its derivative (D).

Pipe: A temporary software connection between two programs or commands. Using a pipe, the output of one process can be used as the input of another process. Pipes are one form of communication between processes in OS-9.

Pixel: Short for picture element, a pixel is a single point in a graphic image.

Pneumatic: Pertaining to or operated by air or other gas.

Port: An interface on a computer to which a peripheral device can be attached.

Position Transducer: A transducer used in the measurement of position.

Potentiometer: A resistor having a continuously adjustable sliding contact that is generally mounted on a rotating shaft, yielding a variable resistance. The value of the resistance is proportional to the rotation of the shaft, so that a potentiometer can be used as either a rotational position transducer, or as an input device for a user to specify the position of a mechanism.

Preformed Seal: Premolded strips of styrene, urethane, neoprene, or other synthetic materials that are inserted into transverse joints in a state of compression. The seals are intended to maintain contact pressure with the joint faces and therefore are not subject to adhesion failures, one of the primary failure modes of field-molded sealants.

Prioritized Interrupt: A signal informing a program that an event has occurred. When a program receives an interrupt signal, it takes a specified action. Interrupt signals can cause a program to suspend itself temporarily in order to service the interrupt. Interrupts can be initiated by either hardware or software. Interrupts will have an associated priority level, which determines the order in which interrupts are serviced.

Process Fork: The method by which one process begins another process. In OS-9, a parent process can fork a child process, and subsequently both processes can run concurrently.

Program Linking: The process of combining several object modules into a single executable program.

Prototype: First or original example of a device or machine that will be copied or developed; model or preliminary version.

Pyrometer: Any of a broad class of temperature measuring devices. They were originally designed to measure high temperatures, but some are now used in any temperature range. Includes radiation pyrometers, thermocouples, resistance pyrometers, and thermistors.

Raceway: A channel used to hold and protect wires, cables, or busbars.

Radii: Plural of radius.

Radius: The distance from the center of a circle to the circle.

Radius of Curvature: The radius of the circle of curvature at a point on the curve.

RAM: Random-Access-Memory. A type of computer memory that can be accessed randomly, i.e. any byte of memory can be accessed without touching the preceding bytes. RAM is the most common type of computer memory. RAM can be both read from and written to, but does not retain its contents when the computer is turned off. Because of this, RAM is referred to as volatile.

RAVE system: A graphical user interface development package which can be customized for a specific application. It has the capability to provide real-time machine control and real-time user feedback.

Redundant Degrees-of-Freedom: Degrees-of-freedom which are not required to position a mechanism at an arbitrary position in its workspace. Redundant degrees-of-freedom can be used in a variety of ways, such as avoiding obstacles with the links of the mechanism, or improving the dexterity of the mechanism.

Reflection Crack: Transverse and longitudinal cracks appearing in an AC surface that overlays weakened plane joints and cracks in PCC pavement. The cracks 'reflect' the weaknesses of the underlying structure.

Relay: An electrical or electronic device in which a variation in the current in one circuit controls the current in a second circuit. A typical use is in the form of an electromechanical relay, in which the first circuit energizes an electromagnet, which operates a switch in a second circuit.

Remediation: Repair.

Repeatability: Specifies how precisely a mechanism such as a robot can return to a certain point.

Resolution: The ability of a measuring device to measure small detail. The smallest increment that a sensor can measure, or resolve.

Resonance: A phenomenon exhibited by a physical system acted upon by an external periodic driving force, in which the resulting amplitude of oscillation of the system becomes large when the frequency of the driving force approaches a natural free oscillation frequency of the system. In general, any phenomenon which is greatly enhanced at frequencies or energies that are at or very close to a given characteristic value.

Ribbon Cable: Flat cable used to connect internal and external devices in a computer system. A cable made of normal, round, insulated wires arranged side by side and fastened together by a cohesion process to form a flexible ribbon.

Robot: A reprogrammable multi-functional manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks.

Robot Payload: The amount of load that the robot can carry in a dynamic fashion, or the actual load that the robot is carrying.

Robot Workspace: The work volume in which the robot can place its tooling.

ROM: Read-Only-Memory. Memory in a computer that can be read from, but not written to. Unlike RAM, ROM retains its contents even when the computer is turned off. Because of this, ROM is referred to as nonvolatile.

ROMable Code: Code which has been written in a fashion which allows it to be written to ROM.

Rotation: Motion of a body in which all the points in the body follow circular paths.

Router: An impact cutting device used to prepare cracks by cutting a channel along the crack in a profile that allows for increased penetration and adhesion of sealant.

RS-232 or RS-232C: A standard interface approved by the Electronics Industry Association (EIA) for connecting serial devices. This standard is also referred to as EIA-232D, but is most commonly known as RS-232.

Rutting: A longitudinal surface depression caused by consolidation or lateral movement of roadbed material under heavy wheel loads.

Screed: A layer of cement, mortar, etc. spread over a surface to make it smooth.

Sealant Applicator: The custom designed and built tooling used to deliver sealant to the roadway crack.

Sealant Float: A floatation device in the sealant applicator which drives a linear potentiometer to provide a feedback signal to monitor and control the amount of sealant in the sealant reservoir.

Sealant Reservoir: The volume of sealant beneath the float in the sealant applicator.

Segmentation: See Image Segmentation.

Sensor: A device used to measure and/or detect a physical quantity, such as light, heat, humidity, pressure, flow rate, etc. The generic name for a device that senses either the absolute value or a change in a physical quantity and converts that change into a useful input signal for an information gathering system.

Serial Communication: Data communication in which data is transmitted one bit at a time.

Servomotor: A motor that controls a larger mechanism. The electric, hydraulic, or other type of motor that serves as the final control element in a servomechanism.

Servo Valve: A valve used in the control of a larger mechanism.

Shape Factor: The ratio of the dimensions of a routed channel.

Shared Memory: An area of memory in a computer system that allows two or more processes to share the data contained in that area. In OS-9, a shared memory area is referred to as a data module. Shared memory is the main method used to communicate information between the various processes in the general integrated ACSM.

Shim: A spacer used for leveling or squaring two bodies.

Signal Conditioning: Process of cleaning up a signal, usually acquired from an external sensor. This process typically involves filtering to remove noise.

Signal: (1) A variable parameter that contains information and by which information is transmitted in an electronic system or circuit. (2) A method of interprocess communication in the OS-9 operating system. A signal is an intentional disturbance in the system, used to synchronize concurrent processes, or to transfer small amounts of data. Signals provide real-time communication between processes, and can also be thought of as software interrupts (see Prioritized Interrupts). Signals were the main method of synchronizing the processes and their access to shared memory in the general integrated ACSM.

Silicone Seal: One-part polymer materials which, upon curing, form a continuous silicone-oxygen-silicone network.

Simulation Program: A computer program used to model a device, process, or system. The simulation can be used to examine the effects of varying inputs, system parameters, etc., before applying to the actual system.

Slurry: A paste consisting of a suspension of a solid in a liquid.

Slurry Seal: A sealing method using an asphalt emulsion applied over an existing AC base to seal fine cracks.

Software Library: A collection of precompiled routines that a program can use. The routines, sometimes called modules, are stored in object format, and can be linked with user-defined programs.

Software Module: A part of a program. Individual modules are combined into a single executable through program linking. A single module can contain one or many routines.

Solenoid: A coil of wire wound on a cylindrical former in which the length of the former is greater than its diameter. When a current is passed through the coil a magnetic field is produced inside the coil parallel to its axis. This field can be made to operate a plunger inside the former so that the solenoid can be used to operate a circuit breaker, valve, or other electromechanical device.

Solid-State Video Camera: See CCD camera.

Source Level Debugger: A program used to find errors (bugs) in other programs. A source level debugger lets the programmer view the original program source code, and stop a program at any point and examine and change the values of variables.

Spalling: Broken or crushed edges on a crack or a route cut.

Spindle: A slender pin or rod which turns or on which something else turns.

Square Wave: A train of rectangular pulses that alternate between two fixed values.

Squeegee: A device used for spreading or wiping liquid on, across, or off a surface. Here, a circular attachment to the sealant applicator used to shape the sealant as it is applied to the crack.

Standard Deviation: The square root of the variance. A measure of the spread or dispersion of a measurement away from the mean value (average) of the measurement.

Statistical Moment: A statistical measurement of the distribution of a data set. Here, the statistical moment is used in the VSS. For the purpose of this report, the kth statistical moment is defined as the sum of the products of the kth power of the gray level distance from the mode times the number of pixels at that point. The first moment is the mean of the distribution, and the variance may be found in terms of the first and second moments.

Stop Bits: In asynchronous communications, every byte of data is preceded by a start bit and followed by one or two stop bits in order to coordinate the communication.

Stowage: The act of securing a piece of equipment for transportation.

Structured Light: An approach to laser vision which extracts a three dimensional surface profile by projecting a laser pattern in a plane perpendicular to the surface being measured. The line of light is then observed by a CCD camera at an angle to allow the surface features to be found.

Synchronous: Occurring at regular intervals. In general, refers to communication. Communication within a computer is usually synchronous and is governed by the microprocessor clock.

System State Debugger: A program used to find errors (bugs) in other programs. A system state debugger can be used to look at the low-level state of a system, i.e. internal CPU registers, flags, etc.

Tandem Axles: A pair of axles on a vehicle, with one positioned directly behind the other.

Teach Pendant: An input device which greatly facilitates the programming and positioning of a robot manipulator. The teach pendant allows the easy positioning of the manipulator tip throughout its workspace, and allows the user to save manipulator positions for subsequent use in programs.

Telnet: The standard program used to log in from one computer to another over an Ethernet connection.

Thermoplastic: A material that will repeatedly soften when heated and harden when cooled.

Thermosetting: A plastic which solidifies when first heated under pressure, and which cannot be remelted or remolded without destroying its original characteristics.

Thin Net Cable: A form of cabling used in Ethernet local-area networks. Thin Net cable uses coaxial connectors and cable with a characteristic impedance of 50 Ω (Ohms).

Thinning Algorithm: An image processing algorithm used to find the skeleton of a shape. A thinning algorithm is used in the path planning algorithm as part of the process of cleaning up the data received from the VSS.

Transducer: A device for converting a nonelectrical signal, such as pressure, light, heat, etc., into an electrical signal, or vice versa. In general, any device or element which converts an input signal into an output signal of a different form.

Transformation Matrix: A matrix used in a transformation operation. See homogeneous transformation.

Translation: Motion of a body in which all the points in the body follow parallel paths.

Transverse Axis: Axis perpendicular to the direction of travel of a vehicle.

Transverse Crack: A crack which is primarily oriented perpendicular to the direction of travel of the vehicle.

Triangulation: A method for measuring distances. In the ACSM, triangulation is used by the LSS to obtain road height information.

Uniformity Level: A parameter in the VSS crack detection algorithm. This parameter determines the number of comparisons made to determine whether or not a crack exists in a given tile.

Uninterruptible Power System: A power supply that includes a batter to maintain power in the event of a power outage. The UPS may also provide signal conditioning on the power signal.

Up-Milling: Method for cutting a surface with a rotating tool in which the direction of the tool rotation tends to push the device in the opposite direction of the tool travel.

Variable: A quantity that may assume a succession of values.

Variance: A measure of the spread or dispersion of a measurement away from the mean value (average) of the measurement.

V-Belt: An endless power-transmission belt with a trapezoidal cross section which runs in a pulley with a V-shaped groove; it transmits higher torque at less width and tension than a flat belt.

Vision Pixel: See pixel.

Vision Tile: A collection of 32x32 (1024) pixels. This is the base unit used in the detection of cracks.

VMEbus: A popular and powerful computer system bus architecture developed by Motorola. The VME bus is an open system with a high bandwidth, and has recently been standardized as IEEE Standard for a Versatile Backplane Bus: VMEbus (ANSI/IEEE 1014-1987).

VSB: VME Subsystem Bus. An extension to the VME bus which allows the expansion of local processor resources, leaving the system bus open for access to global memory and system I/O or for interprocessor communication on a multiprocessing system.

Workstation: A type of computer used for engineering applications, such as CAD/CAM, software development, and other types of applications that require a moderate amount of computing power and relatively high quality graphics capability.

World Coordinate System: A Cartesian coordinate system that is fixed with respect to the world. This coordinate system is the coordinate system in which all other moving and fixed coordinate are defined.

World Frame: See World Coordinate System.

Yaw: Rotation of a body about a vertical axis

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Appendix A: Detailed Drawings

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1.5.2 Inside Pipe
1.5.3 Outside Pipe
1.5.4 Bearing Rod
1.5.5 Insulating Washer 1
1.5.6 Insulating Washer 2
1.5.7 Heat Transfer Fins
1.5.8 Cone
1.5.9 Cone-Stop
1.5.10 Cone Support/Spring Holder
1.5.11 Hot Oil Inlet
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1.5.15 Rotation Block
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1.5.31 Applicator Plate
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1.5.33 Flex Cable Adapter
1.5.34 Adapter Drive Shaft
1.5.35 Squeegee Plate Lock
1.5.36 Squeegee Components
1.5.37 Floater Assembly
1.5.38 Floater A
1.5.39 Floater B

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2.1 Control Booth
2.2 Control Booth Details

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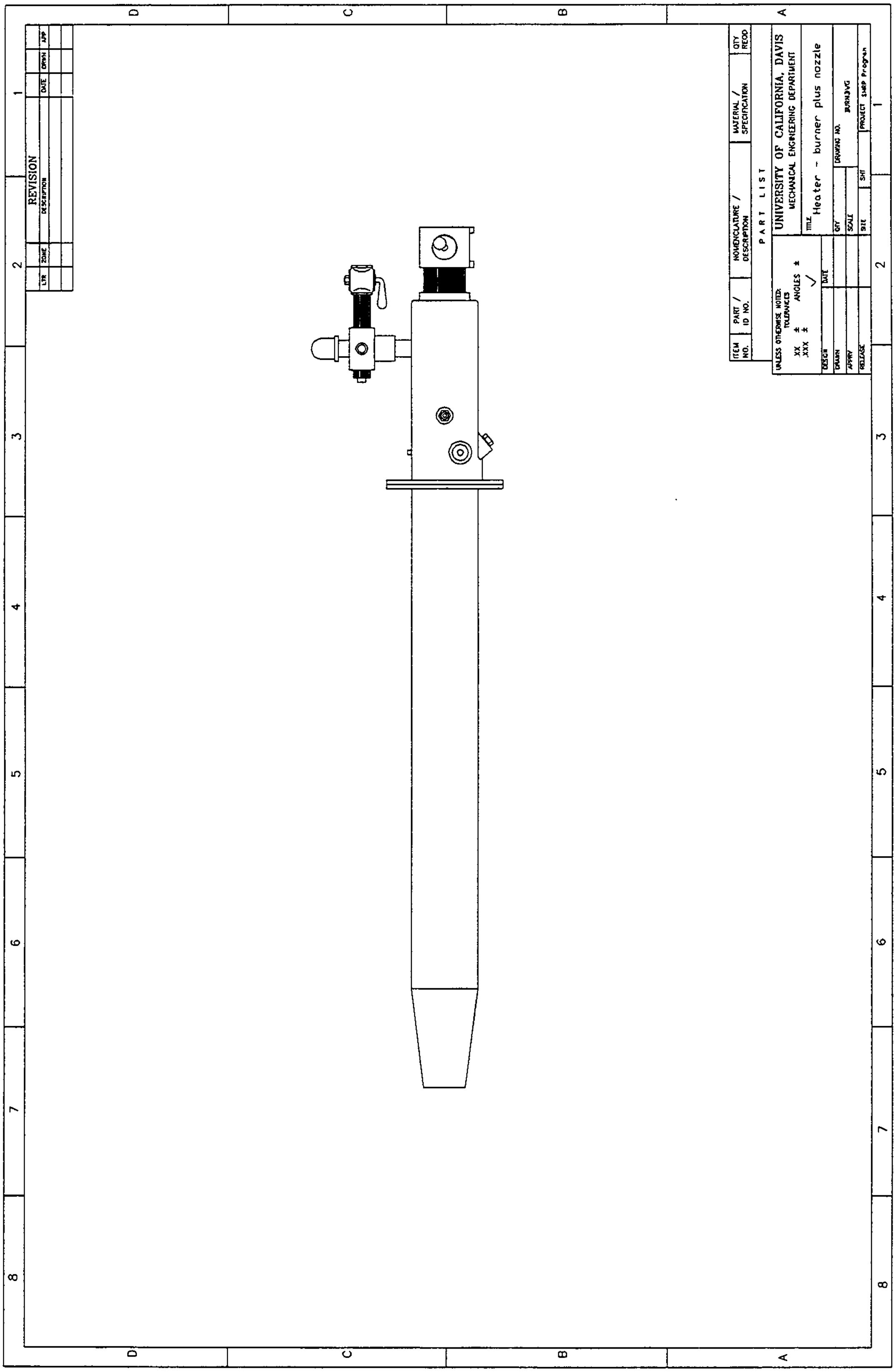
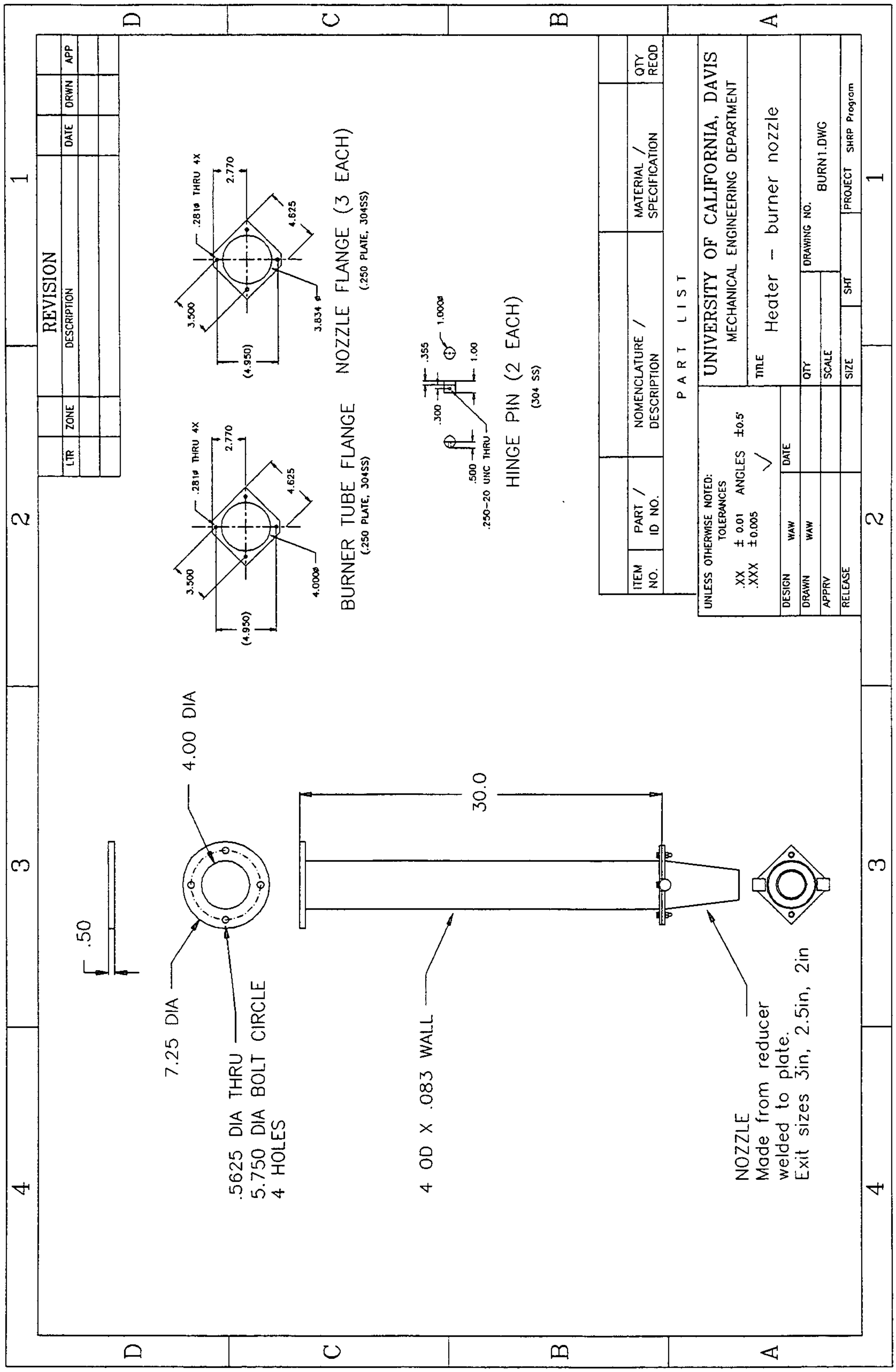
3.1 Production System
3.1.1 Hydraulic Cylinder
3.1.2 Sliding Cable Trays Assembly
3.1.3 Sliding Cable Trays
3.1.4 Router Cart Mount Bracket
3.1.5 Router and Cart Mount Assembly
3.1.6 LRPS/APS Assembly - Top View
3.1.7 LRPS/APS Assembly - Side View

A.2 - Drawings


REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Heater - burner plus nozzle

Drawing 1.1.1



REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
.50
7.25 DIA
4.00 DIA
.5625 DIA THRU
5.750 DIA BOLT CIRCLE
4 HOLES
30.0
4 OD X .083 WALL
NOZZLE
Made from reducer
welded to plate.
Exit sizes 3in, 2.5in, 2in
BURNER TUBE FLANGE
(.250 PLATE, 304SS)
NOZZLE FLANGE (3 EACH)
(.250 PLATE, 304SS)
.281ø THRU 4X
2.770
4.625
3.500
(4.950)
4.000ø
3.834 ø
HINGE PIN (2 EACH)
(304 SS)
.355
1.000ø
1.00
.300
.500
.250-20 UNC THRU
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
UNLESS OTHERWISE NOTED:
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.XXX ± 0.005
ANGLES ±0.5°
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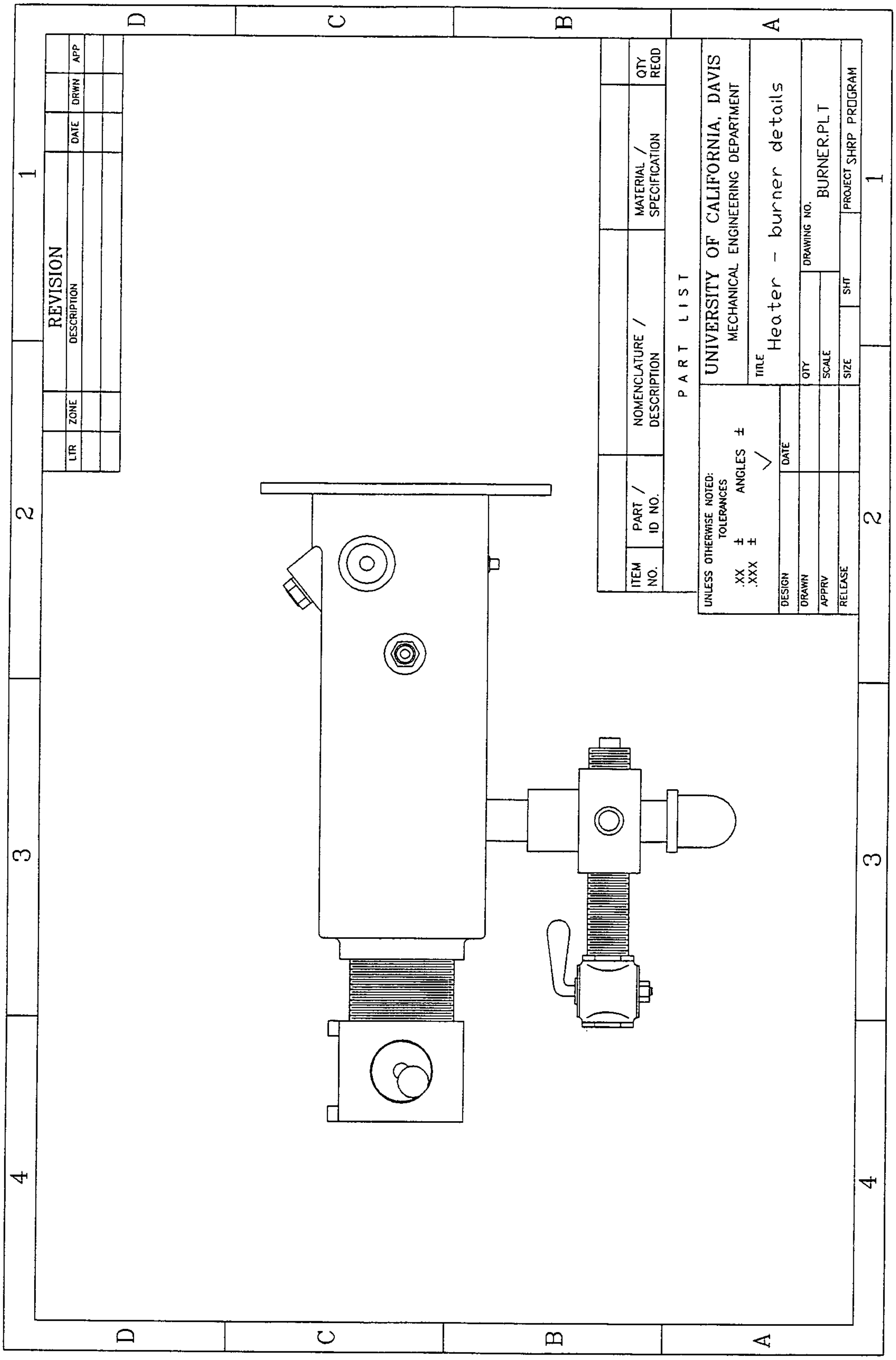
Heater - burner nozzle
DESIGN WAW
DRAWN WAW
APPRV
RELEASE
DATE
QTY
SCALE
SIZE
SHT
DRAWING NO.
BURN1.DWG
PROJECT SHRP Program

Drawing 1.1.2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UNLESS OTHERWISE NOTED: TOLERANCES
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ANGLES ±
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
Heater - burner details
DESIGN
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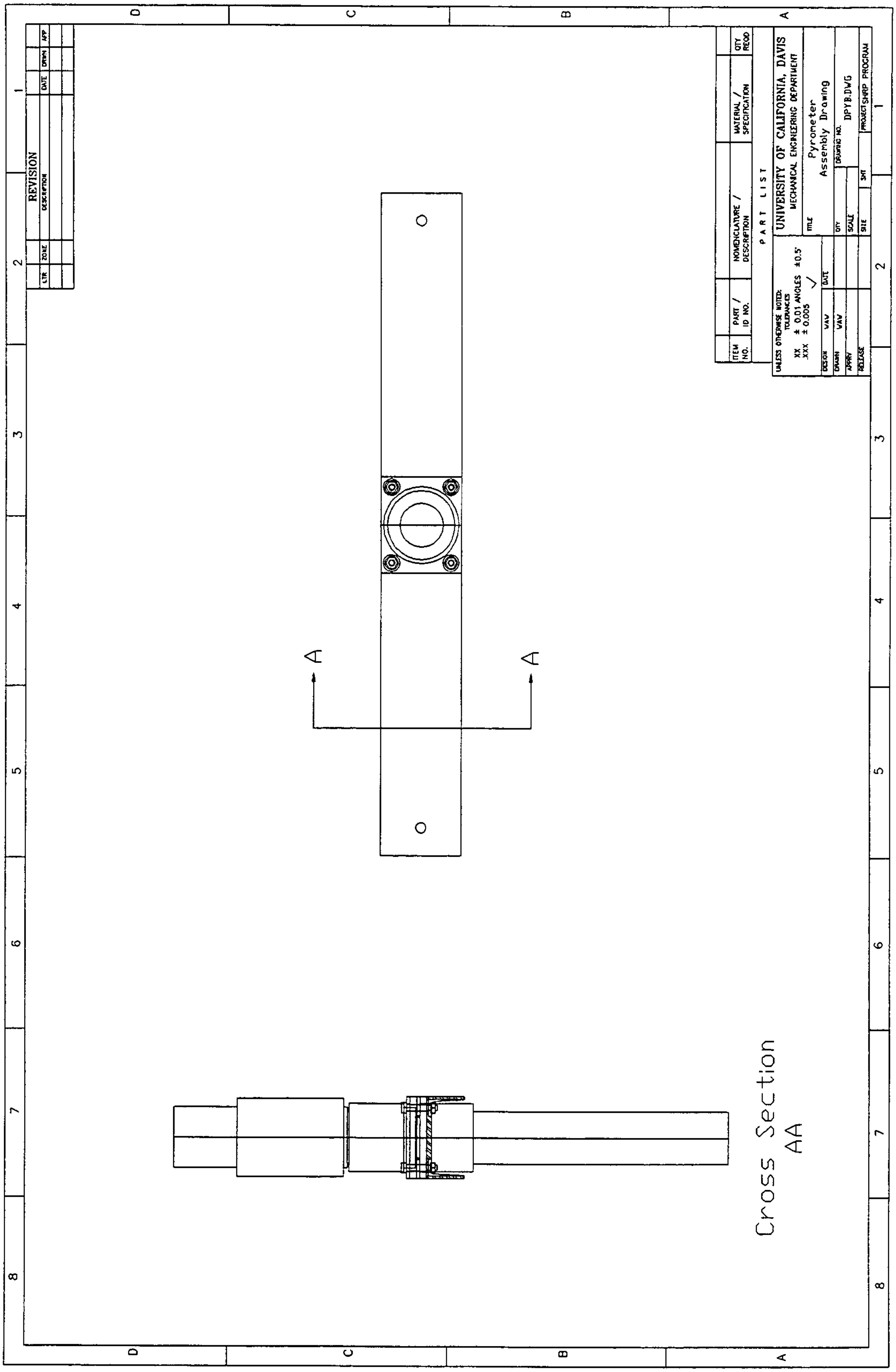
APPRV
RELEASE
DATE
QTY
SCALE
SIZE
SHT
DRAWING NO.
BURNER.PLT
PROJECT SHRP PROGRAM

Drawing 1.1.3


REVISION
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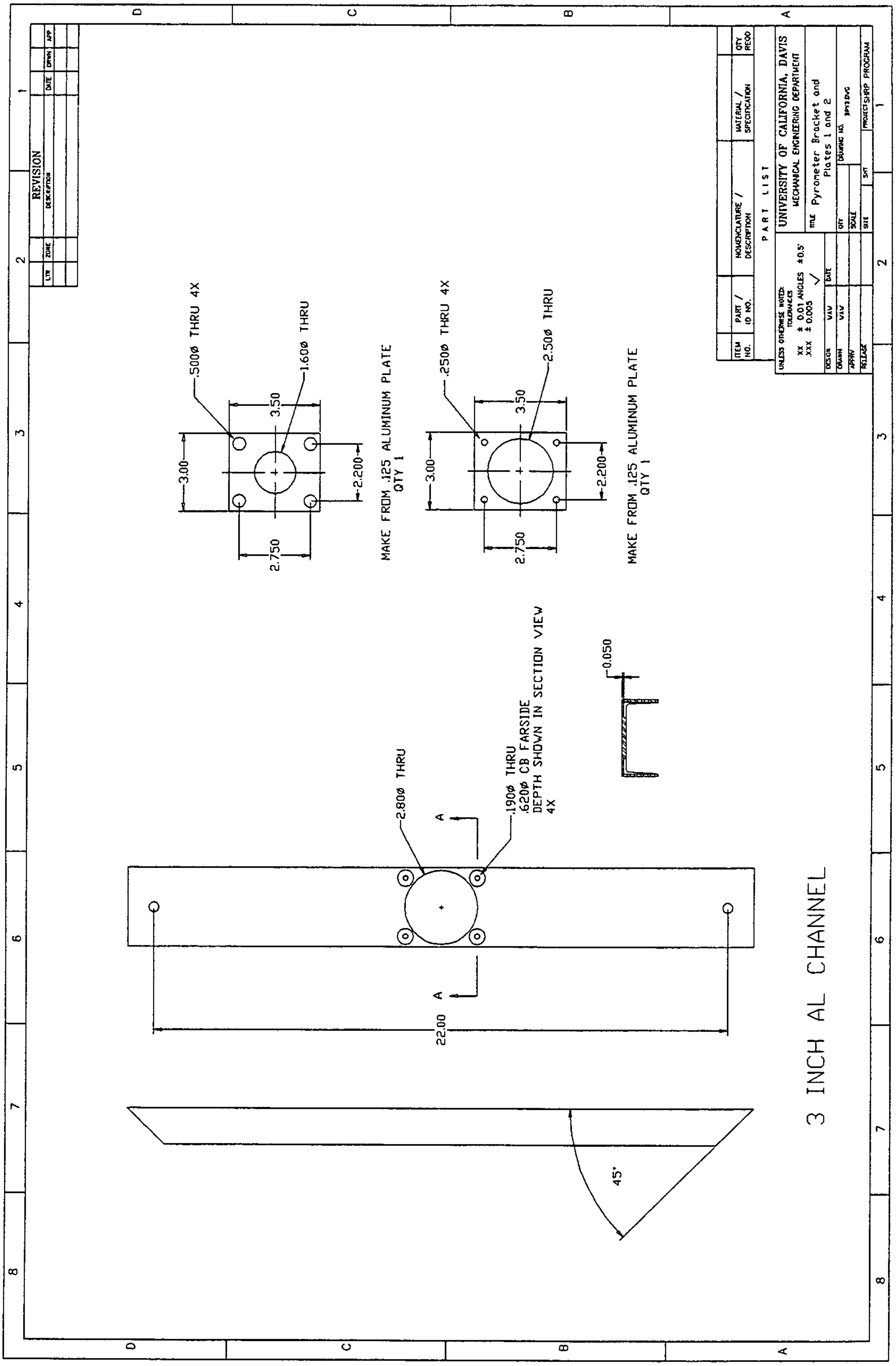
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Pyrometer
Assembly Drawing
DPYB.DWG
PROJECT SHRP PROGRAM
Cross Section
AA

Drawing 1.1.4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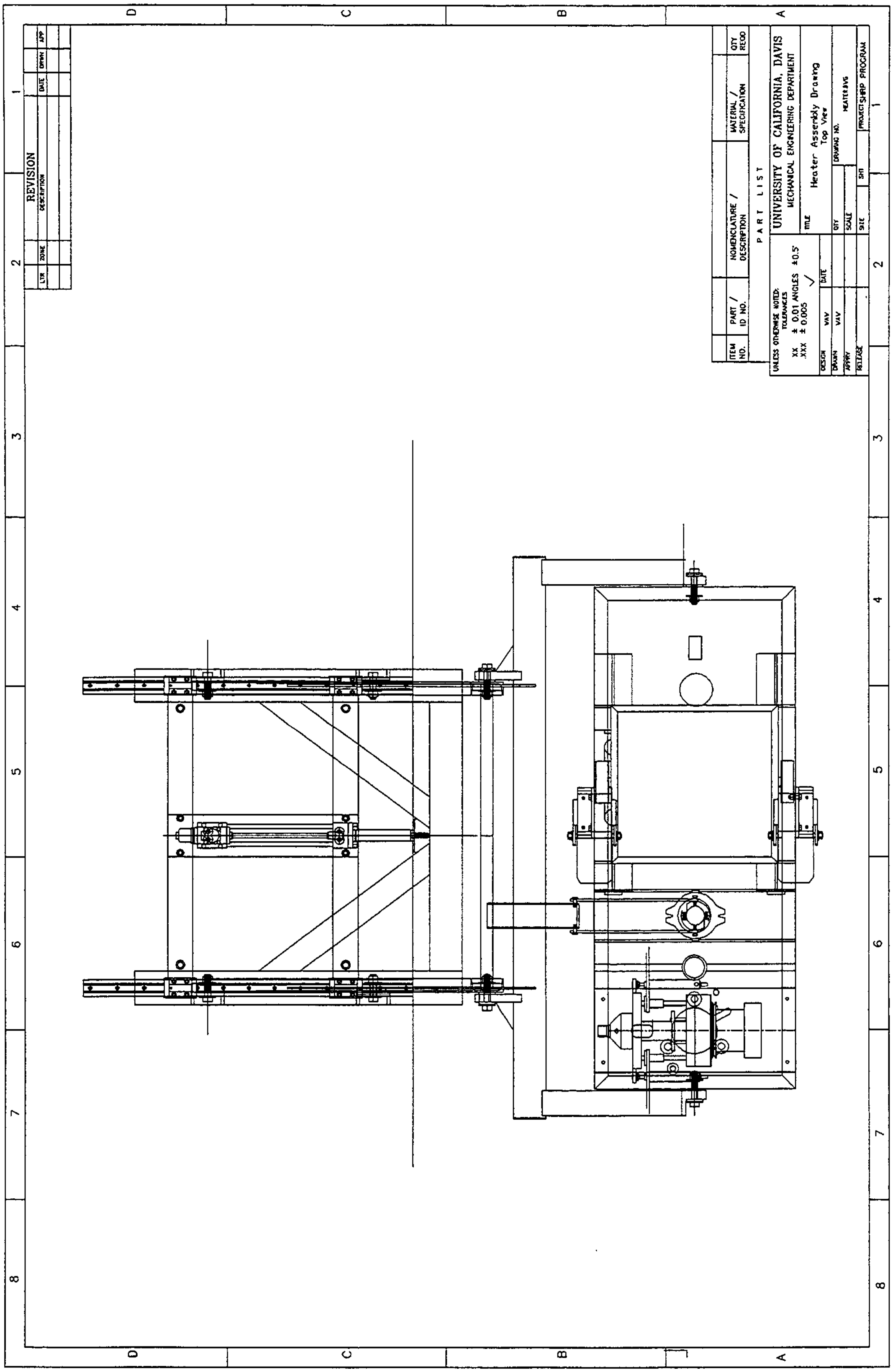
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Pyrometer Bracket and Plates 1 and 2
.500Ø THRU 4X
1.60Ø THRU
MAKE FROM .125 ALUMINUM PLATE
QTY 1
.250Ø THRU 4X
2.50Ø THRU
MAKE FROM .125 ALUMINUM PLATE
QTY 1
2.80Ø THRU
.190Ø THRU
.620Ø CB FARSIDE
DEPTH SHOWN IN SECTION VIEW
4X
0.050
22.00
45°
3 INCH AL CHANNEL

Drawing 1.1.5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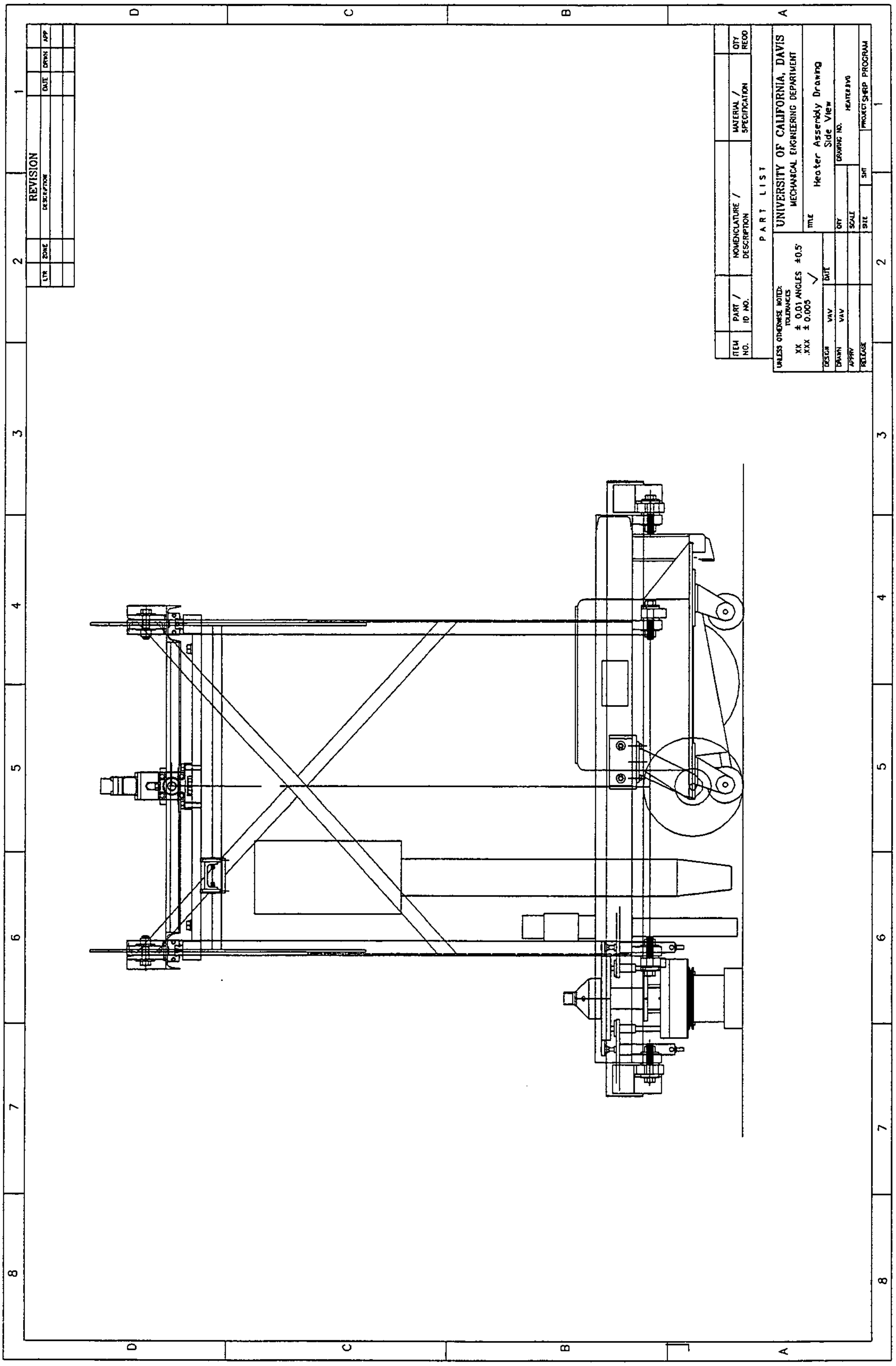
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Heater Assembly Drawing
Top View
SHRP PROGRAM

Drawing 1.1.6


REVISION
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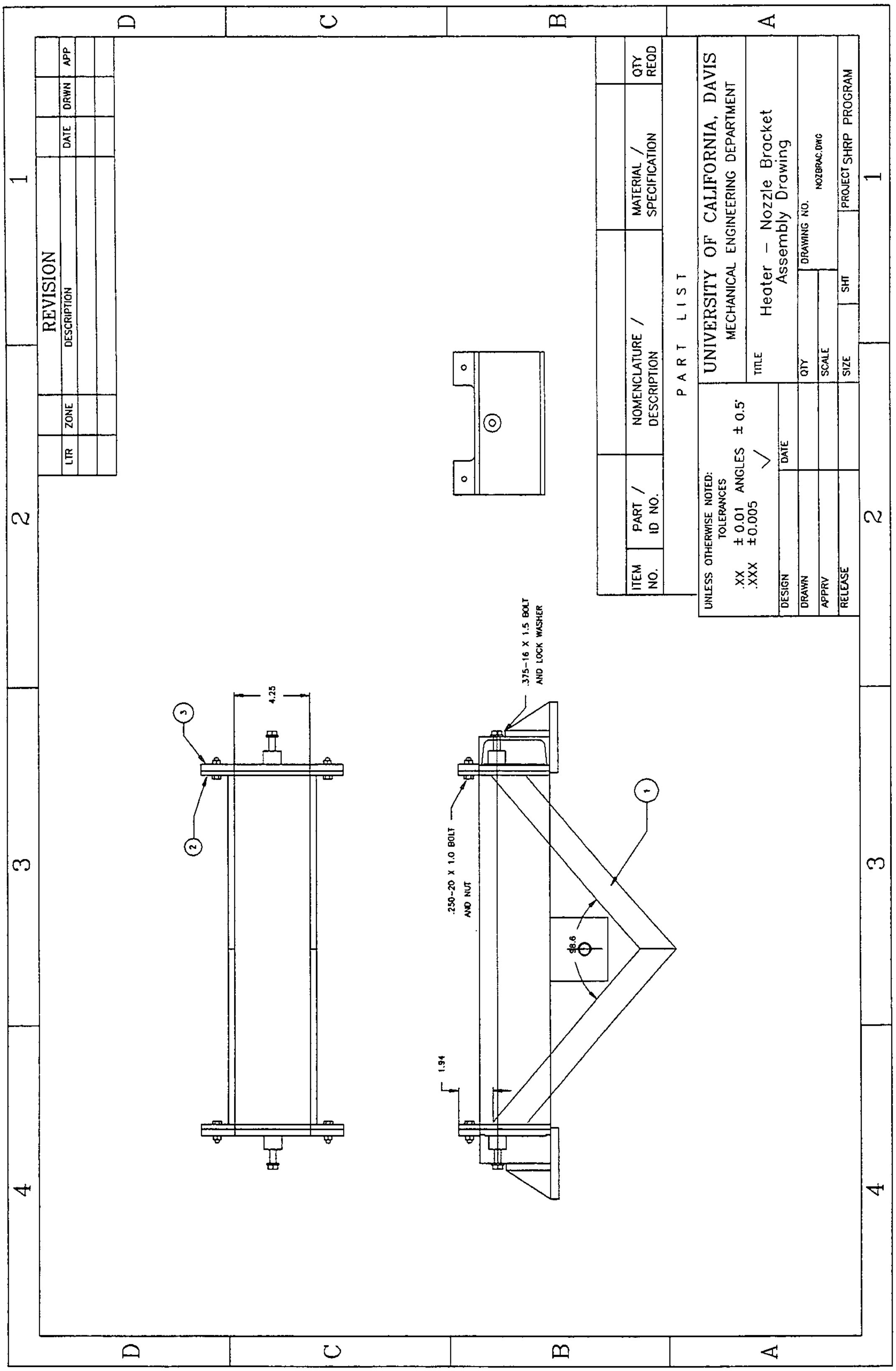
MECHANICAL ENGINEERING DEPARTMENT
Heater Assembly Drawing
Side View
PROJECT SHRP PROGRAM

Drawing 1.1.7


UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Heater – Nozzle Bracket
Assembly Drawing
NOZBRAC.DWG
PROJECT SHRP PROGRAM
PART LIST
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
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DESCRIPTION
DATE
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UNLESS OTHERWISE NOTED:
TOLERANCES
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.XXX ± 0.005
DESIGN
DRAWN
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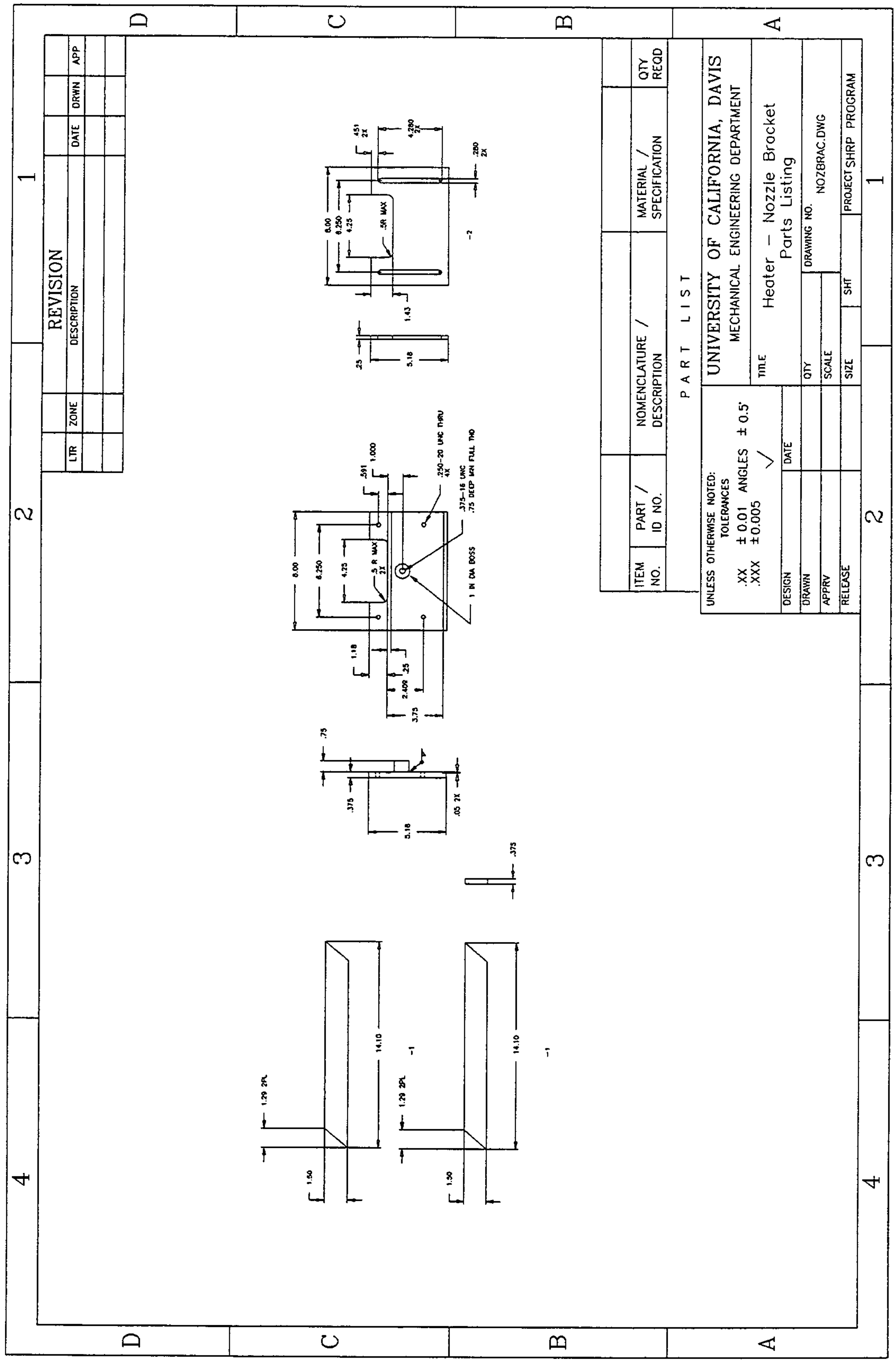
RELEASE
DATE
QTY
SCALE
SIZE
SHT
TITLE
DRAWING NO.
.375-16 X 1.5 BOLT
AND LOCK WASHER
.250-20 X 1.0 BOLT
AND NUT
4.25
1.94

Drawing 1.1.8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NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
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P A R T L I S T
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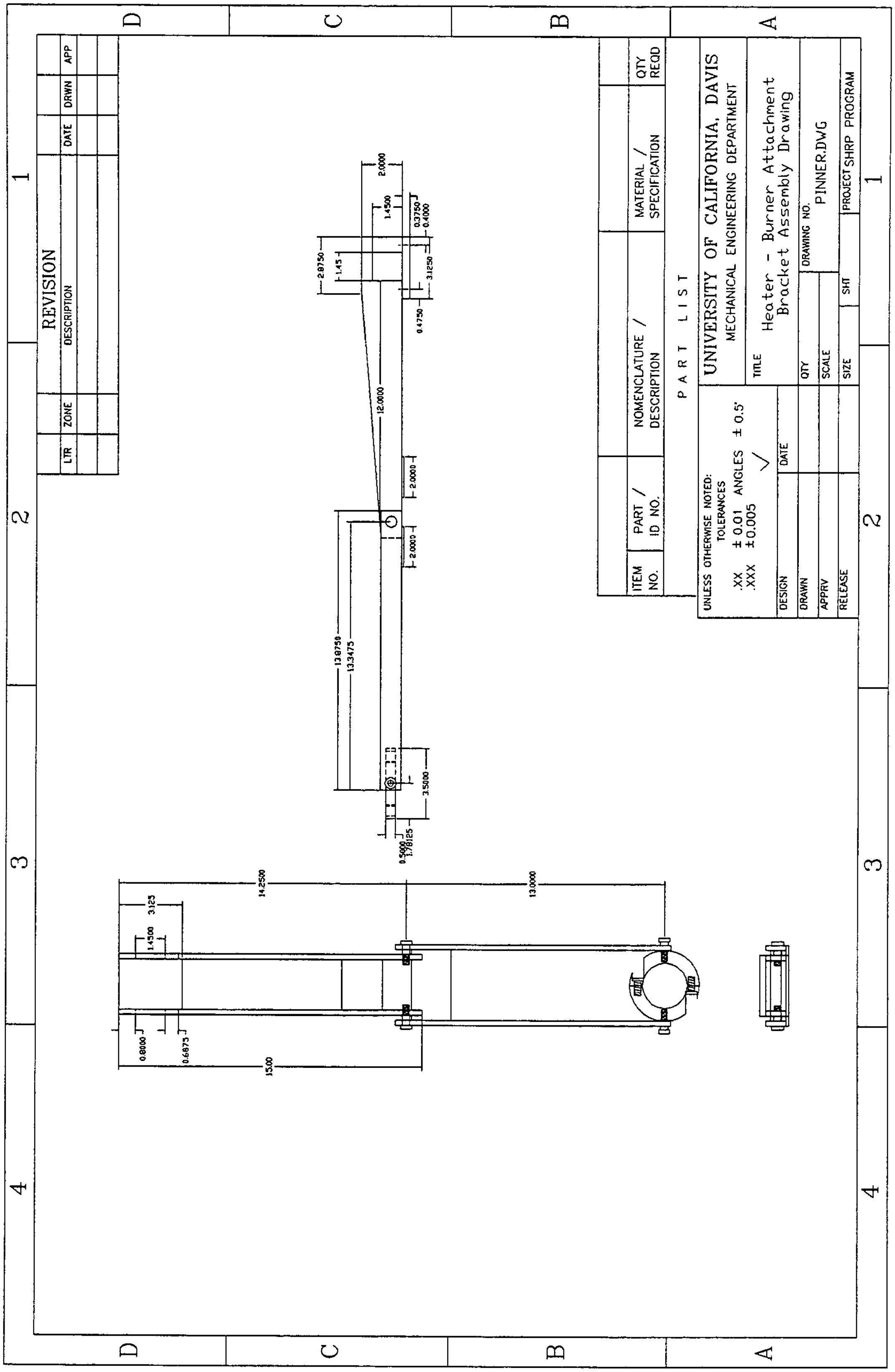
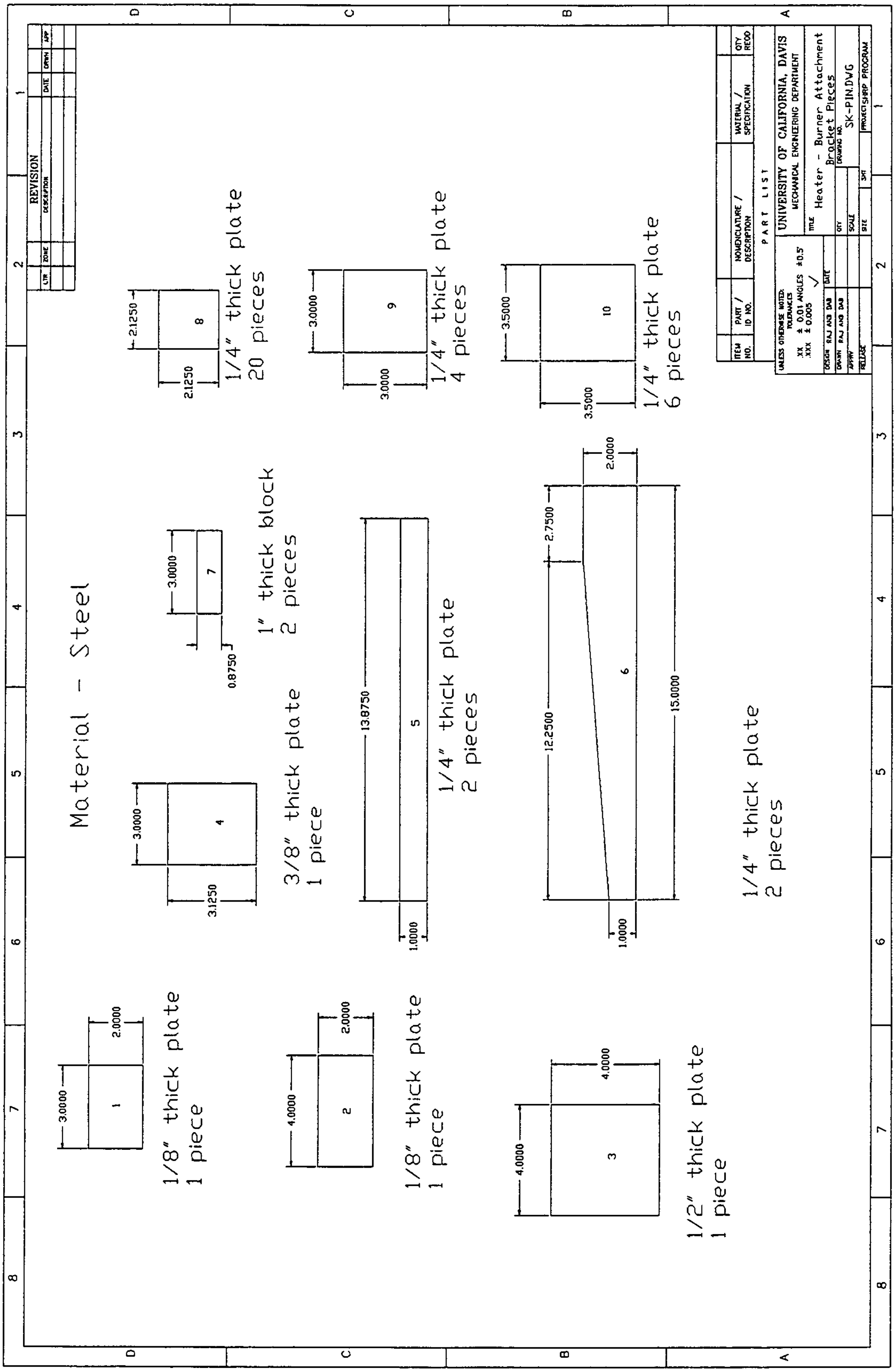
APPRV
RELEASE
DATE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
Heater – Nozzle Brocket
Parts Listing
DRAWING NO.
NOZBRAC.DWG
QTY
SCALE
SIZE
SHT
PROJECT SHRP PROGRAM

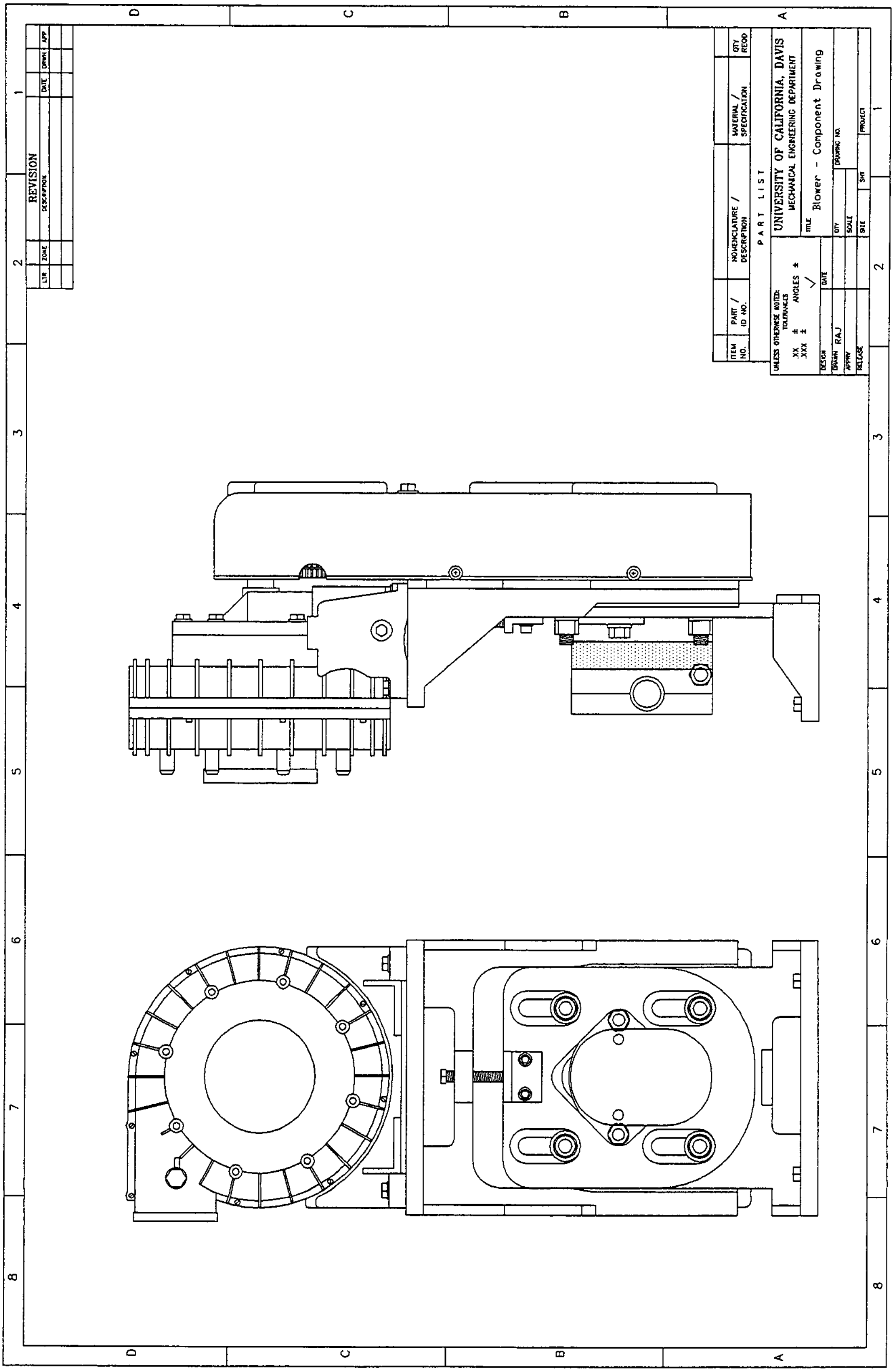
Drawing 1.1.9



Drawing 1.1.10



Drawing 1.1.11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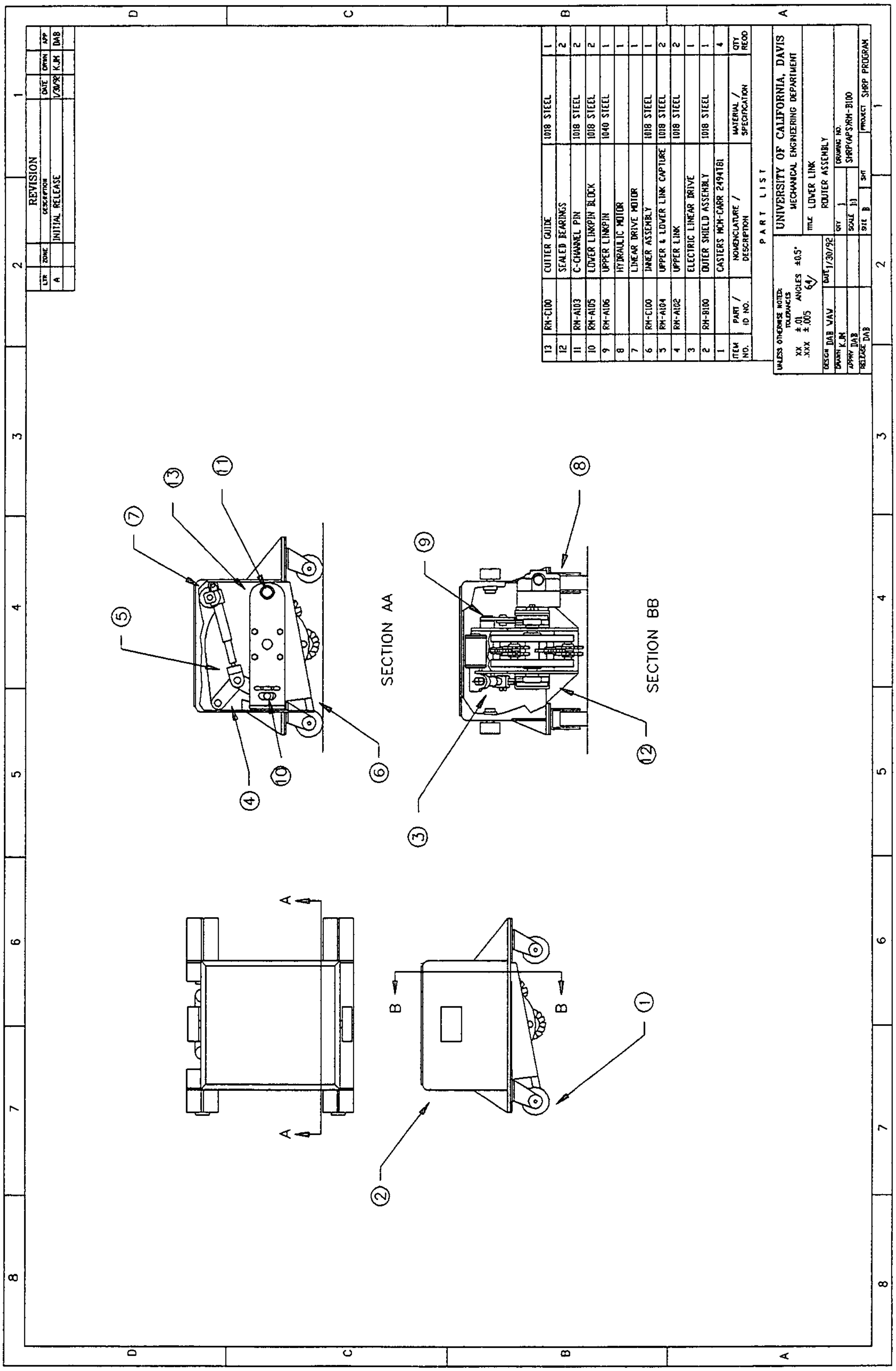
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Blower - Component Drawing
RAJ

Drawing 1.2.1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SECTION AA
SECTION BB
PART LIST
13 RM-C100 CUTTER GUIDE 1018 STEEL 1
12 SEALED BEARINGS 2
11 RM-A103 C-CHANNEL PIN 1018 STEEL 2
10 RM-A105 LOWER LINKPIN BLOCK 1018 STEEL 2
9 RM-A106 UPPER LINKPIN 1040 STEEL 1
8 HYDRAULIC MOTOR 1
7 LINEAR DRIVE MOTOR 1
6 RM-C100 INNER ASSEMBLY 1018 STEEL 1
5 RM-A104 UPPER & LOWER LINK CAPTURE 1018 STEEL 2
4 RM-A102 UPPER LINK 1018 STEEL 2
3 ELECTRIC LINEAR DRIVE 1
2 RM-B100 OUTER SHIELD ASSEMBLY 1018 STEEL 1
1 CASTERS MCM-CARR 2494T81 4
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.XXX ±.005
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APPRV DAB
RELEASE DAB
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE LOWER LINK
ROUTER ASSEMBLY
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SIZE B
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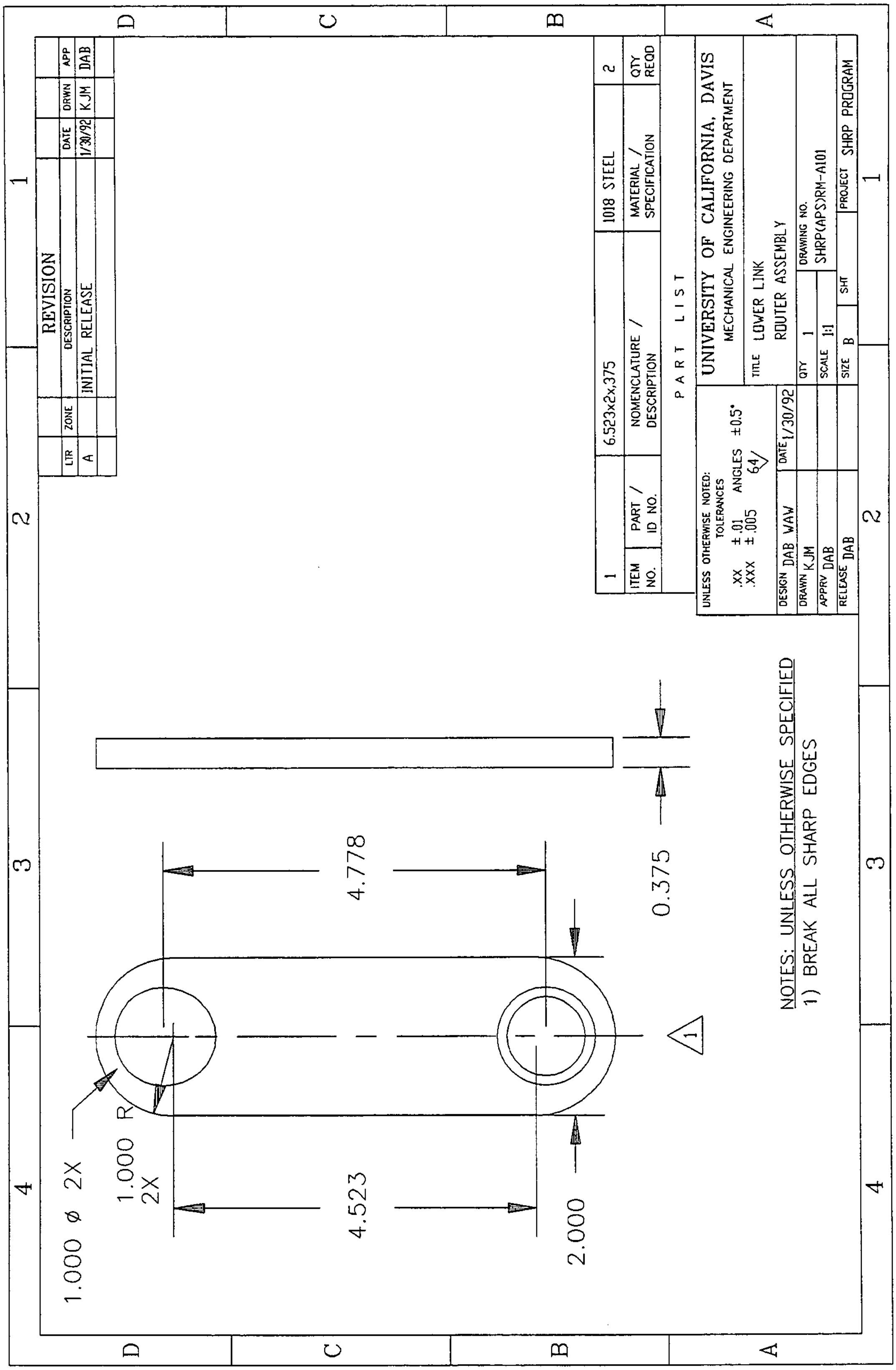
PROJECT SHRP PROGRAM

Drawing 1.3.1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DESCRIPTION
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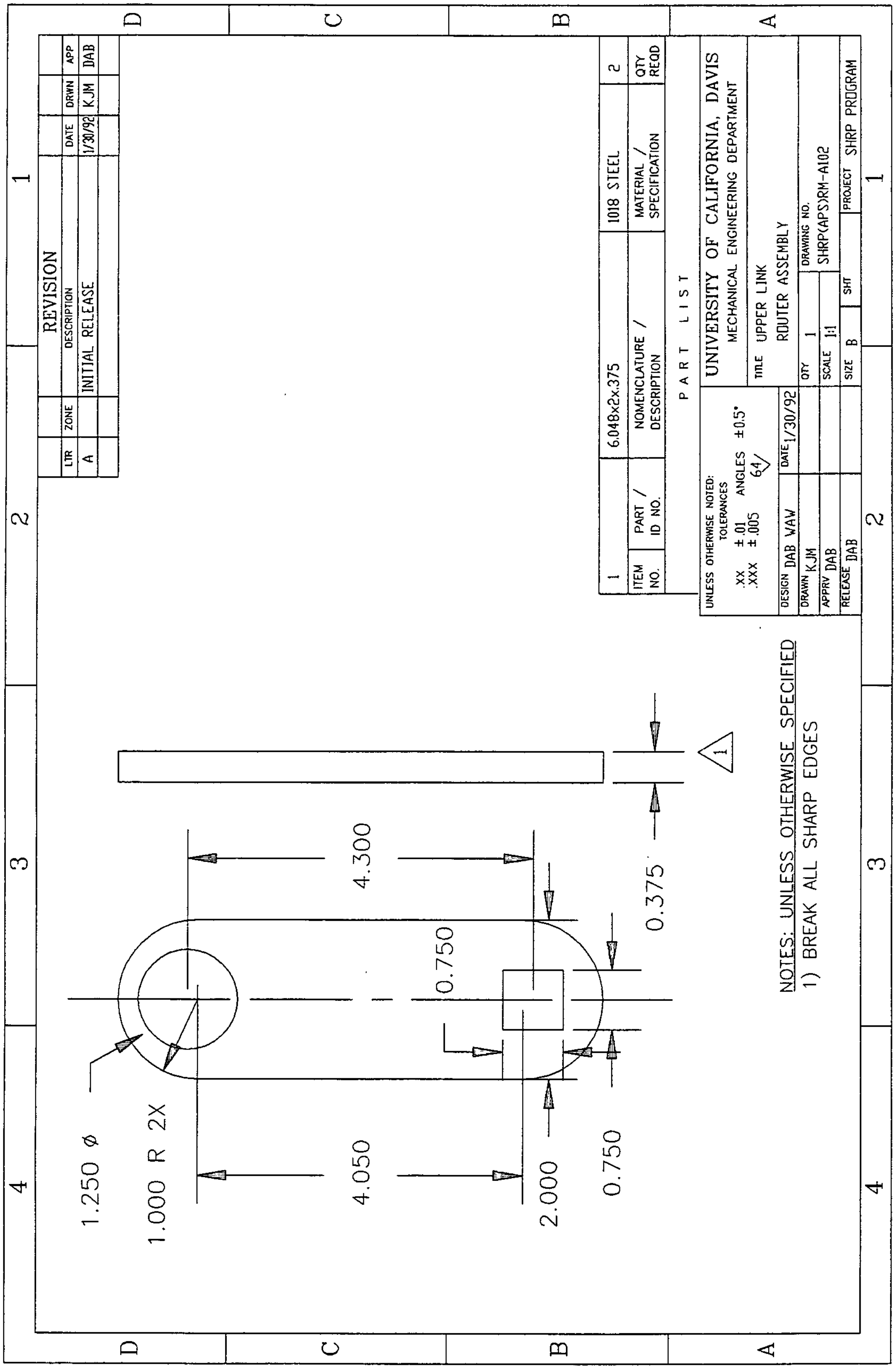
KJM
DAB
1.000 ø 2X
1.000 R
2X
4.523
4.778
2.000
0.375
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
1
6.523x2x.375
1018 STEEL
2
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.01
.XXX ±.005
ANGLES ±0.5°
64
DESIGN DAB WAW
DATE 1/30/92
DRAWN KJM
APPRV DAB
RELEASE DAB
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE LOWER LINK
ROUTER ASSEMBLY
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)RM-A101
PROJECT SHRP PROGRAM

Drawing 1.3.2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1 6.048x2x.375 1018 STEEL 2
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.01
.XXX ±.005
ANGLES ±0.5°
64
DESIGN DAB WAW
DATE 1/30/92
DRAWN KJM
APPRV DAB
RELEASE DAB
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE UPPER LINK
ROUTER ASSEMBLY
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)RM-A102
PROJECT SHRP PROGRAM
1.250 ϕ
1.000 R 2X
4.050
4.300
2.000
0.750
0.750
0.375
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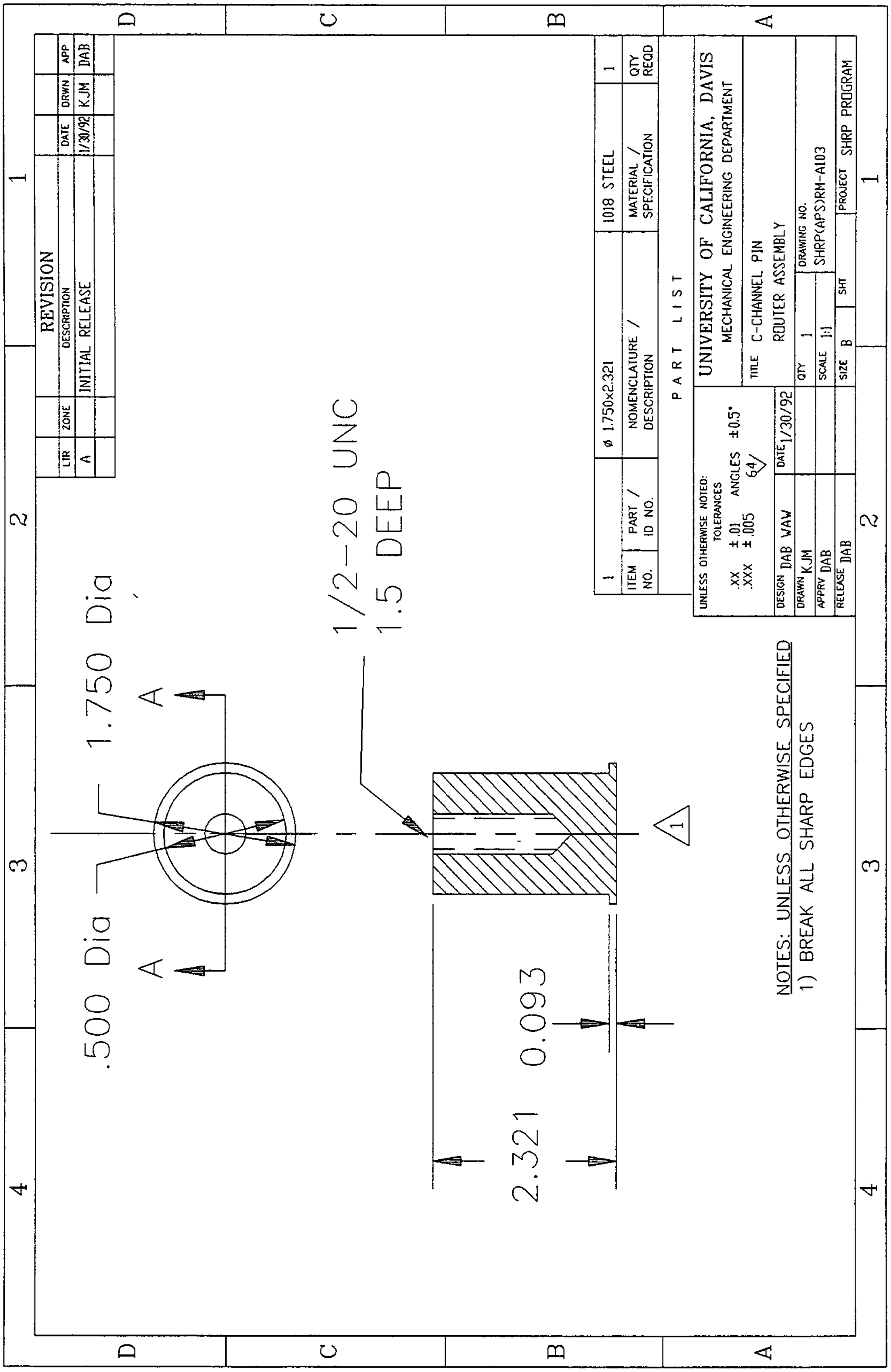
1) BREAK ALL SHARP EDGES

Drawing 1.3.3



REVISION
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A INITIAL RELEASE 1/30/92 KJM DAB
.500 Dia
1.750 Dia
A
A
1/2-20 UNC
1.5 DEEP
2.321
0.093
1
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
1 ø 1.750x2.321 1018 STEEL 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .01
.XXX ± .005
ANGLES ±0.5°
64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE C-CHANNEL PIN
ROUTER ASSEMBLY
DESIGN DAB WAW
DATE 1/30/92
DRAWN KJM
APPRV DAB
RELEASE DAB
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SIZE B
SHT
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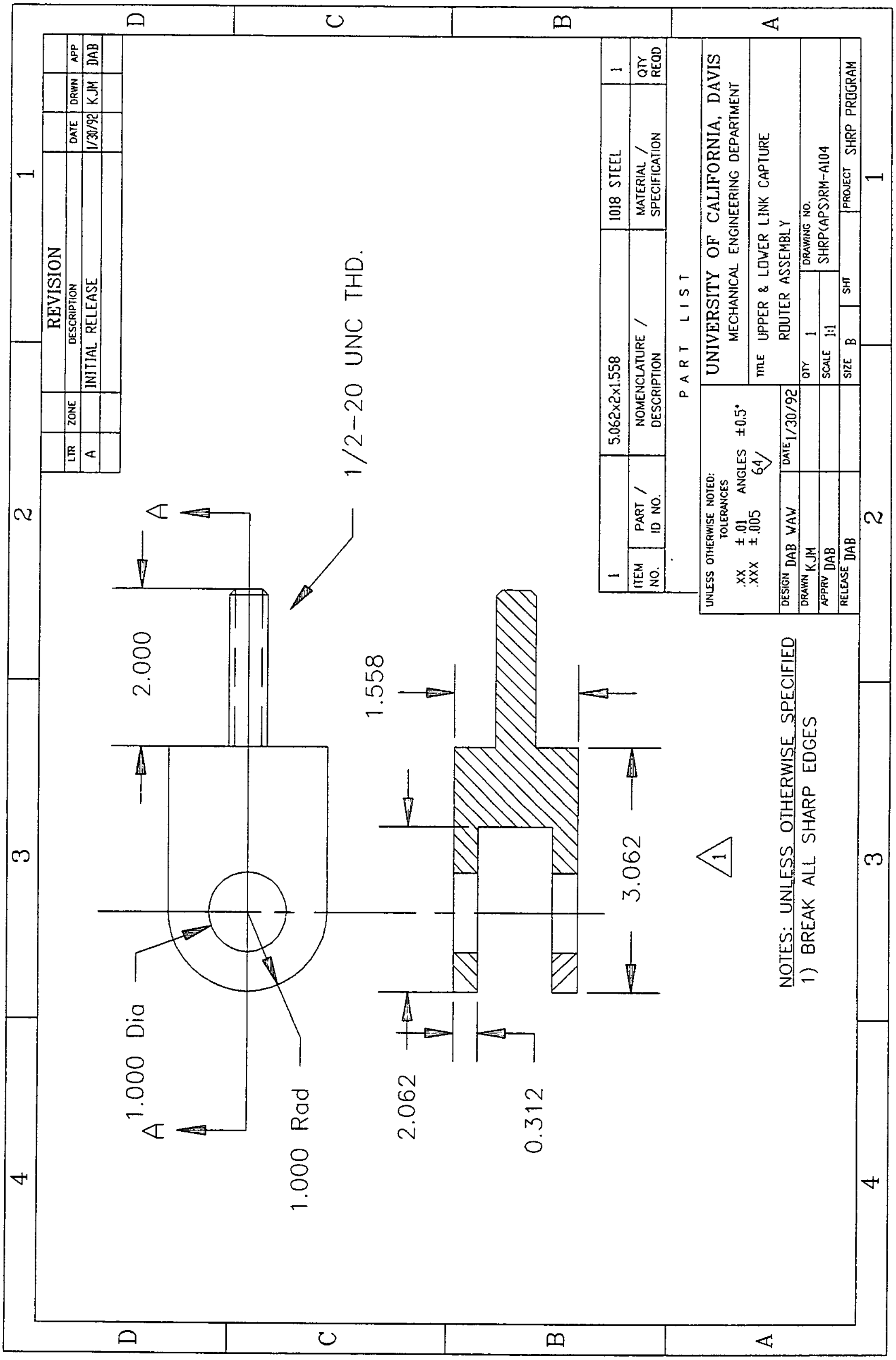
PROJECT SHRP PROGRAM

Drawing 1.3.4



REVISION
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1/2-20 UNC THD.
2.000
1.558
3.062
2.062
0.312
1.000 Dia
1.000 Rad
A
1
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
1 | 5.062x2x1.558 | 1018 STEEL | 1
ITEM NO. | PART / ID NO. | NOMENCLATURE / DESCRIPTION | MATERIAL / SPECIFICATION | QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.01 ANGLES ±0.5°
.XXX ±.005
64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE UPPER & LOWER LINK CAPTURE ROUTER ASSEMBLY
DESIGN DAB WAV DATE 1/30/92
DRAWN KJM
APPRV DAB
RELEASE DAB
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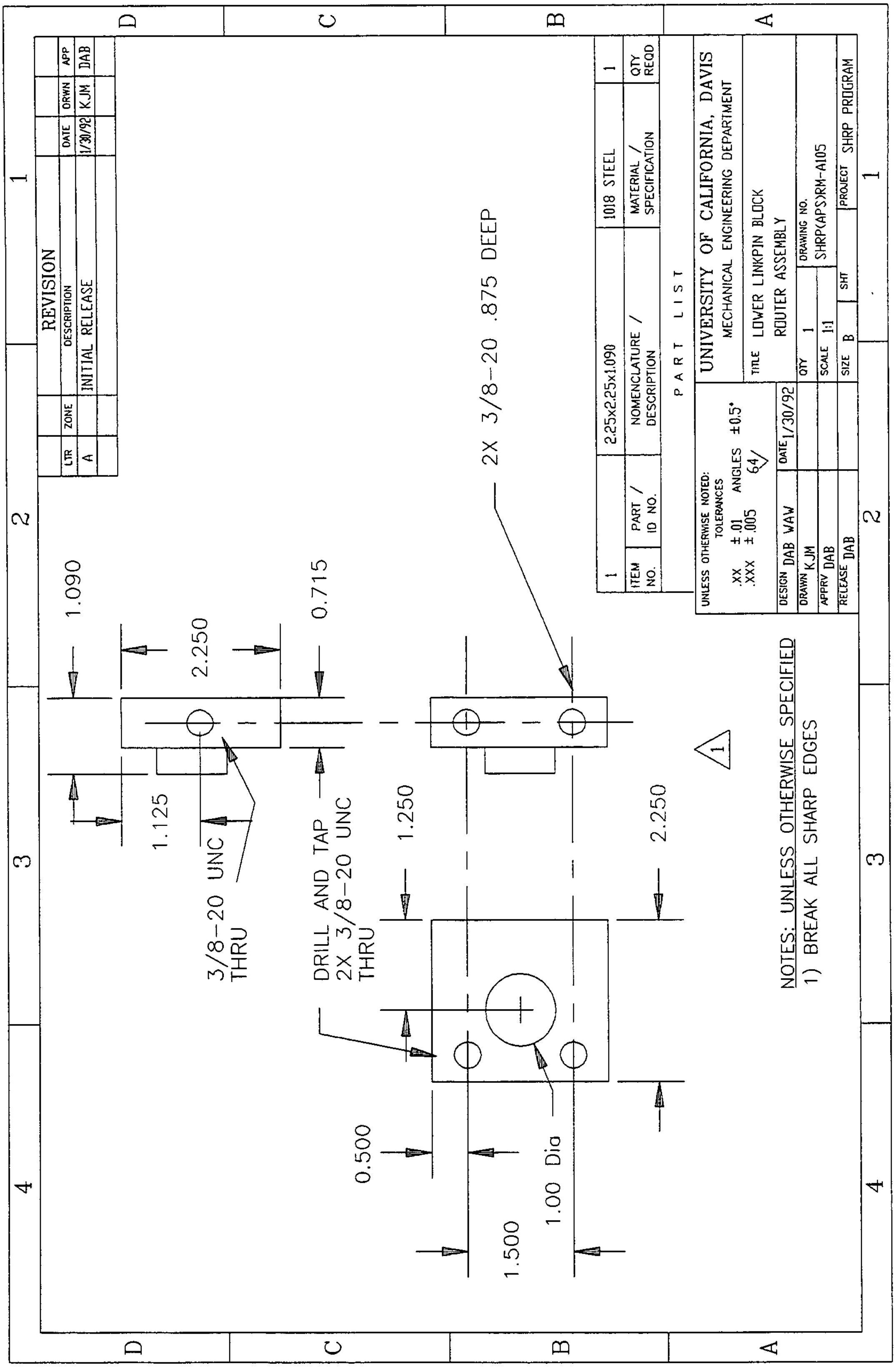
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)RM-A104
PROJECT SHRP PROGRAM

Drawing 1.3.5


REVISION
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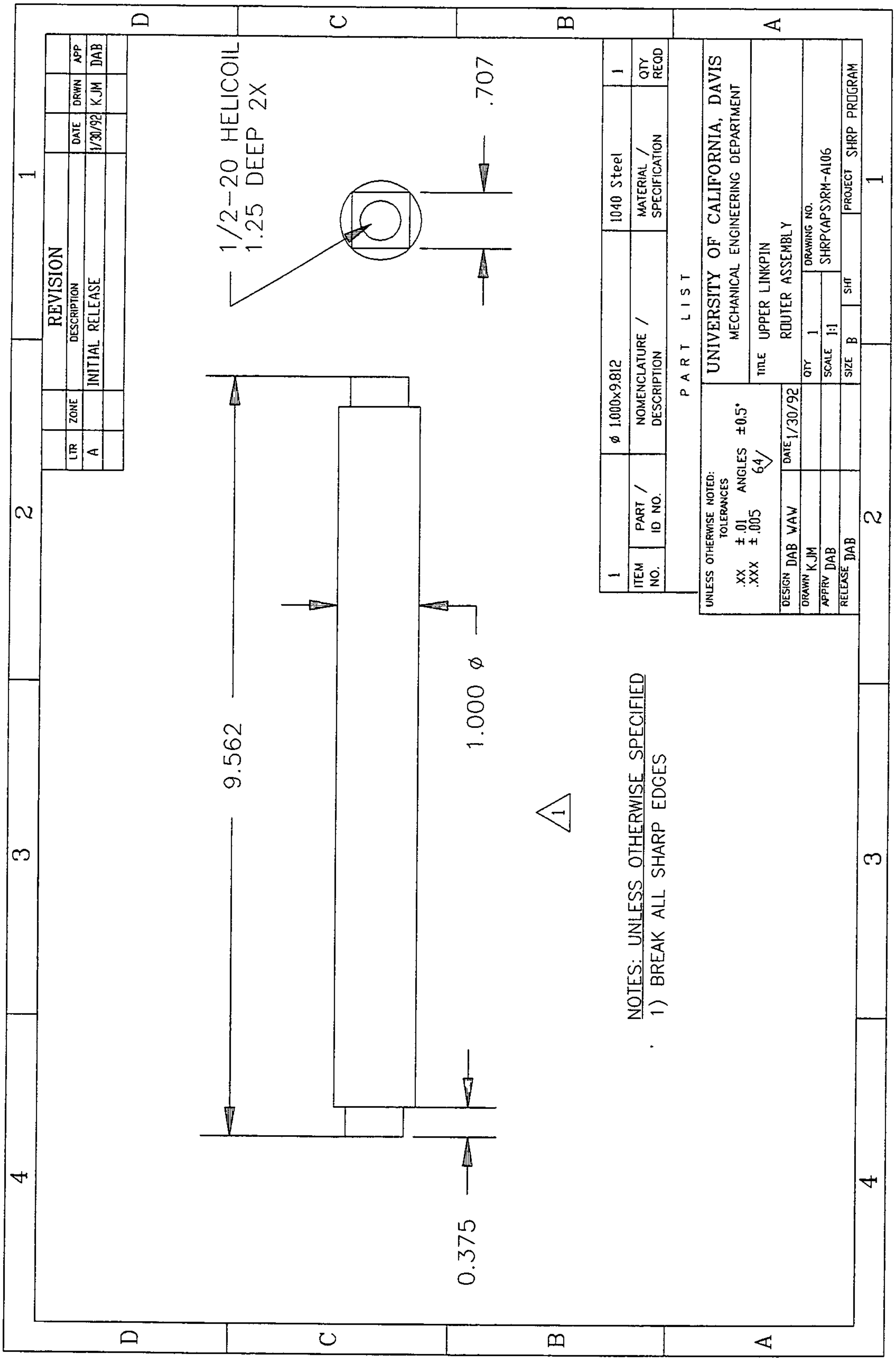
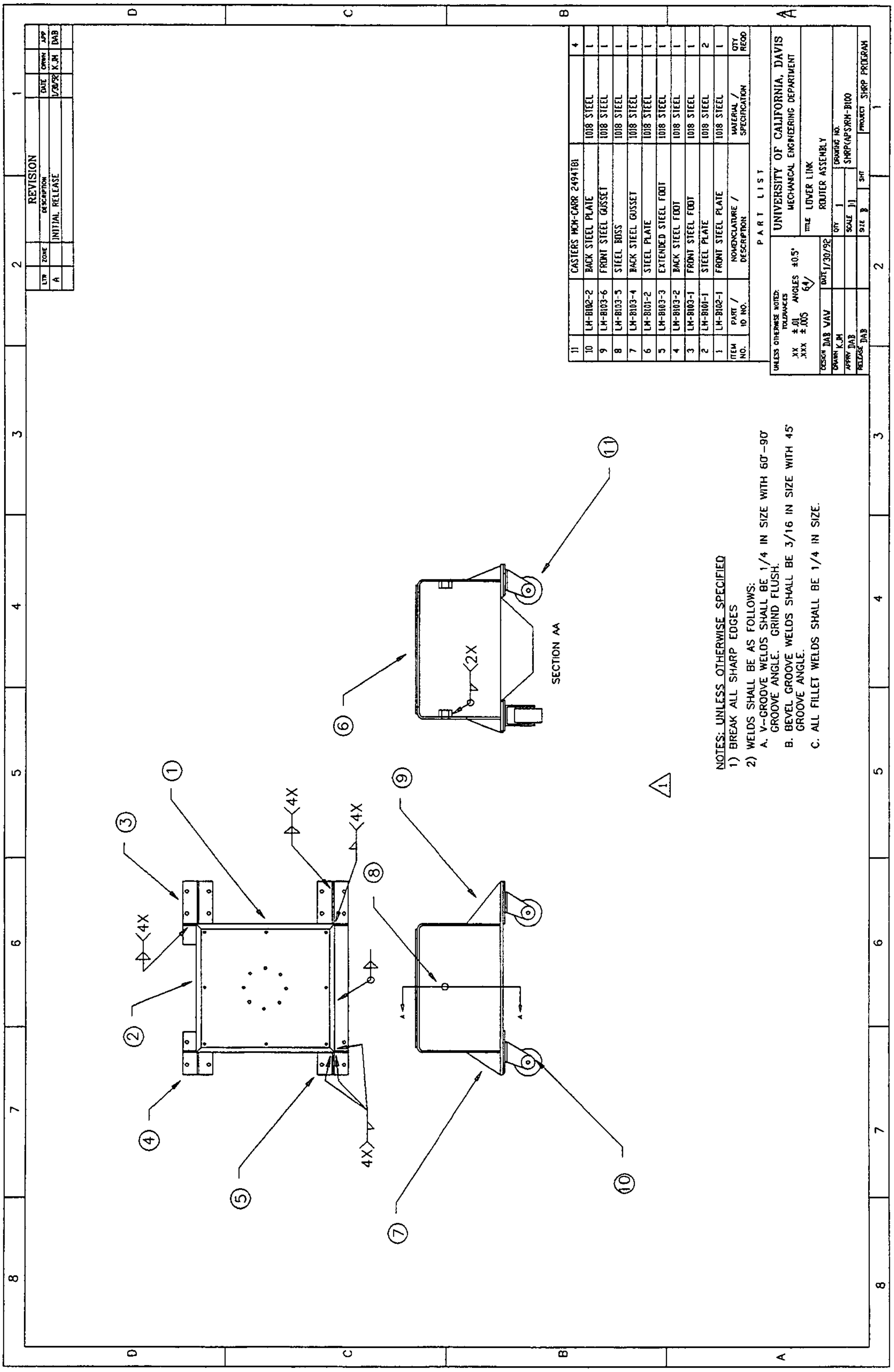
DESCRIPTION
DATE
DRWN
APP
A
INITIAL RELEASE
1/30/92
KJM
DAB
1.090
2.250
0.715
1.125
3/8-20 UNC THRU
DRILL AND TAP 2X 3/8-20 UNC THRU
1.250
2.250
2X 3/8-20 .875 DEEP
0.500
1.00 Dia
1.500
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
1
2.25x2.25x1.090
1018 STEEL
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
P A R T L I S T
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .01
.XXX ± .005
ANGLES ±0.5°
DESIGN DAB WAW
DRAWN KJM
APPRV DAB
RELEASE DAB
DATE 1/30/92
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE LOWER LINKPIN BLOCK ROUTER ASSEMBLY
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)RM-A105
PROJECT SHRP PROGRAM

Drawing 1.3.6

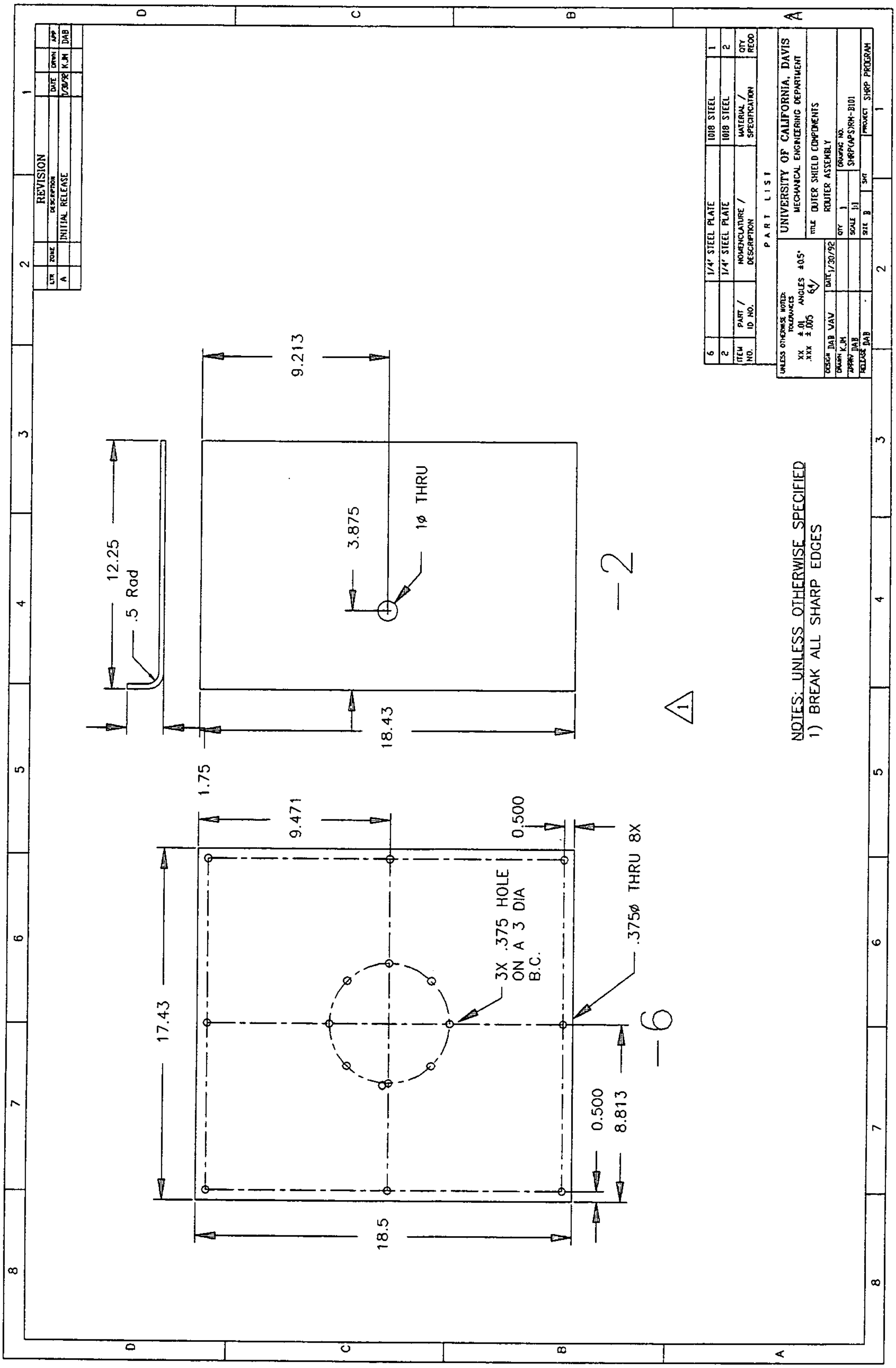


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 1/30/92 KJM DAB
1/2-20 HELICOIL
1.25 DEEP 2X
.707
9.562
1.000 ⌀
0.375
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
1
1 ⌀ 1.000x9.812 1040 Steel 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.01
.XXX ±.005
ANGLES ±0.5°
64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
DESIGN DAB WAW
DATE 1/30/92
TITLE UPPER LINKPIN
ROUTER ASSEMBLY
DRAWN KJM
APPRV DAB
RELEASE DAB
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)RM-A106
PROJECT SHRP PROGRAM

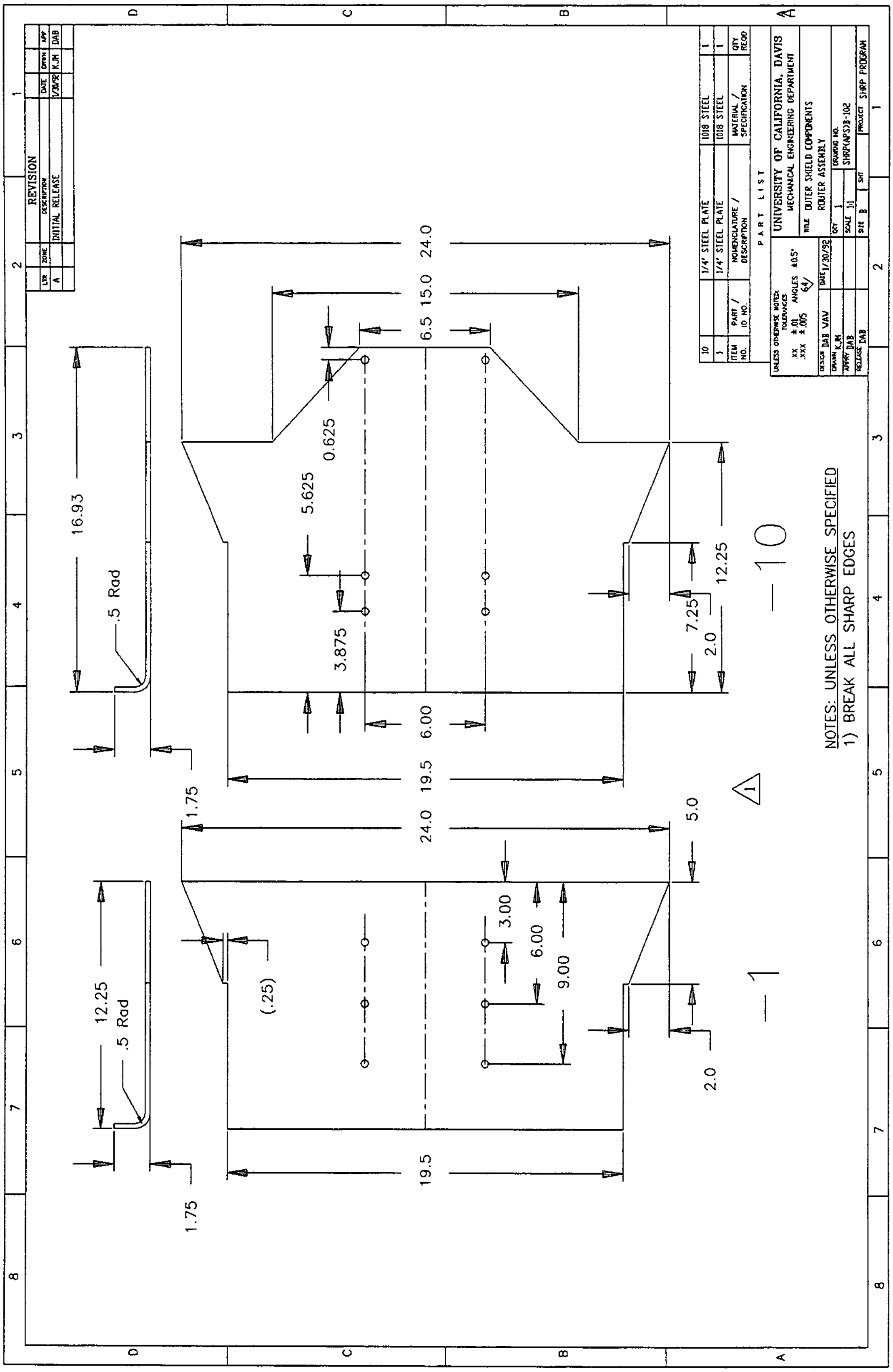
Drawing 1.3.7


REVISION
A INITIAL RELEASE 1/30/92 KJH DAB
SECTION AA
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) WELDS SHALL BE AS FOLLOWS:
A. V-GROOVE WELDS SHALL BE 1/4 IN SIZE WITH 60°-90° GROOVE ANGLE. GRIND FLUSH.
B. BEVEL GROOVE WELDS SHALL BE 3/16 IN SIZE WITH 45° GROOVE ANGLE.
C. ALL FILLET WELDS SHALL BE 1/4 IN SIZE.
11 CASTERS MCM-CARR 2494T81 4
10 LH-B102-2 BACK STEEL PLATE 1018 STEEL 1
9 LH-B103-6 FRONT STEEL GUSSET 1018 STEEL 1
8 LH-B103-5 STEEL BOSS 1018 STEEL 1
7 LH-B103-4 BACK STEEL GUSSET 1018 STEEL 1
6 LH-B101-2 STEEL PLATE 1018 STEEL 1
5 LH-B103-3 EXTENDED STEEL FOOT 1018 STEEL 1
4 LH-B103-2 BACK STEEL FOOT 1018 STEEL 1
3 LH-B103-1 FRONT STEEL FOOT 1018 STEEL 1
2 LH-B101-1 STEEL PLATE 1018 STEEL 2
1 LH-B102-1 FRONT STEEL PLATE 1018 STEEL 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE LOWER LINK ROUTER ASSEMBLY
DRAWING NO. SHRP(AP)SXRH-B100
PROJECT SHRP PROGRAM

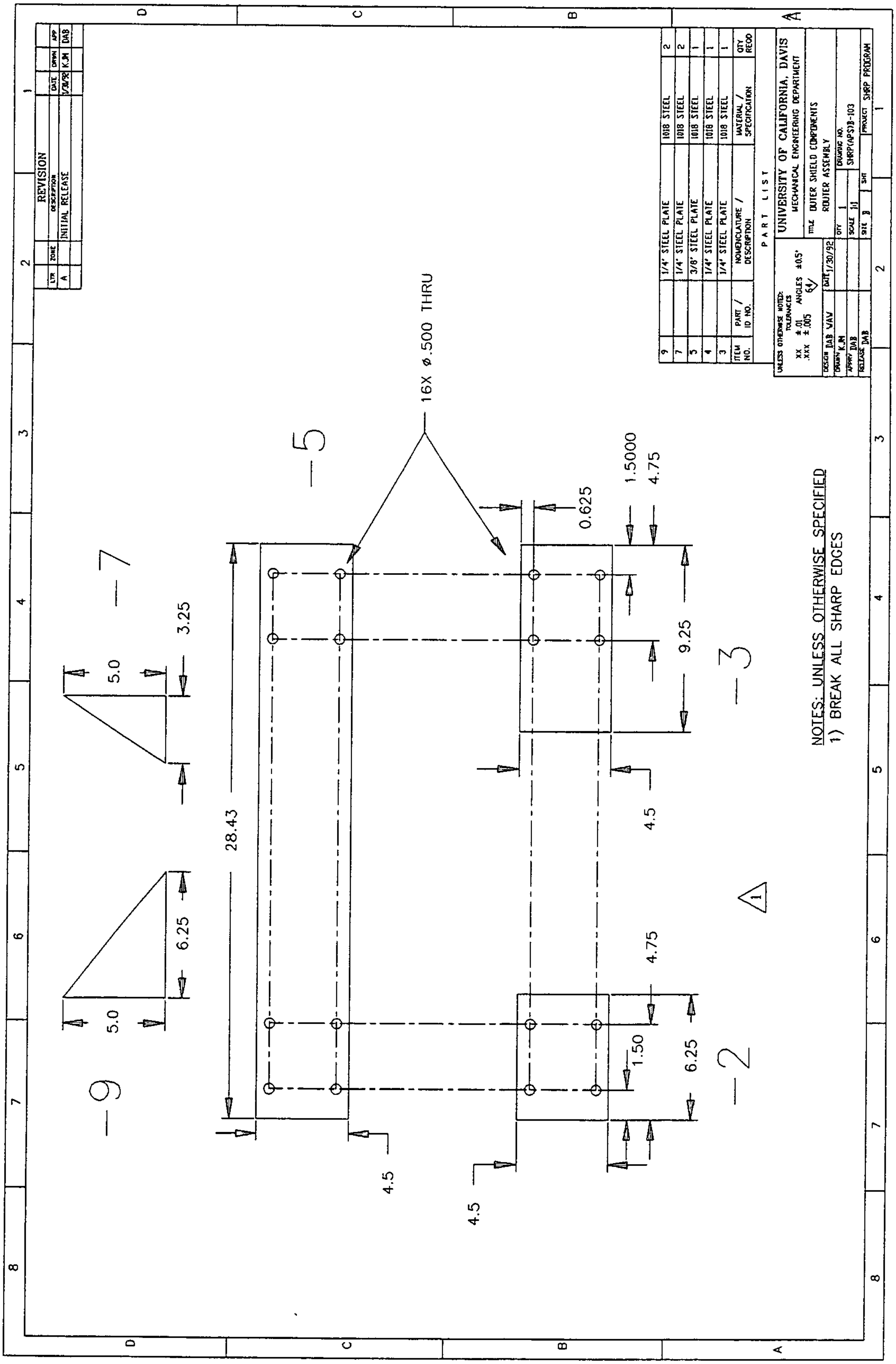
Drawing 1.3.8


REVISION
INITIAL RELEASE
9.213
12.25
.5 Rad
3.875
1ø THRU
18.43
1.75
9.471
0.500
3X .375 HOLE
ON A 3 DIA
B.C.
.375ø THRU 8X
17.43
0.500
8.813
18.5
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
1/4" STEEL PLATE
1018 STEEL
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
OUTER SHIELD COMPONENTS
ROUTER ASSEMBLY
SHRP PROGRAM

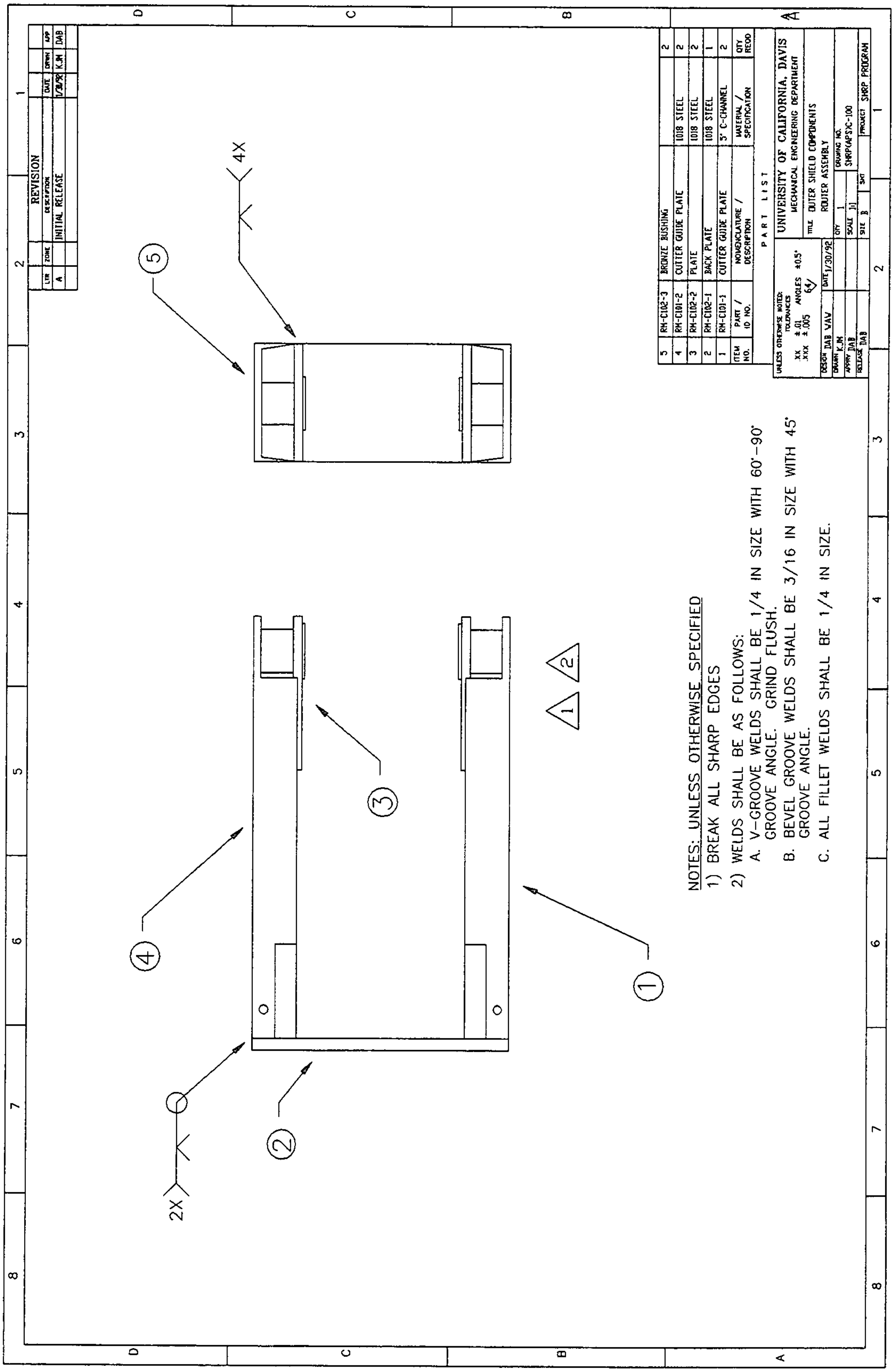
Drawing 1.3.9



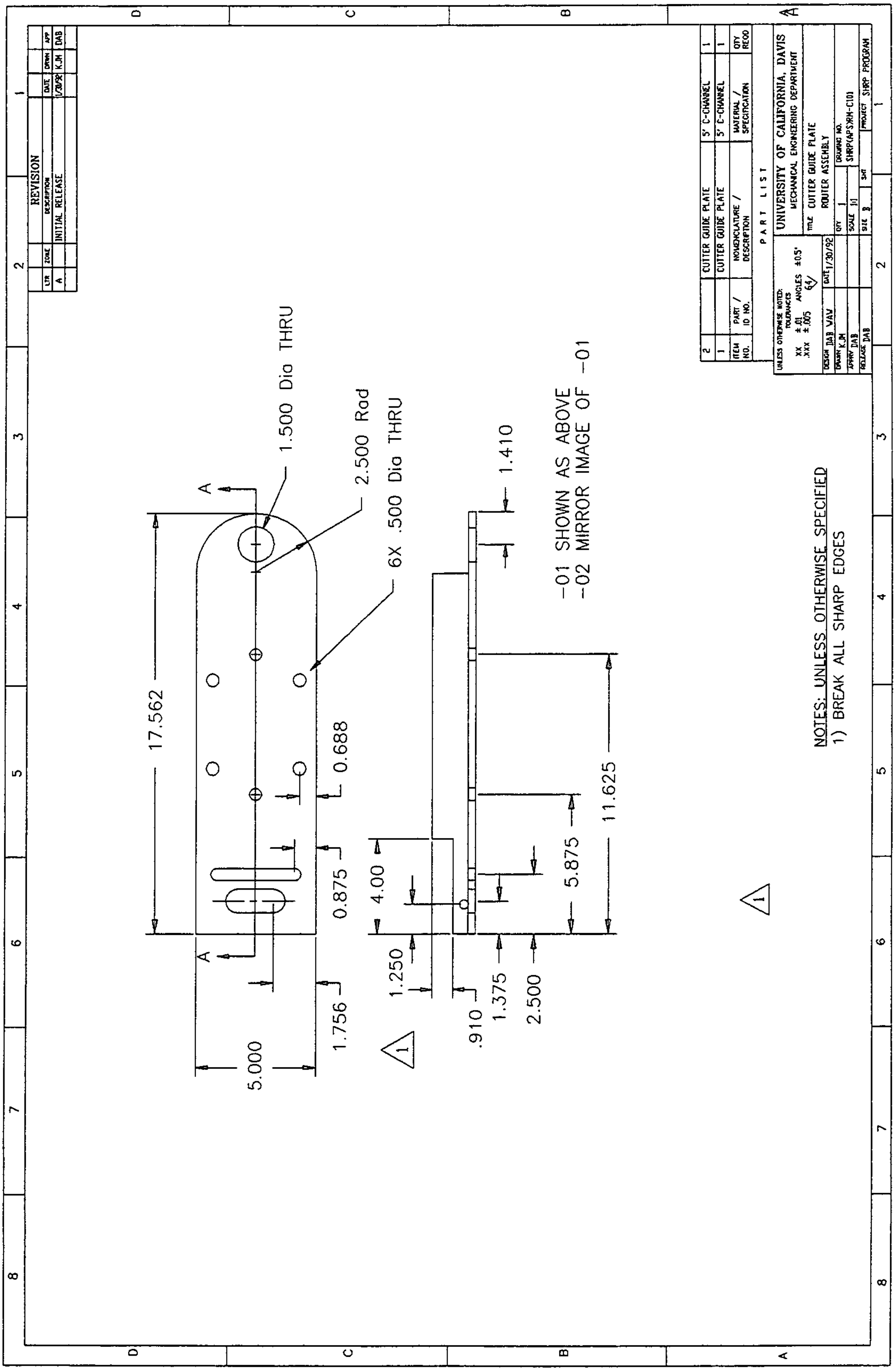
Drawing 1.3.10



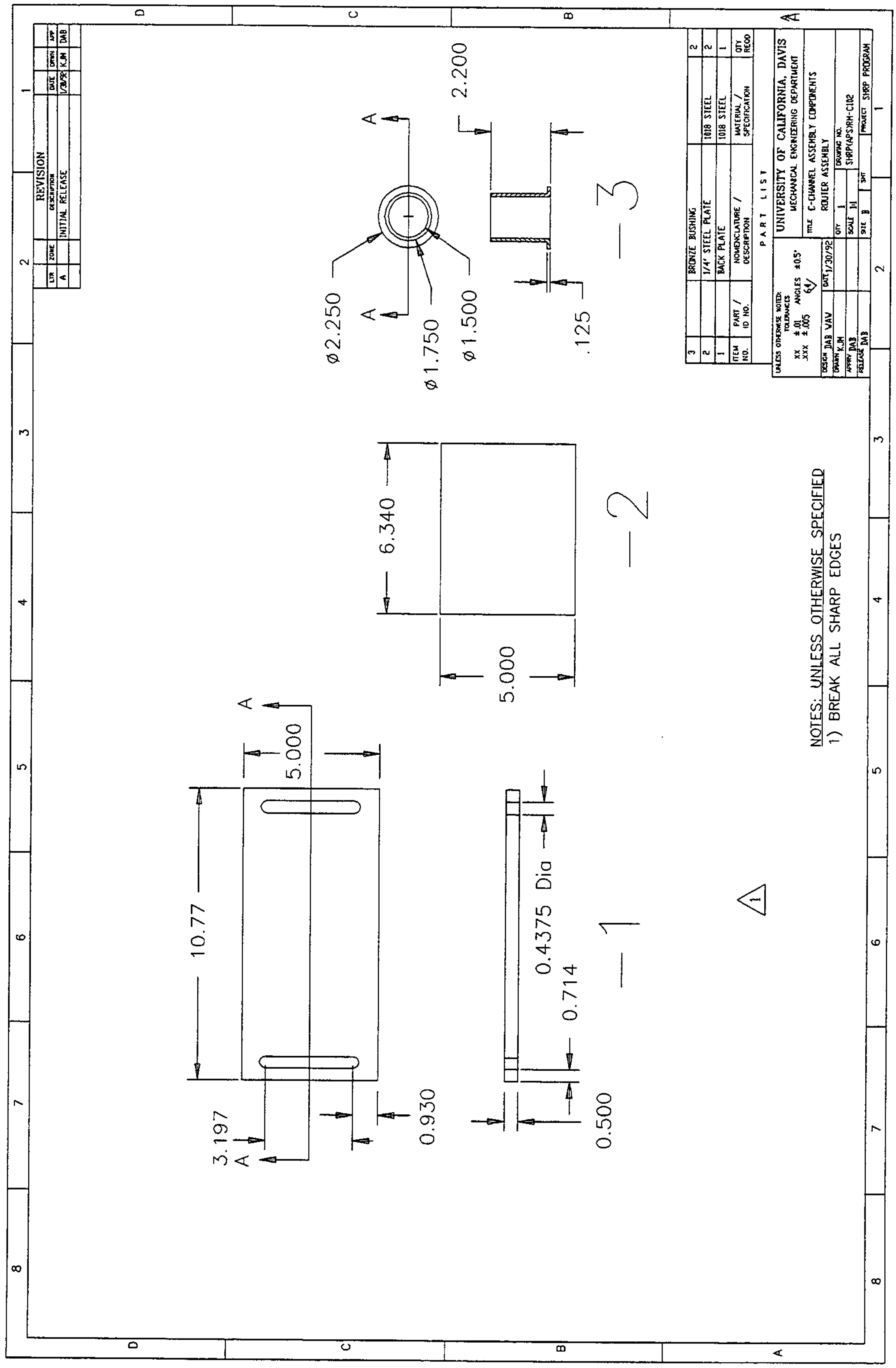
Drawing 1.3.11



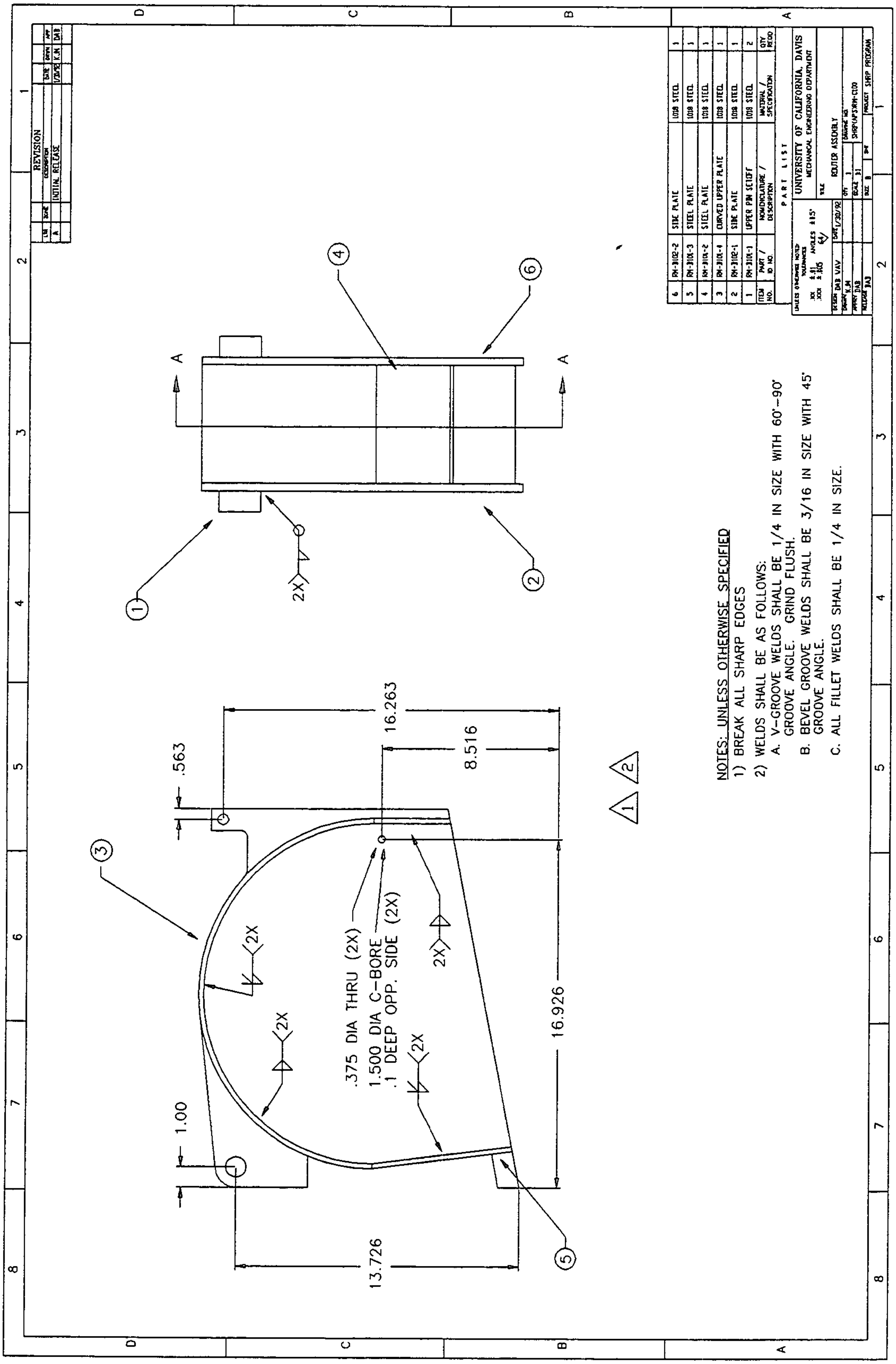
Drawing 1.3.12



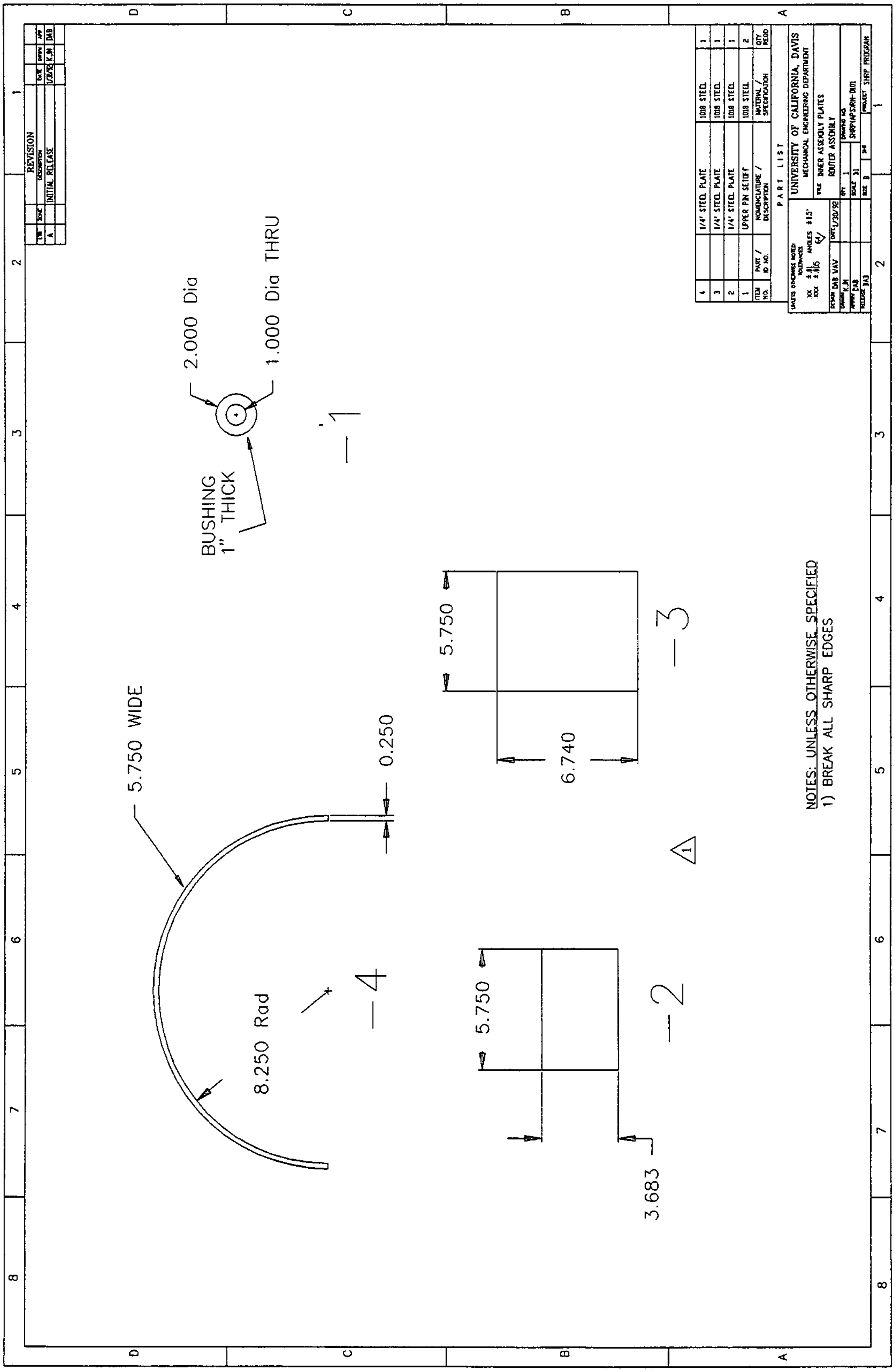
Drawing 1.3.13



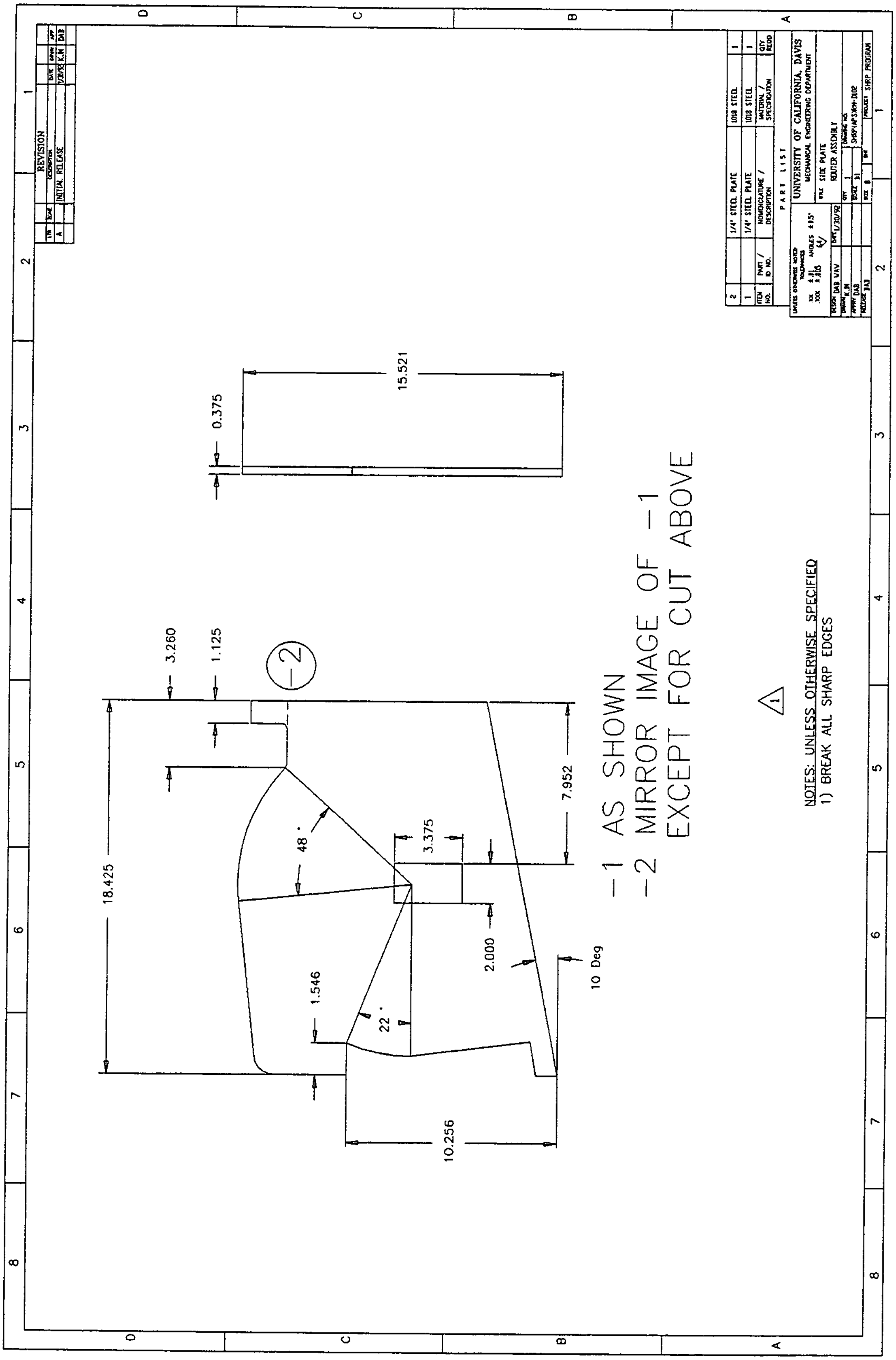
Drawing 1.3.14



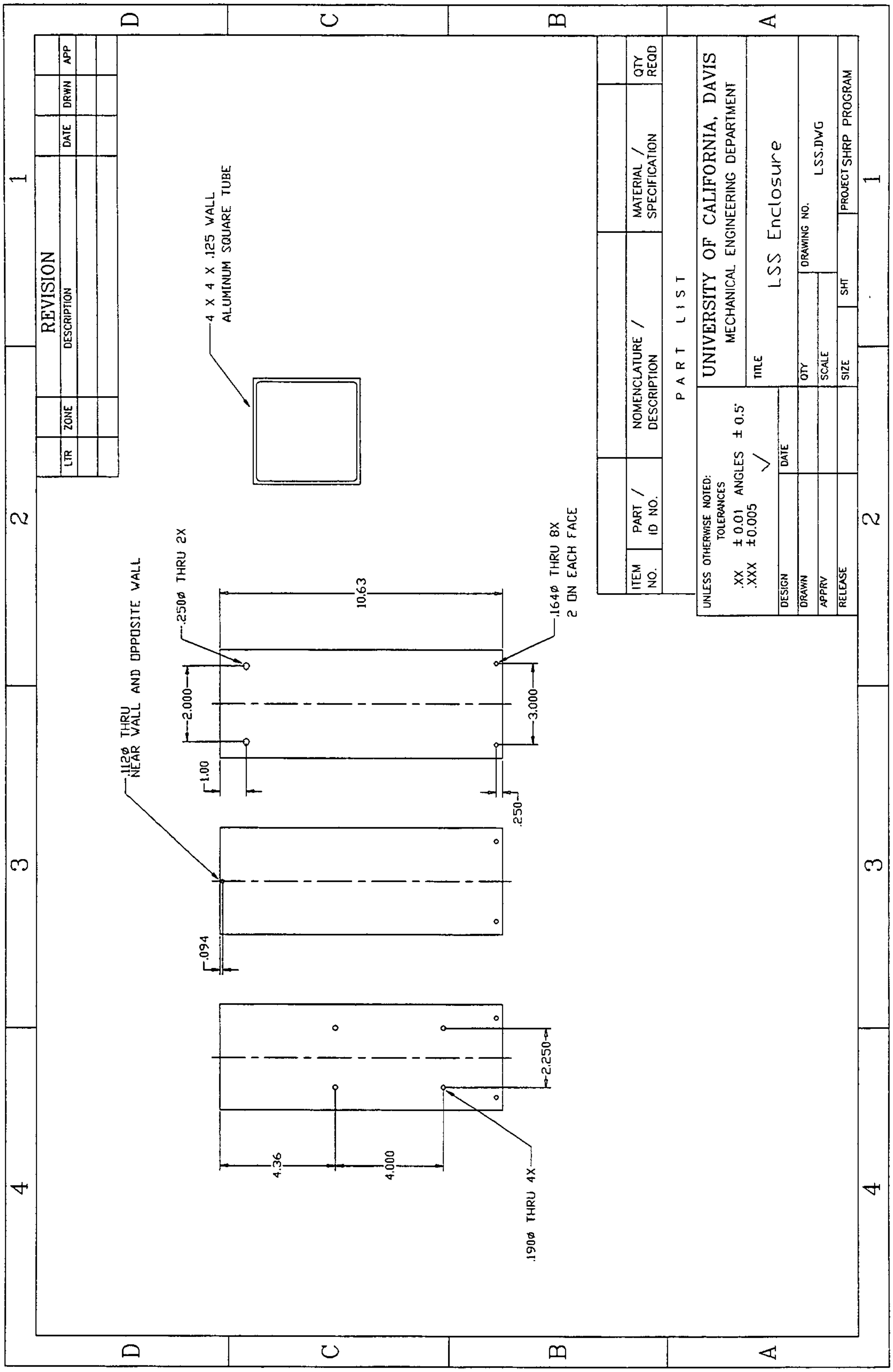
Drawing 1.3.15



Drawing 1.3.16

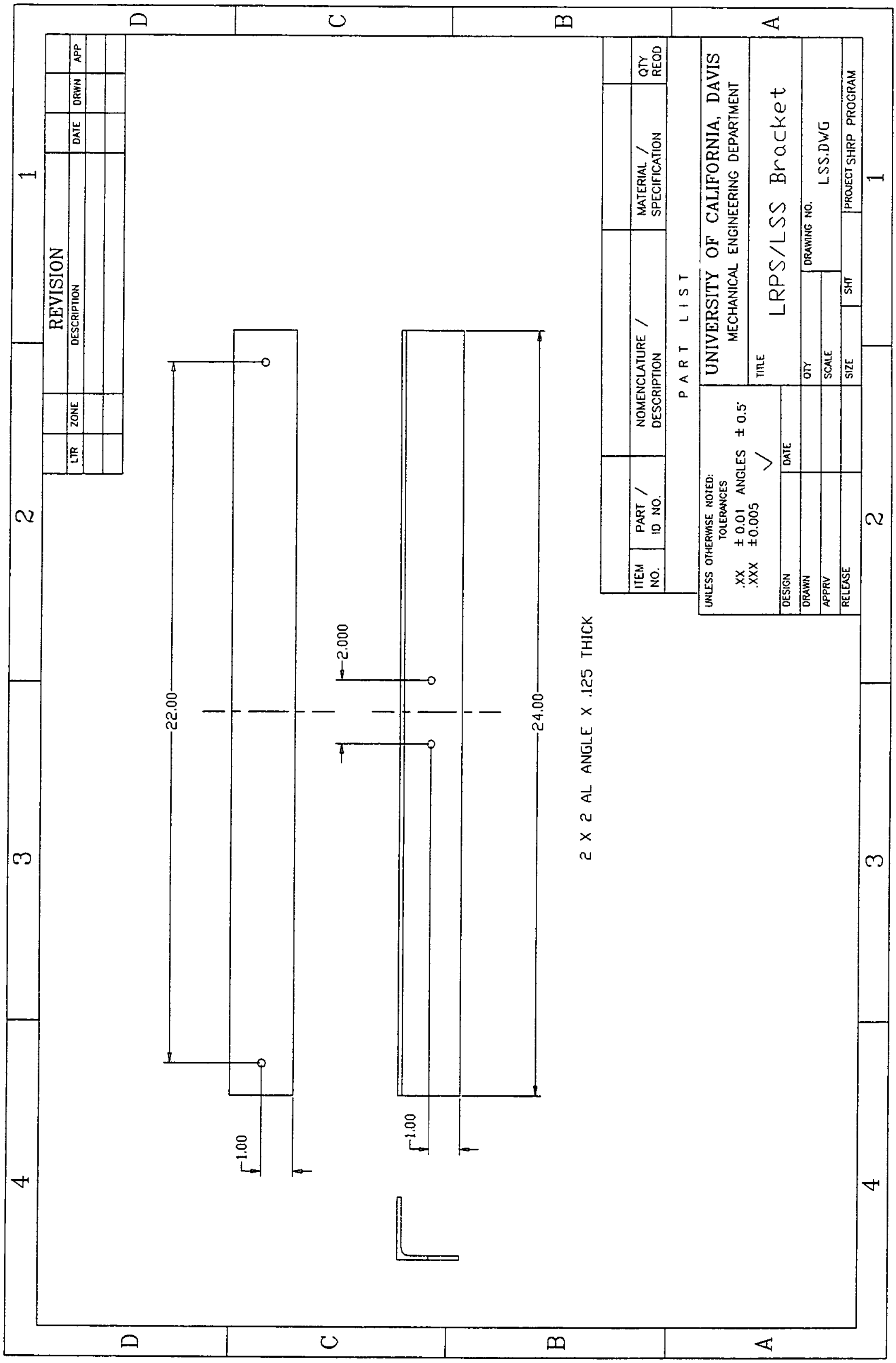


Drawing 1.3.17

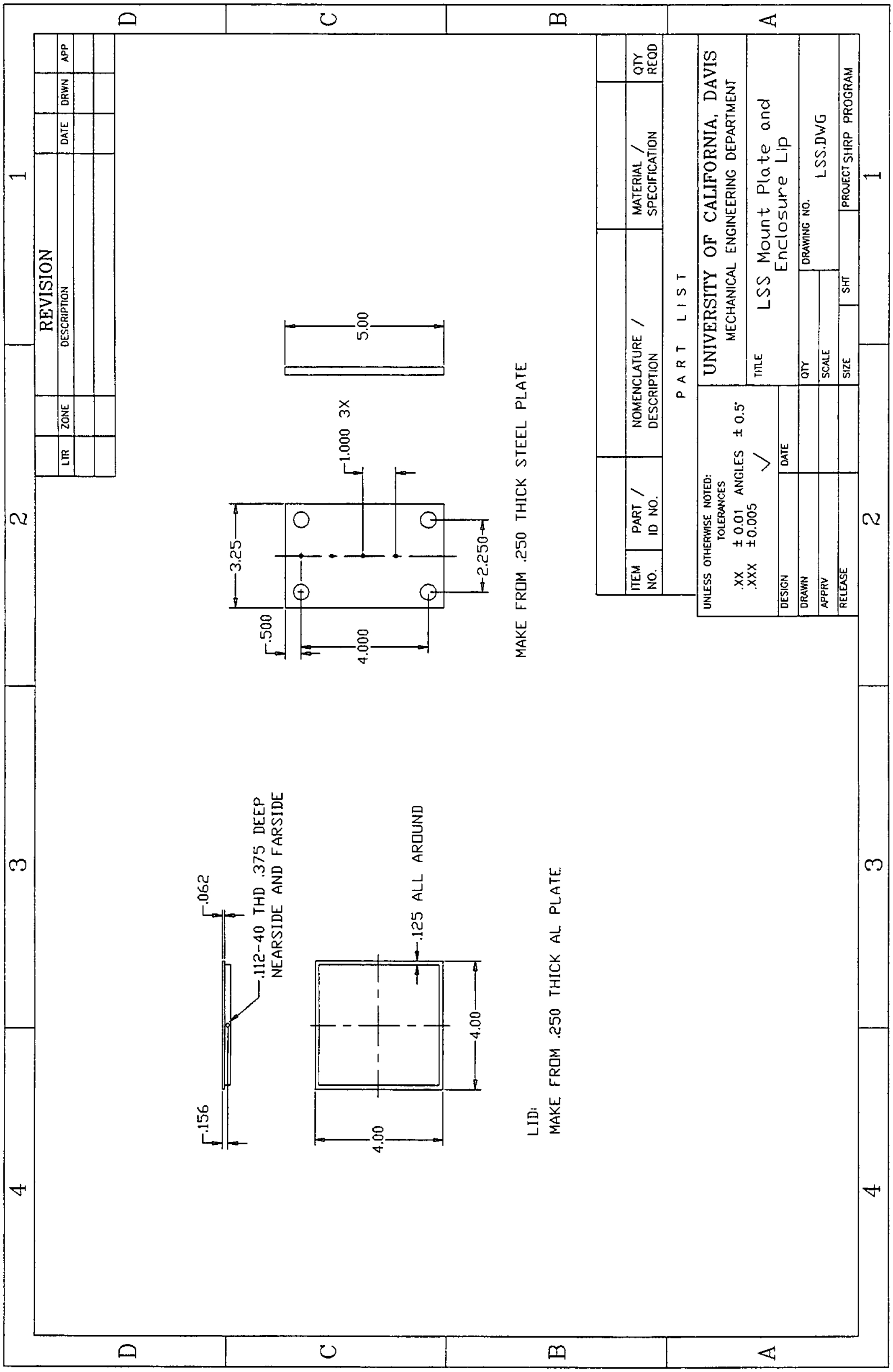


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
4 X 4 X .125 WALL
ALUMINUM SQUARE TUBE
.250ø THRU 2X
10.63
.164ø THRU 8X
2 ON EACH FACE
.112ø THRU
NEAR WALL AND OPPOSITE WALL
2.000
3.000
1.00
.250
.094
2.250
4.36
4.000
.190ø THRU 4X
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± 0.01
.XXX ± 0.005
ANGLES ± 0.5°
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
LSS Enclosure
DESIGN
DRAWN
APPRV
RELEASE
DATE
QTY
SCALE
SIZE
SHT
DRAWING NO.
LSS.DWG
PROJECT SHRP PROGRAM

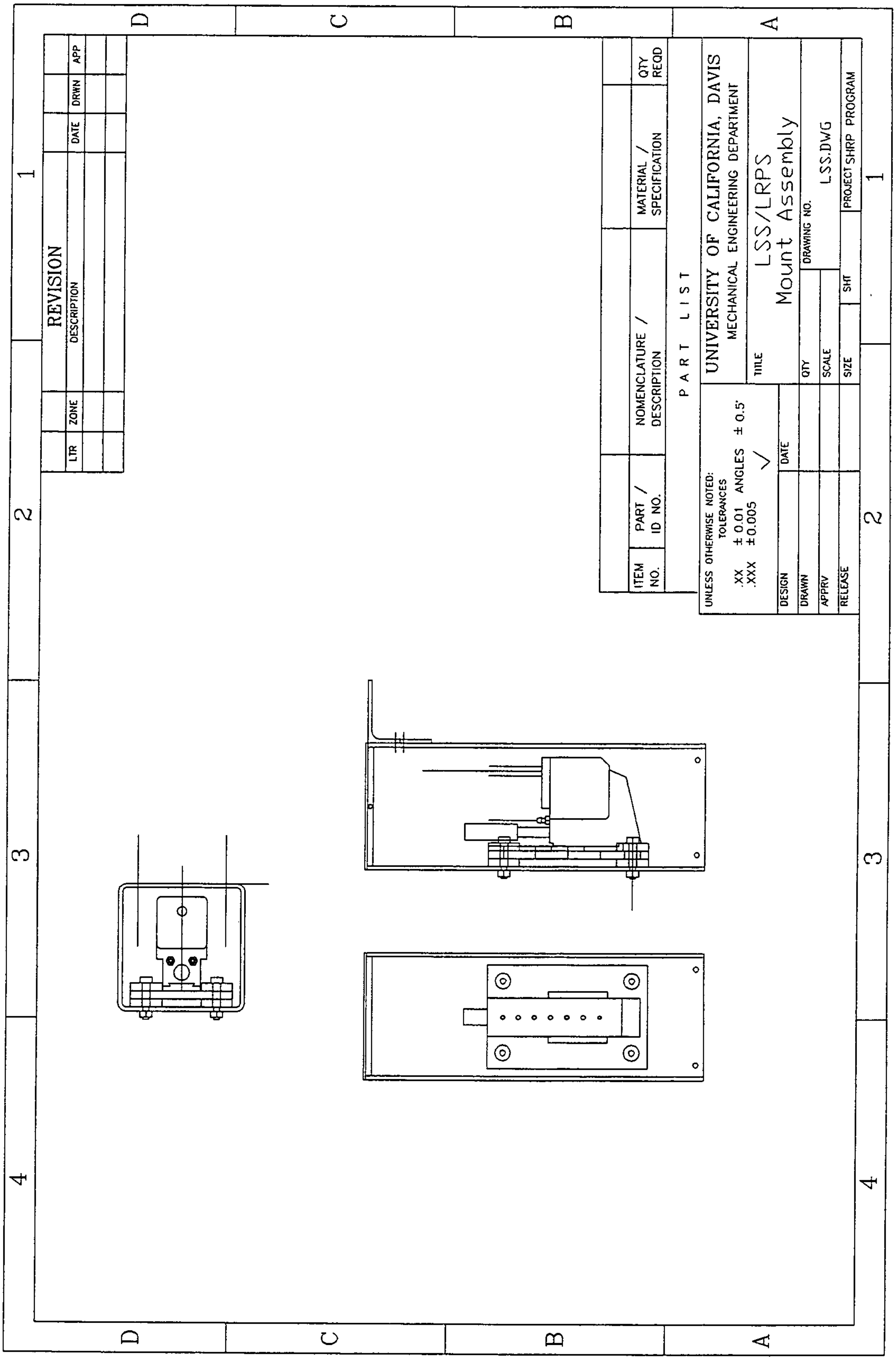
Drawing 1.4.1


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
22.00
2.000
24.00
1.00
1.00
2 X 2 AL ANGLE X .125 THICK
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± 0.01 ANGLES ± 0.5°
.XXX ±0.005
DESIGN
DRAWN
APPRV
RELEASE
DATE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
LRPS/LSS Bracket
QTY
SCALE
SIZE
DRAWING NO.
LSS.DWG
SHT
PROJECT SHRP PROGRAM

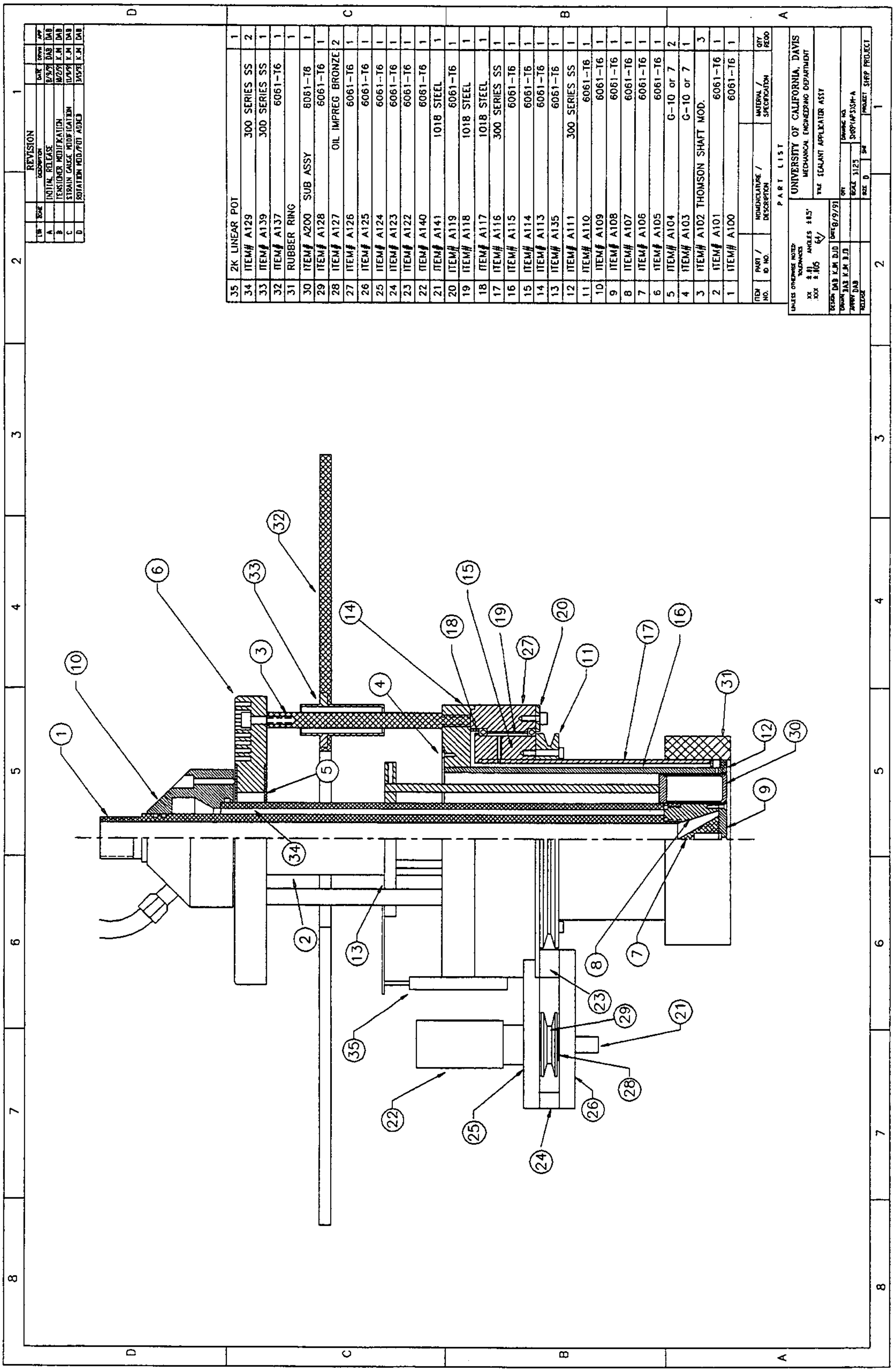
Drawing 1.4.2


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
5.00
1.000 3X
3.25
2.250
.500
4.000
MAKE FROM .250 THICK STEEL PLATE
.062
.112-40 THD .375 DEEP
NEARSIDE AND FARSIDE
.125 ALL AROUND
4.00
4.00
.156
LID:
MAKE FROM .250 THICK AL PLATE
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
P A R T L I S T
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± 0.01 ANGLES ± 0.5°
.XXX ± 0.005
DESIGN
DRAWN
APPRV
RELEASE
DATE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
LSS Mount Plate and
Enclosure Lip
QTY
SCALE
SIZE
SHT
DRAWING NO.
LSS.DWG
PROJECT SHRP PROGRAM

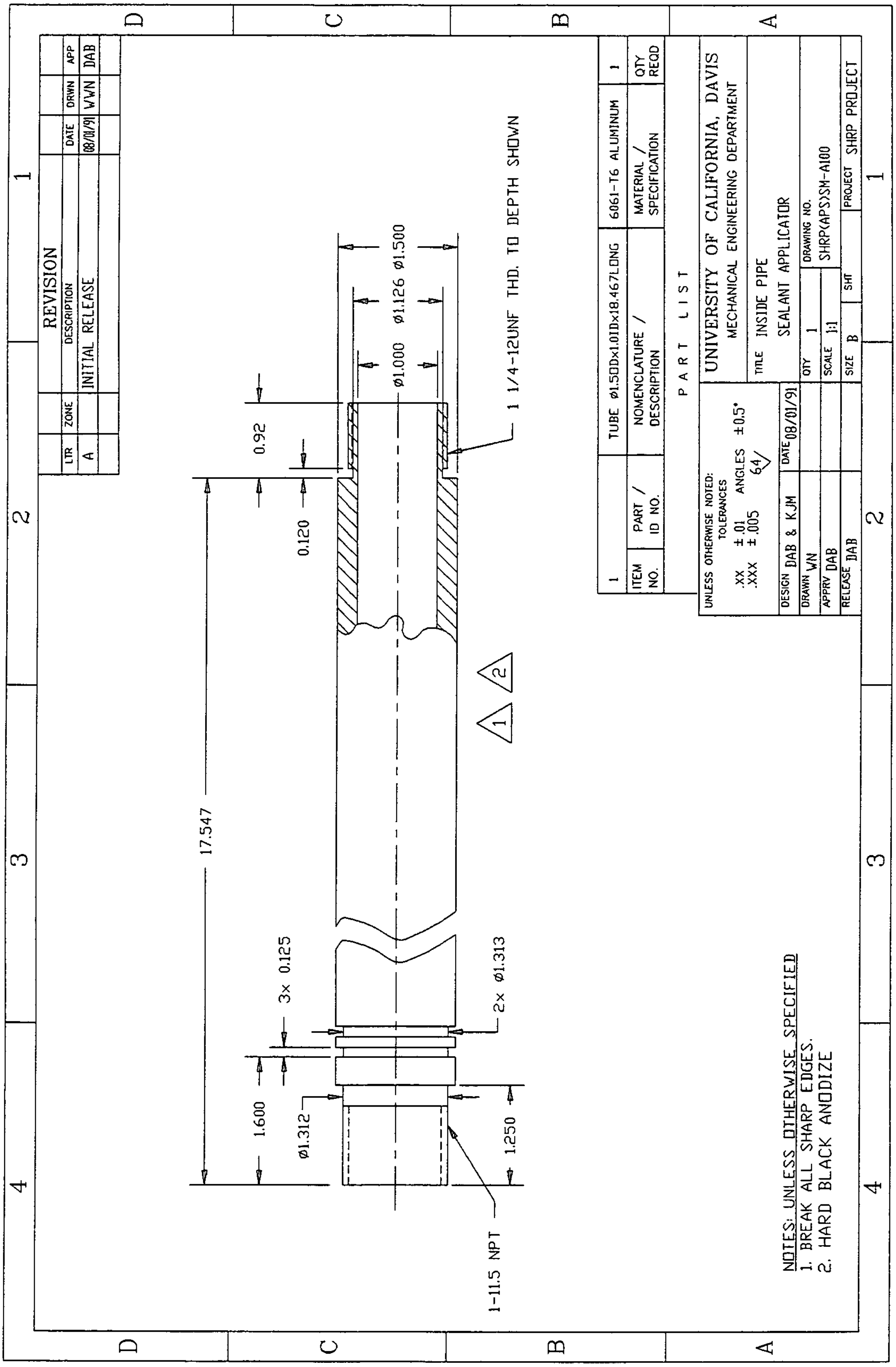
Drawing 1.4.3


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
P A R T L I S T
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± 0.01 ANGLES ± 0.5°
.XXX ± 0.005
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
LSS/LRPS
Mount Assembly
DESIGN
DRAWN
APPRV
RELEASE
DATE
QTY
SCALE
SIZE
SHT
DRAWING NO.
LSS.DWG
PROJECT SHRP PROGRAM

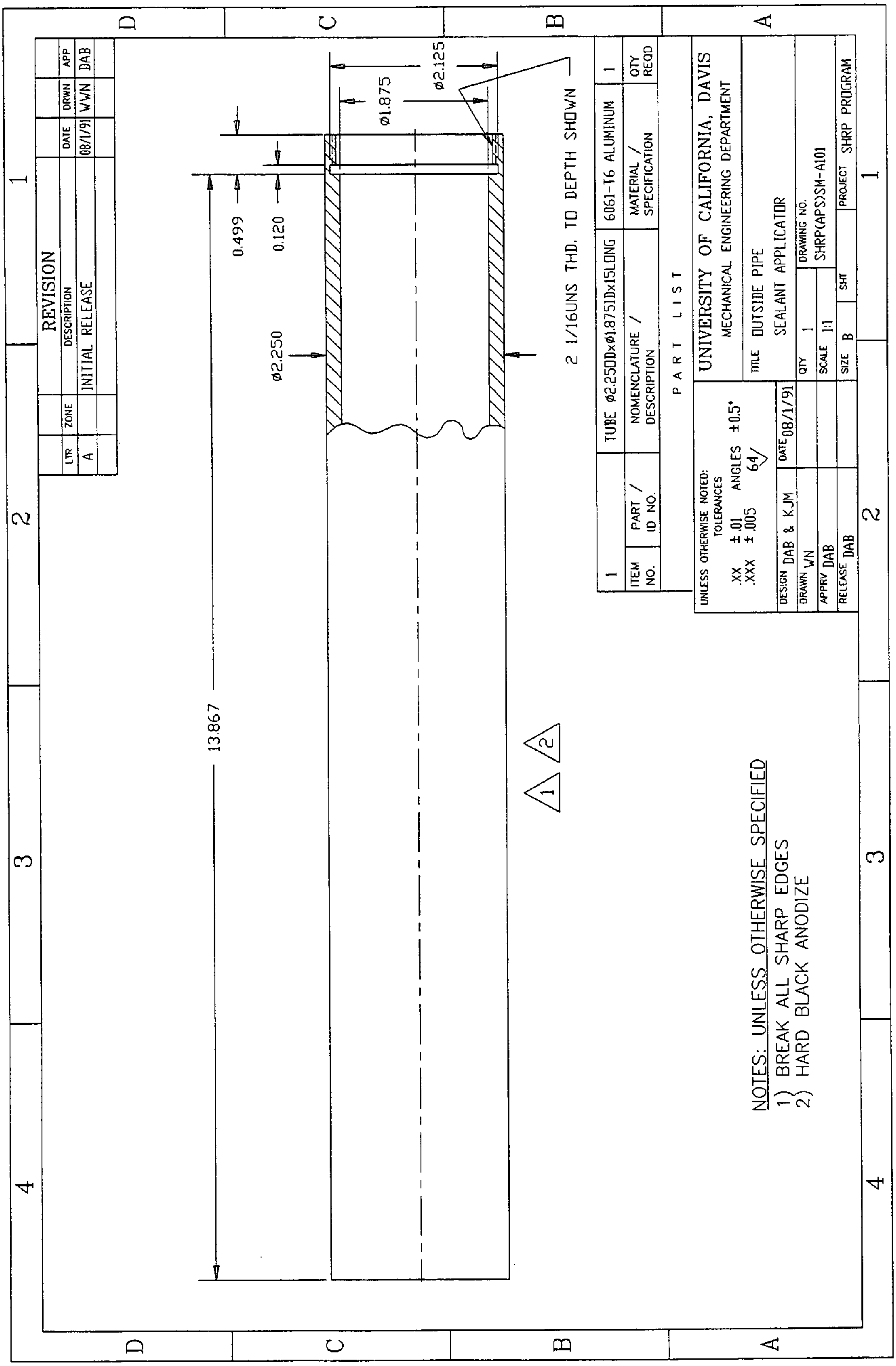
Drawing 1.4.4


PART LIST
35 2K LINEAR POT 1
34 ITEM# A129 300 SERIES SS 2
33 ITEM# A139 300 SERIES SS 1
32 ITEM# A137 6061-T6 1
31 RUBBER RING 1
30 ITEM# A200 SUB ASSY 6061-T6 1
29 ITEM# A128 6061-T6 1
28 ITEM# A127 OIL IMPREG BRONZE 2
27 ITEM# A126 6061-T6 1
26 ITEM# A125 6061-T6 1
25 ITEM# A124 6061-T6 1
24 ITEM# A123 6061-T6 1
23 ITEM# A122 6061-T6 1
22 ITEM# A140 6061-T6 1
21 ITEM# A141 1018 STEEL 1
20 ITEM# A119 6061-T6 1
19 ITEM# A118 1018 STEEL 1
18 ITEM# A117 1018 STEEL 1
17 ITEM# A116 300 SERIES SS 1
16 ITEM# A115 6061-T6 1
15 ITEM# A114 6061-T6 1
14 ITEM# A113 6061-T6 1
13 ITEM# A135 6061-T6 1
12 ITEM# A111 300 SERIES SS 1
11 ITEM# A110 6061-T6 1
10 ITEM# A109 6061-T6 1
9 ITEM# A108 6061-T6 1
8 ITEM# A107 6061-T6 1
7 ITEM# A106 6061-T6 1
6 ITEM# A105 6061-T6 1
5 ITEM# A104 G-10 or 7 2
4 ITEM# A103 G-10 or 7 1
3 ITEM# A102 THOMSON SHAFT MOD. 3
2 ITEM# A101 6061-T6 1
1 ITEM# A100 6061-T6 1
REVISION
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
SEALANT APPLICATOR ASSY

Drawing 1.5.1

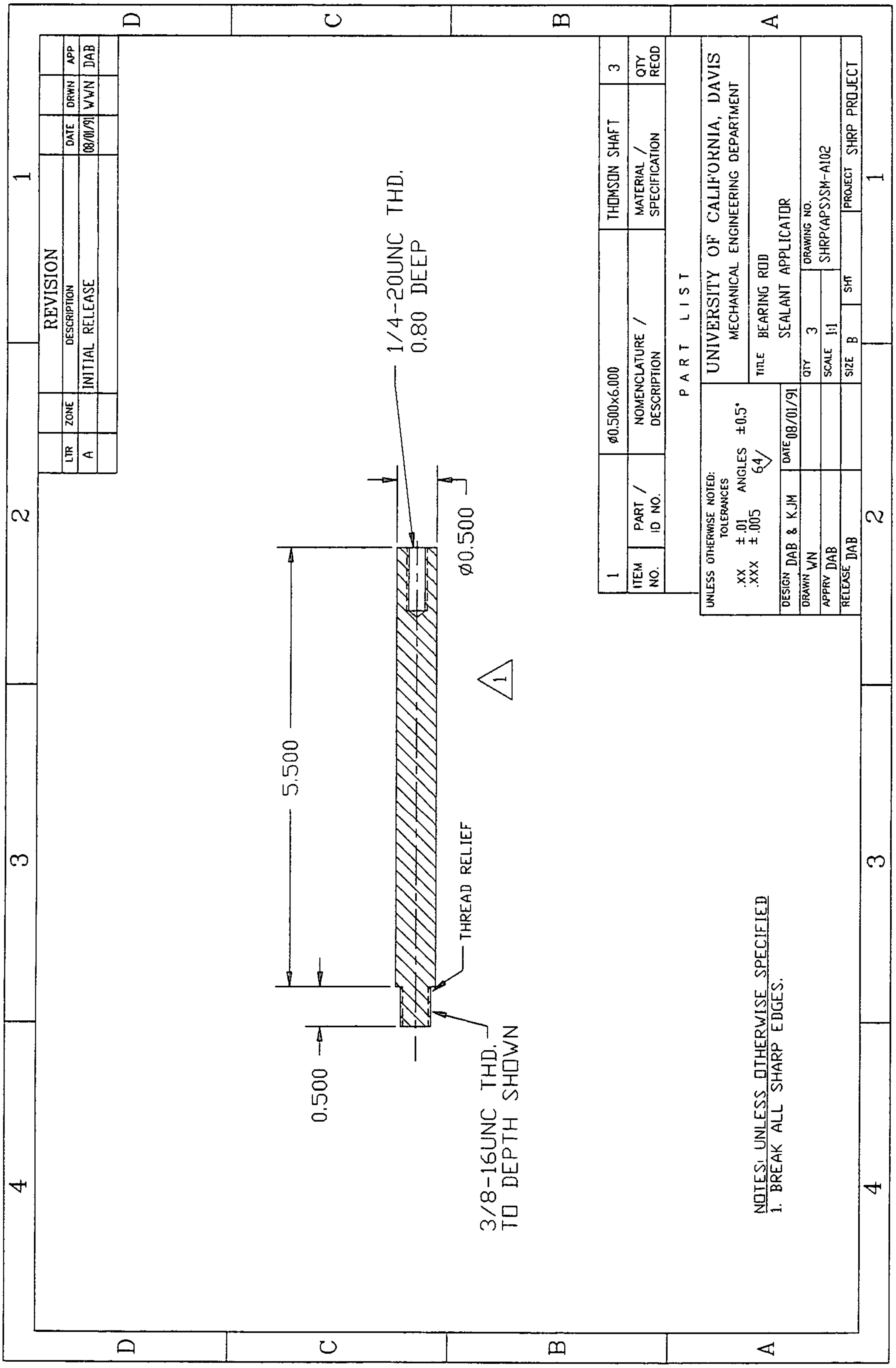

REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 08/01/91 WWN DAB
17.547
1.600
3x 0.125
ø1.312
0.92
0.120
ø1.000 ø1.126 ø1.500
1-11.5 NPT
1.250
2x ø1.313
1 1/4-12UNF THD. TO DEPTH SHOWN
1 TUBE ø1.50D×1.01D×18.467LONG 6061-T6 ALUMINUM 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.01 ANGLES ±0.5°
.XXX ±.005
64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE INSIDE PIPE
SEALANT APPLICATOR
DESIGN DAB & KJM DATE 08/01/91
DRAWN WN
APPRV DAB
RELEASE DAB
QTY 1
SCALE 1:1
SIZE B SHT
DRAWING NO. SHRP(APS)SM-A100
PROJECT SHRP PROJECT
NOTES: UNLESS OTHERWISE SPECIFIED
1. BREAK ALL SHARP EDGES.
2. HARD BLACK ANODIZE

Drawing 1.5.2

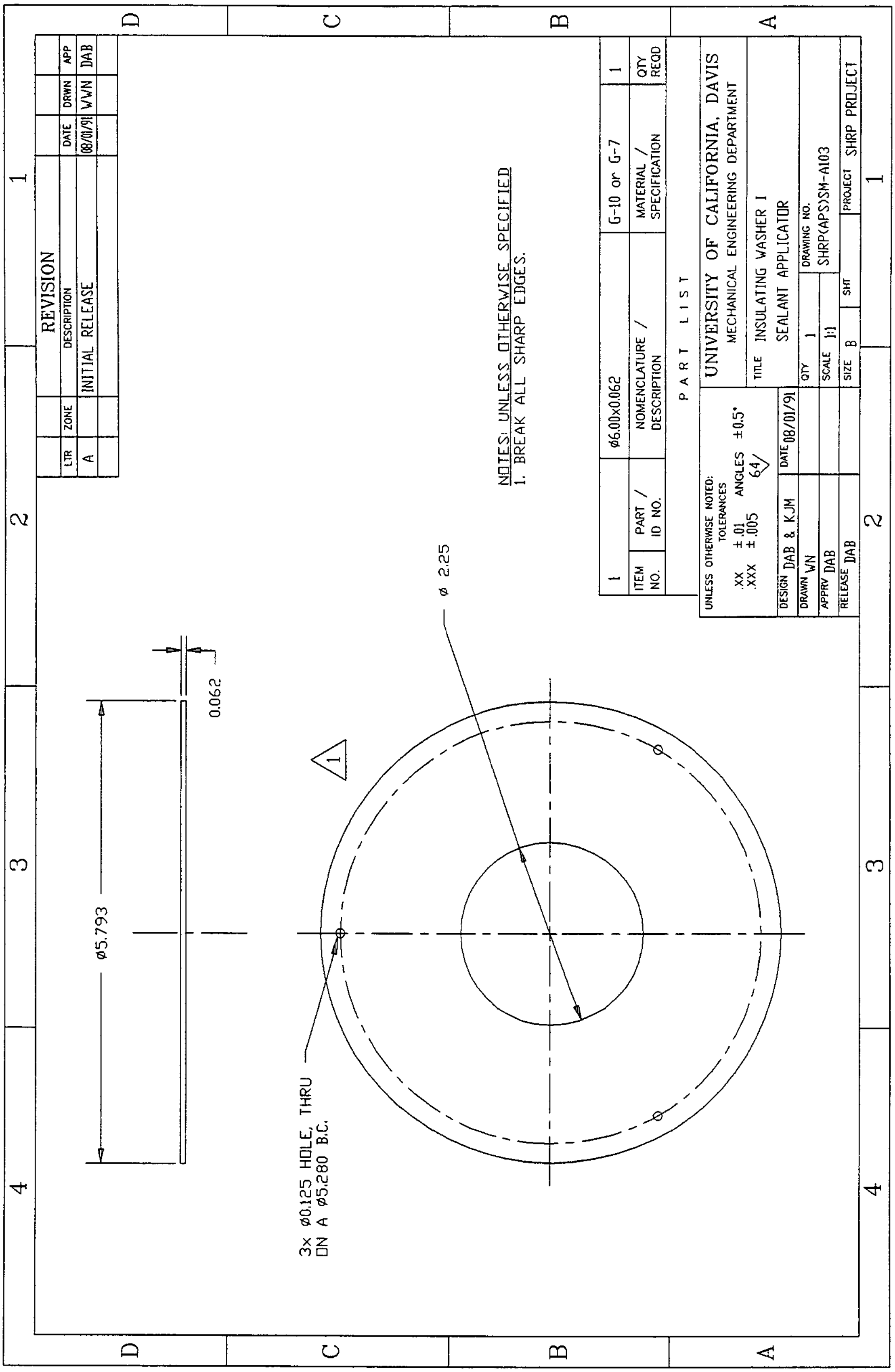


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 08/1/91 WWN DAB
Ø1.875
Ø2.125
2 1/16UNS THD. TO DEPTH SHOWN
0.499
0.120
Ø2.250
13.867
1
2
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) HARD BLACK ANODIZE
1 TUBE Ø2.250OD×Ø1.875ID×15LONG 6061-T6 ALUMINUM 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.01 ANGLES ±0.5°
.XXX ±.005 64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE OUTSIDE PIPE
SEALANT APPLICATOR
DESIGN DAB & KJM DATE 08/1/91
DRAWN WN
APPRV DAB
RELEASE DAB
QTY 1
SCALE 1:1
SIZE B SHT
DRAWING NO. SHRP(APS)SM-A101
PROJECT SHRP PROGRAM

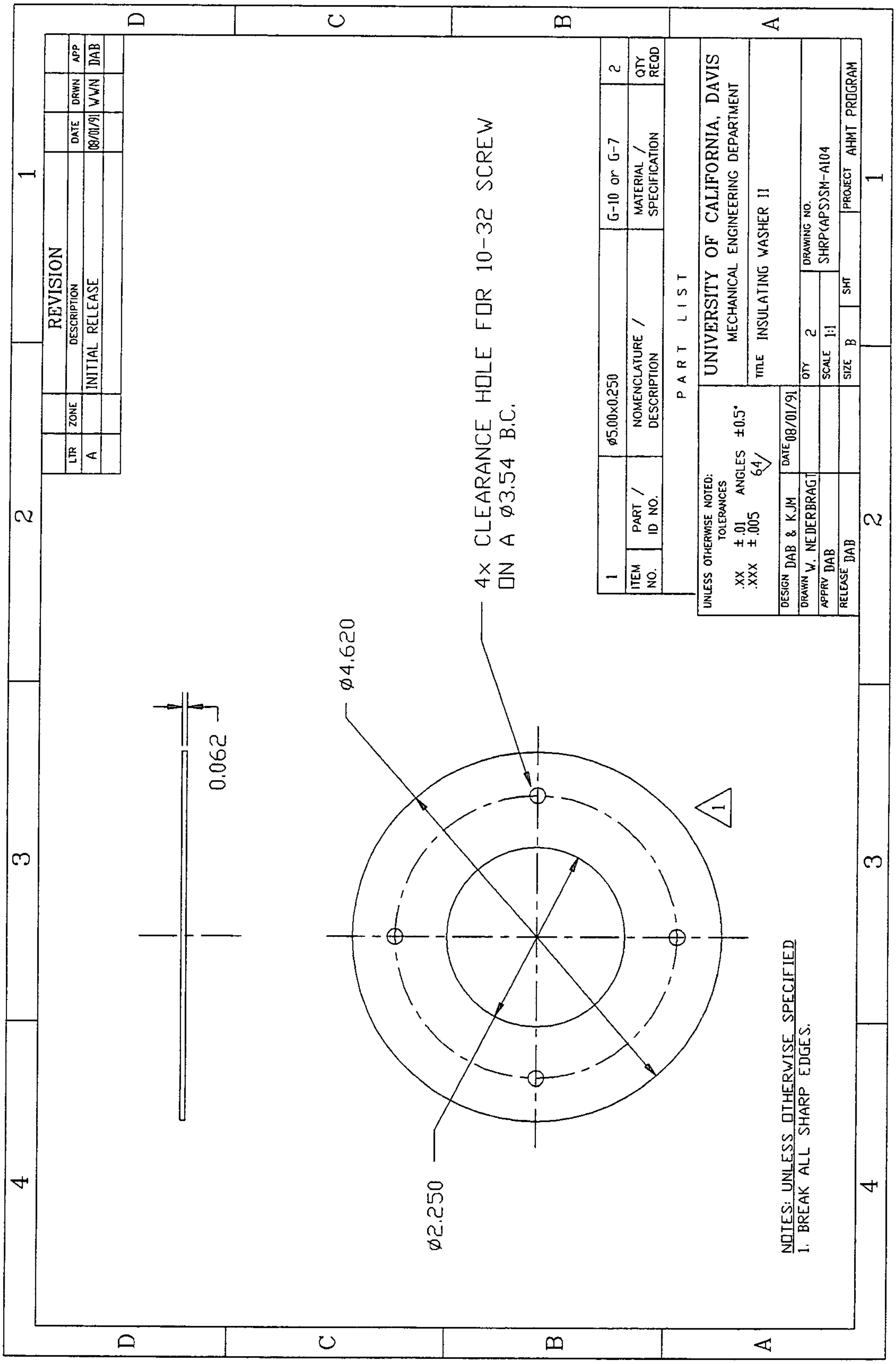
Drawing 1.5.3


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 08/01/91 WWN DAB
1/4-20UNC THD.
0.80 DEEP
Ø0.500
5.500
THREAD RELIEF
0.500
3/8-16UNC THD.
TO DEPTH SHOWN
NOTES: UNLESS OTHERWISE SPECIFIED
1. BREAK ALL SHARP EDGES.
1 Ø0.500x6.000 THOMSON SHAFT 3
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .01
.XXX ± .005
ANGLES ±0.5°
DESIGN DAB & KJM
DATE 08/01/91
DRAWN WN
APPRV DAB
RELEASE DAB
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE BEARING ROD
SEALANT APPLICATOR
QTY 3
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)SM-A102
PROJECT SHRP PROJECT

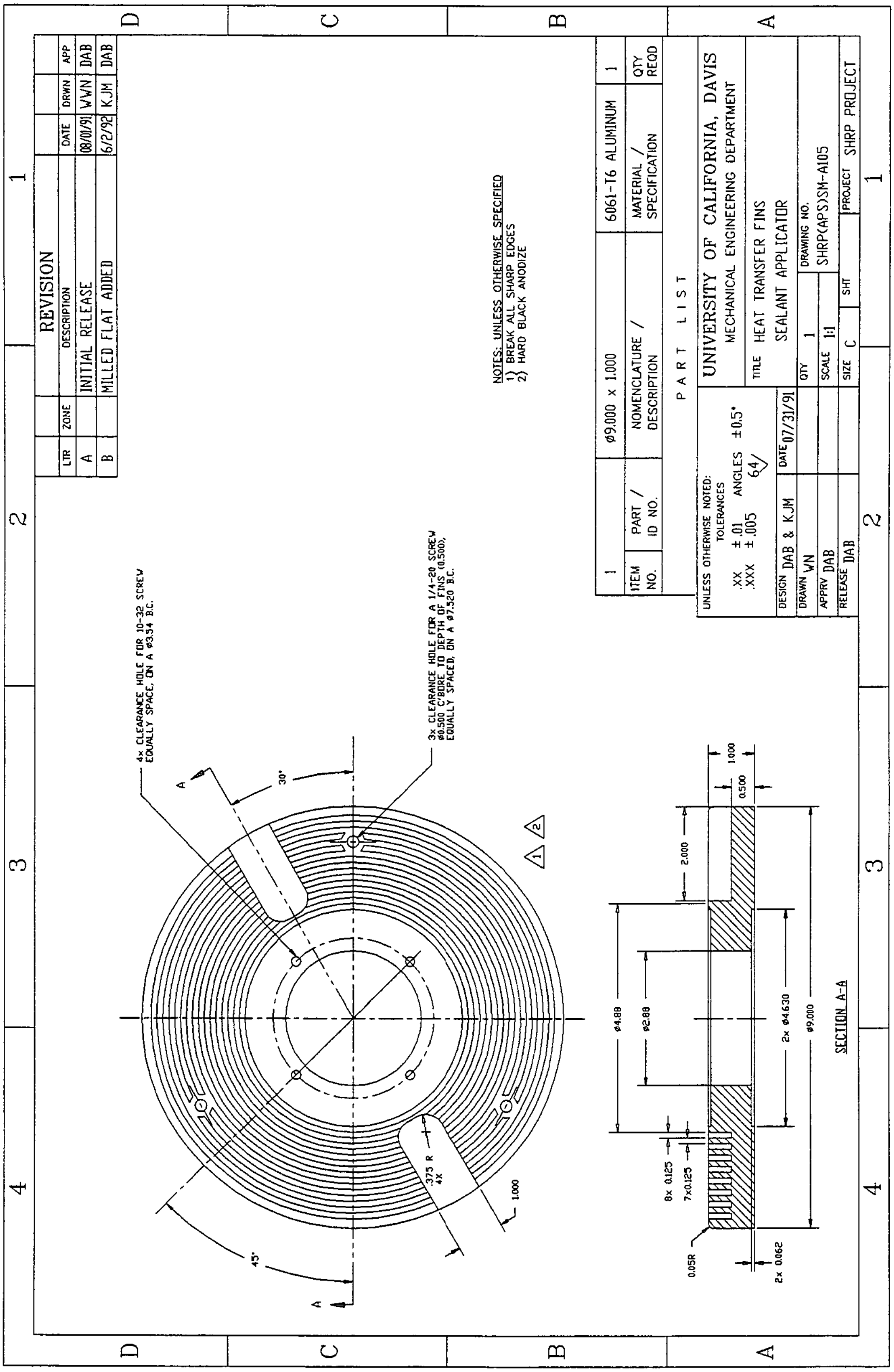
Drawing 1.5.4


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
A
INITIAL RELEASE
08/01/91
WWN
DAB
NOTES: UNLESS OTHERWISE SPECIFIED
1. BREAK ALL SHARP EDGES.
ø 2.25
0.062
ø5.793
1
3x ø0.125 HOLE, THRU
ON A ø5.280 B.C.
1
ø6.00x0.062
G-10 or G-7
1
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .01
.XXX ± .005
ANGLES ±0.5°
64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE INSULATING WASHER I
SEALANT APPLICATOR
DESIGN DAB & KJM
DATE 08/01/91
DRAWN WN
APPRV DAB
RELEASE DAB
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)SM-A103
PROJECT SHRP PROJECT

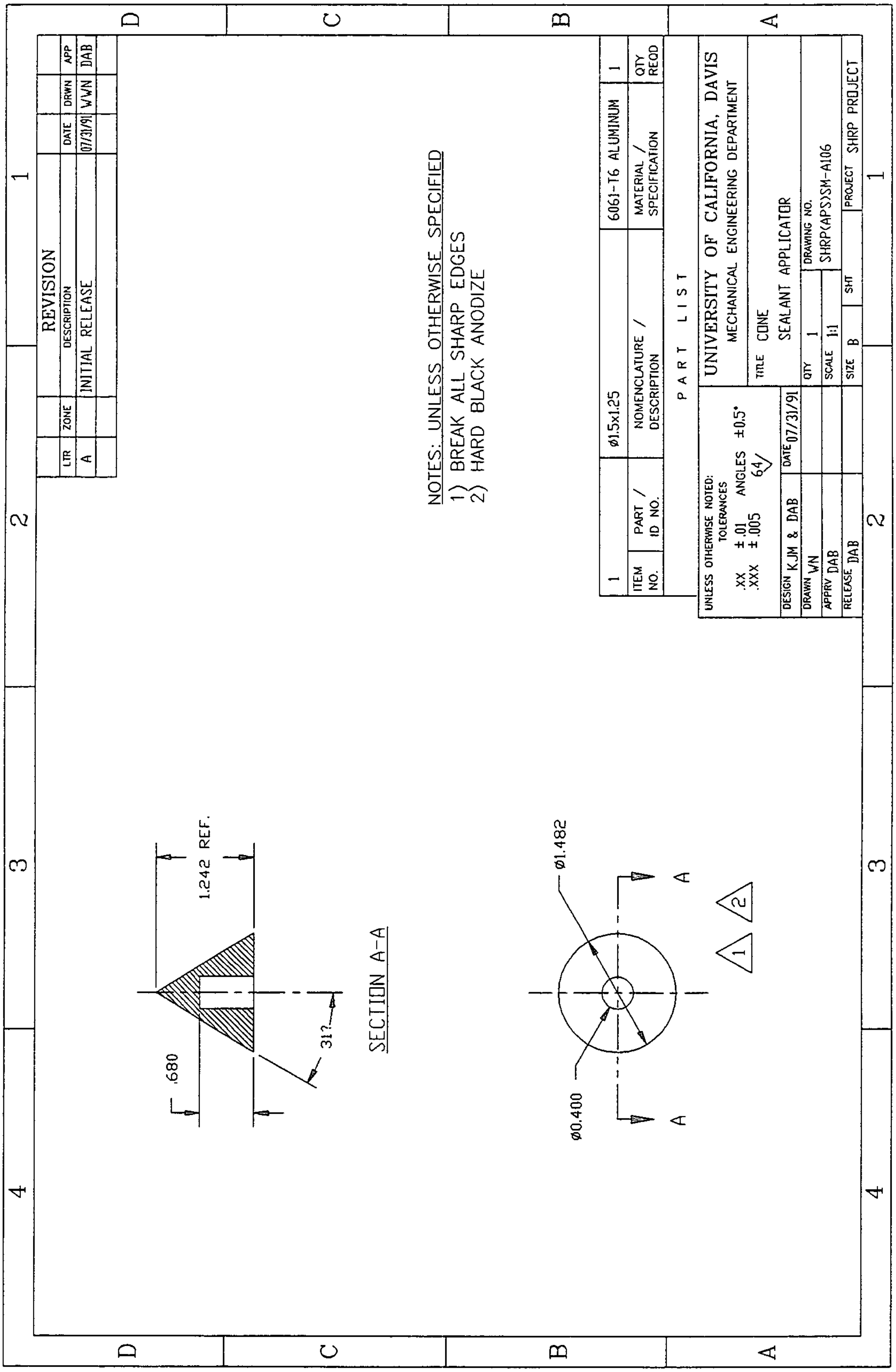
Drawing 1.5.5


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 08/01/91 WVN DAB
4x CLEARANCE HOLE FOR 10-32 SCREW
ON A Ø3.54 B.C.
Ø4.620
0.062
Ø2.250
1
NOTES: UNLESS OTHERWISE SPECIFIED
1. BREAK ALL SHARP EDGES.
1 Ø5.00x0.250 G-10 or G-7 2
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.01
.XXX ±.005
ANGLES ±0.5°
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE INSULATING WASHER II
DESIGN DAB & KJM
DATE 08/01/91
DRAWN W. NEDERBRAGT
APPRV DAB
RELEASE DAB
QTY 2
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)SM-A104
PROJECT AHMT PROGRAM

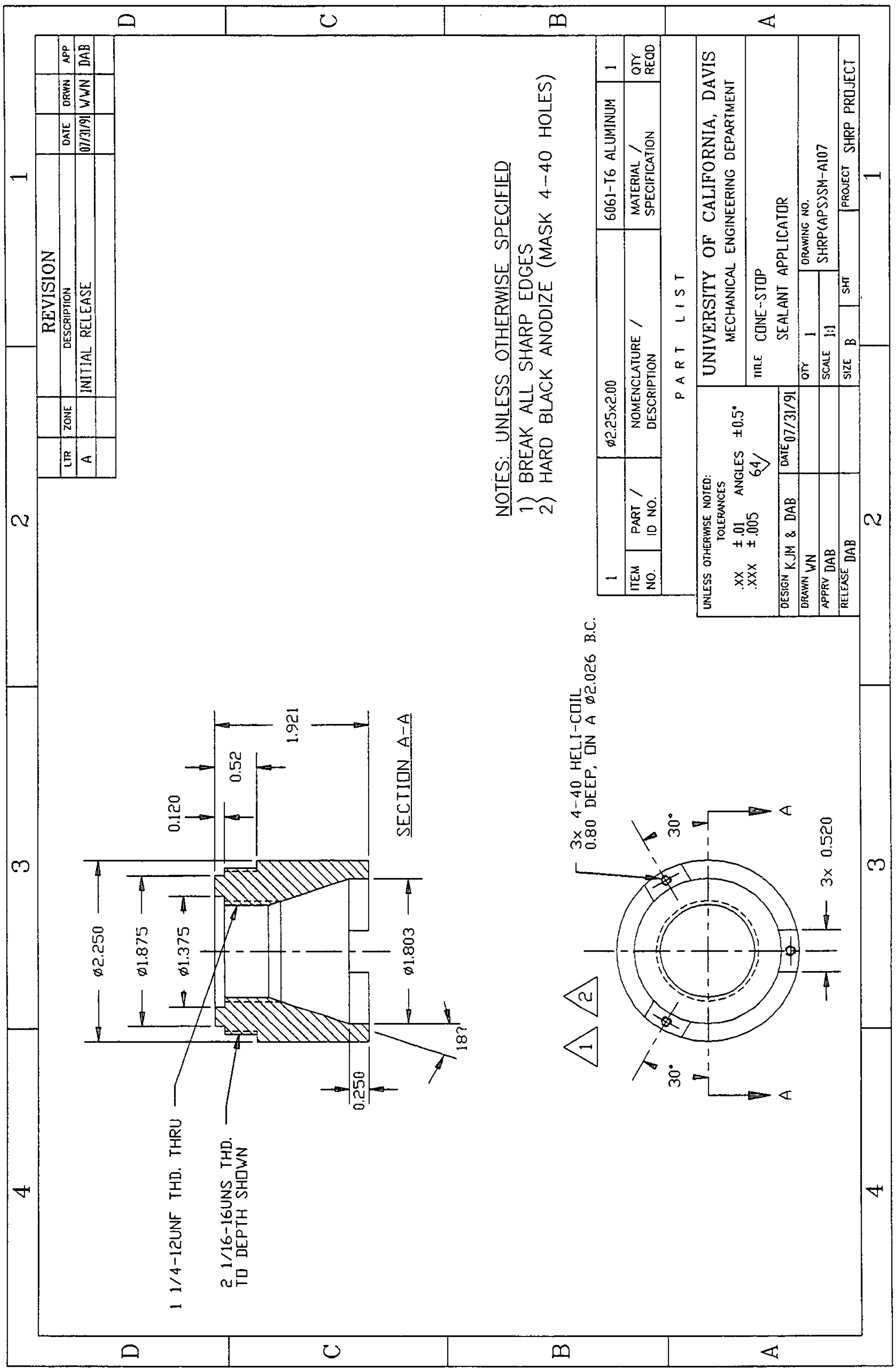
Drawing 1.5.6


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 08/01/91 WWN DAB
B MILLED FLAT ADDED 6/2/92 KJM DAB
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) HARD BLACK ANODIZE
4x CLEARANCE HOLE FOR 10-32 SCREW EQUALLY SPACE, ON A ø3.54 B.C.
3x CLEARANCE HOLE FOR A 1/4-20 SCREW ø0.500 C'BORE TO DEPTH OF FINS (0.500), EQUALLY SPACED, ON A ø7.520 B.C.
.375 R 4X
1.000
30°
45°
A
SECTION A-A
ø4.88
ø2.88
2x ø4.630
ø9.000
2.000
0.500
1.000
8x 0.125
7x0.125
0.05R
2x 0.062
1 ø9.000 x 1.000 6061-T6 ALUMINUM 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
P A R T L I S T
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .01
.XXX ± .005
ANGLES ±0.5°
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE HEAT TRANSFER FINS SEALANT APPLICATOR
DESIGN DAB & KJM DATE 07/31/91
DRAWN WN
APPRV DAB
RELEASE DAB
QTY 1
SCALE 1:1
SIZE C SHT
DRAWING NO. SHRP(APS)SM-A105
PROJECT SHRP PROJECT

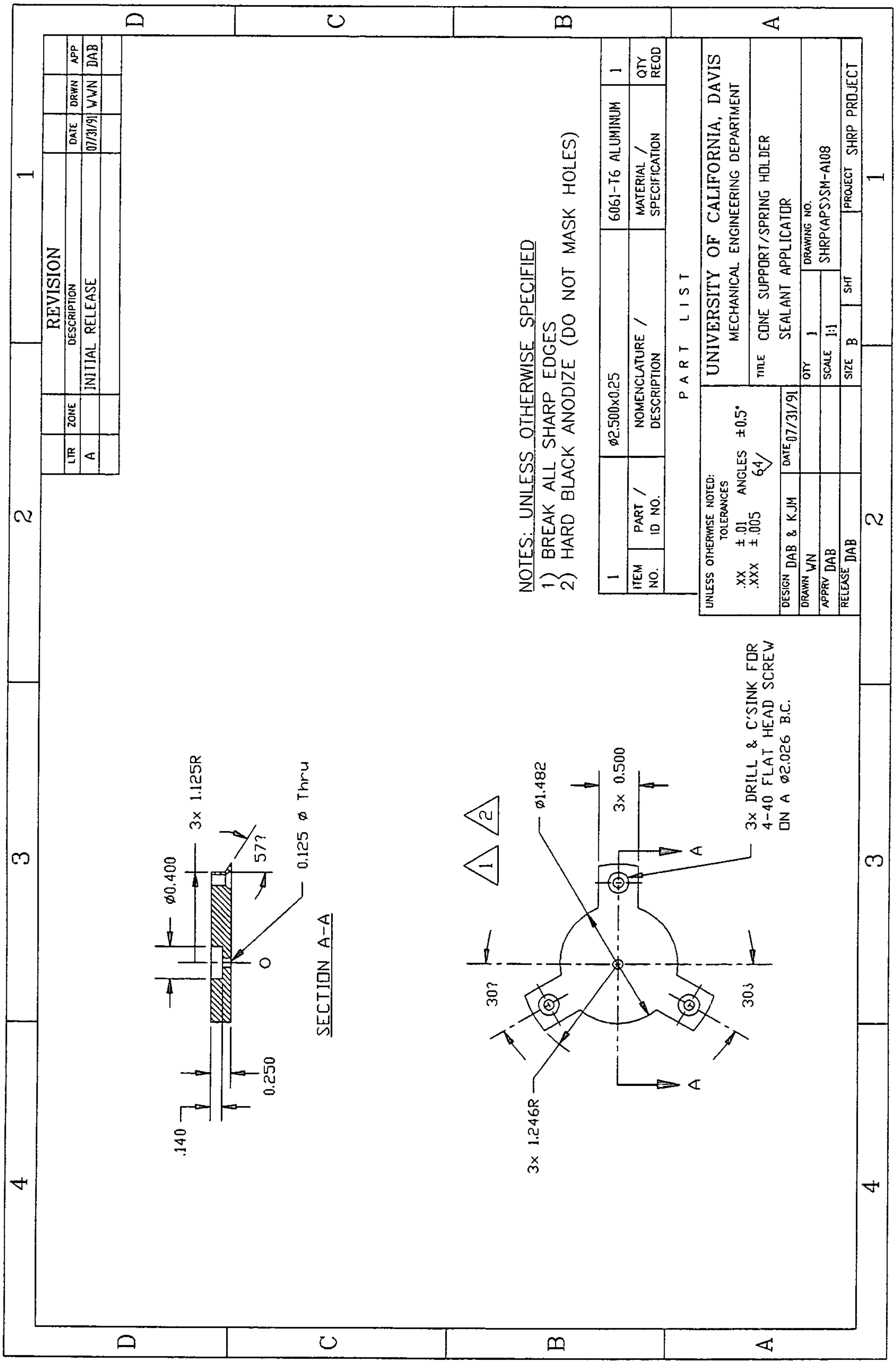
Drawing 1.5.7


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 07/31/91 WWN DAB
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) HARD BLACK ANODIZE
1 Ø1.5x1.25 6061-T6 ALUMINUM 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.01
.XXX ±.005
ANGLES ±0.5°
64
DESIGN KJM & DAB
DATE 07/31/91
DRAWN WN
APPRV DAB
RELEASE DAB
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE CONE
SEALANT APPLICATOR
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)SM-A106
PROJECT SHRP PROJECT
1.242 REF.
.680
31?
SECTION A-A
Ø1.482
Ø0.400
A
A
1
2

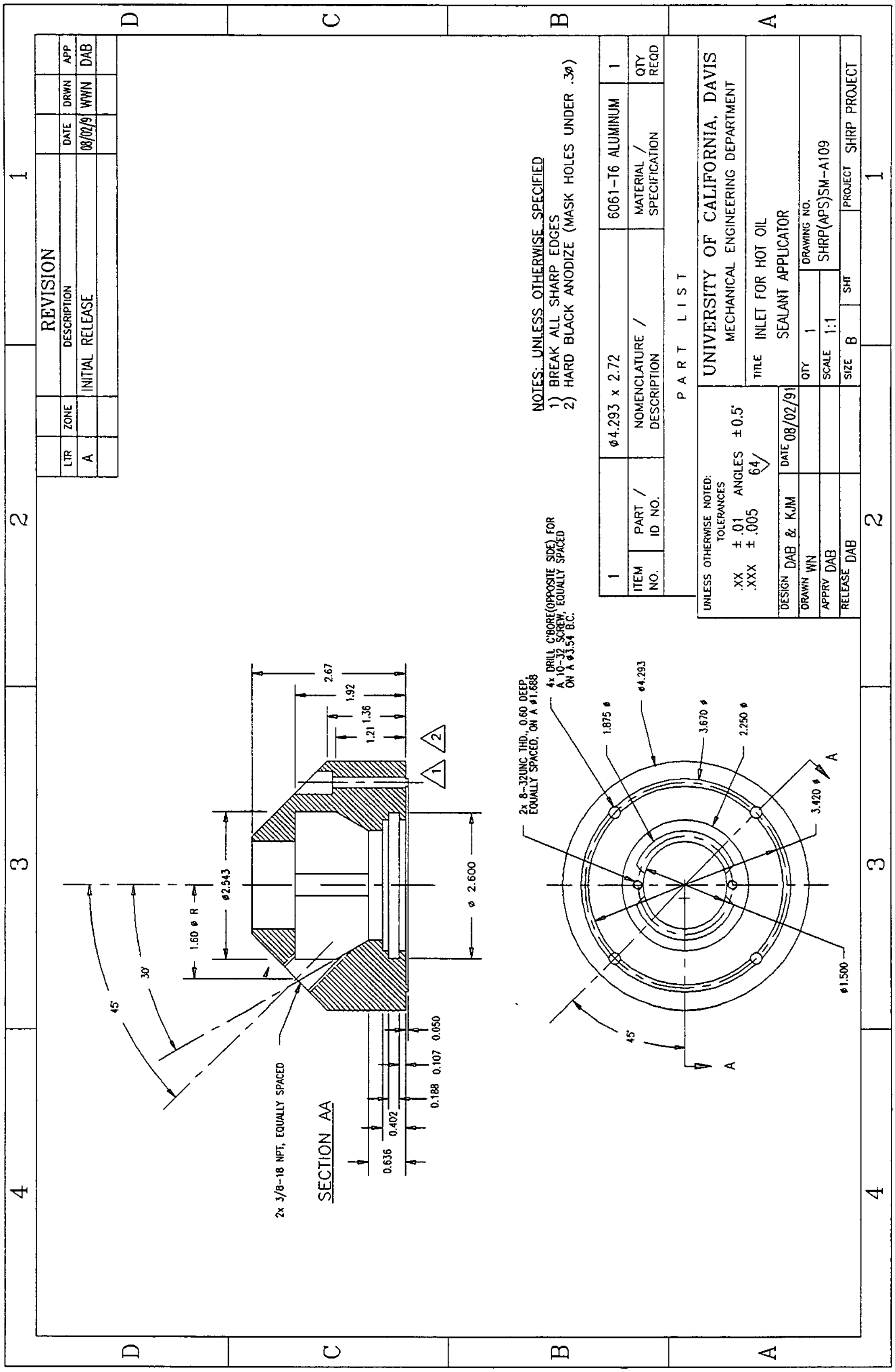
Drawing 1.5.8


REVISION
LTR | ZONE | DESCRIPTION | DATE | DRWN | APP
A | INITIAL RELEASE | 07/31/91 | WWN | DAB
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) HARD BLACK ANODIZE (MASK 4-40 HOLES)
1 | ø2.25x2.00 | 6061-T6 ALUMINUM | 1
ITEM NO. | PART / ID NO. | NOMENCLATURE / DESCRIPTION | MATERIAL / SPECIFICATION | QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES .XX ±.01 .XXX ±.005 ANGLES ±0.5° 64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE CONE-STOP SEALANT APPLICATOR
DESIGN KJM & DAB DATE 07/31/91
DRAWN WN
APPRV DAB
RELEASE DAB
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO. SHRP(APS)SM-A107
PROJECT SHRP PROJECT
ø2.250
ø1.875
ø1.375
ø1.803
0.120
0.52
1.921
0.250
18°
SECTION A-A
1 1/4-12UNF THD. THRU
2 1/16-16UNS THD. TO DEPTH SHOWN
3x 4-40 HELI-COIL 0.80 DEEP, ON A ø2.026 B.C.
30°
30°
3x 0.520
A
A
1
2
D C B A
1 2 3 4

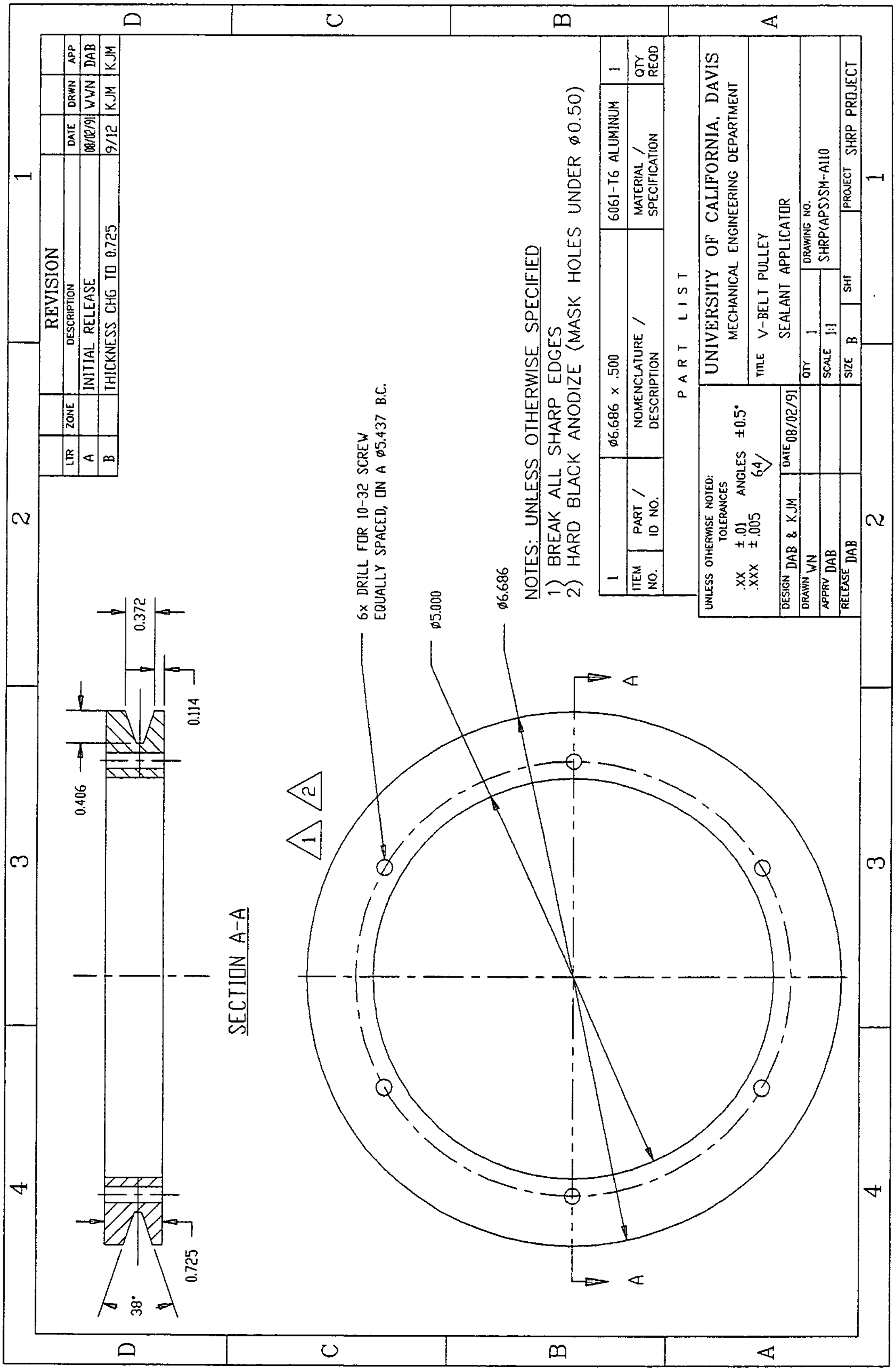
Drawing 1.5.9



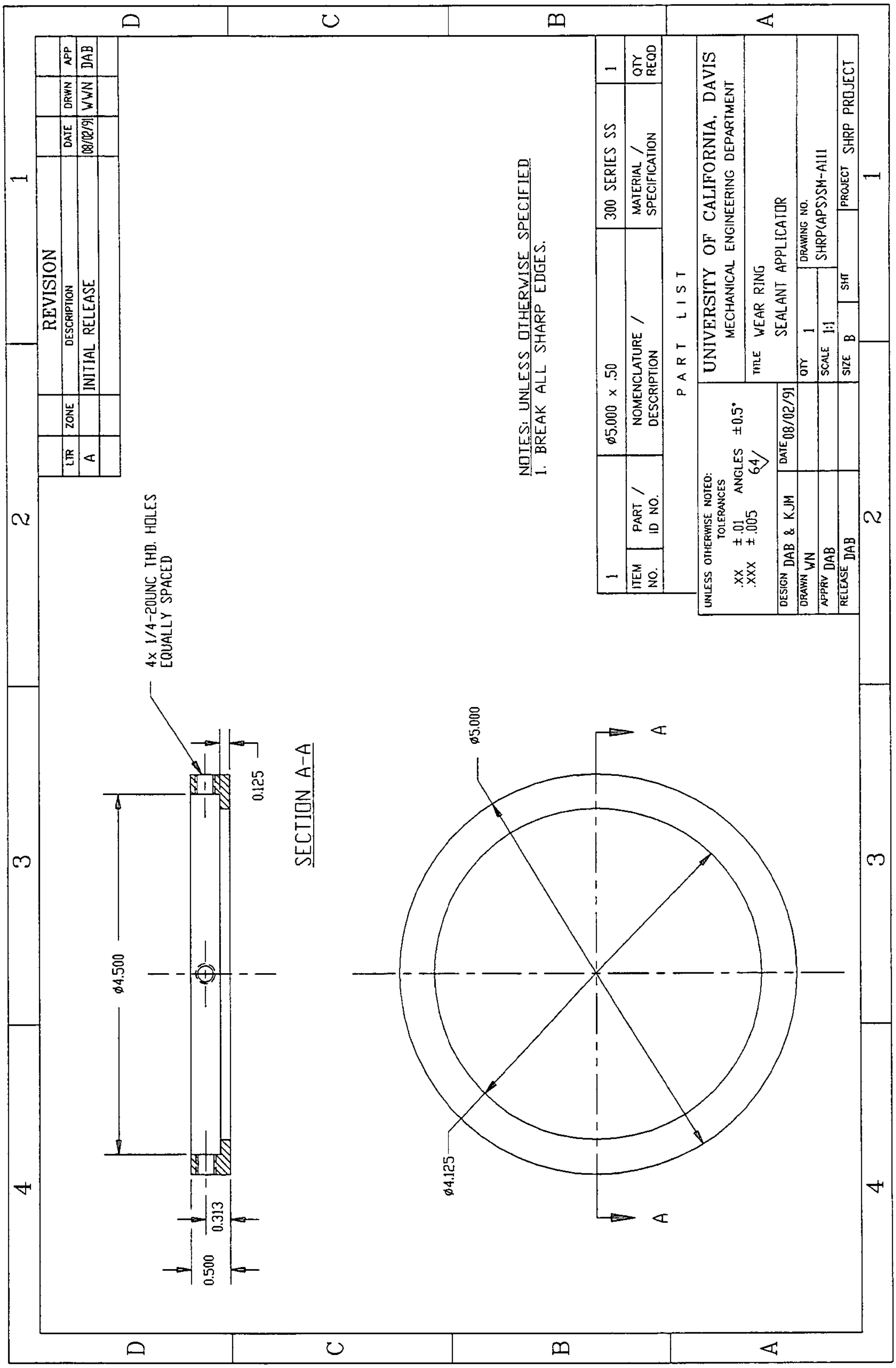
Drawing 1.5.10



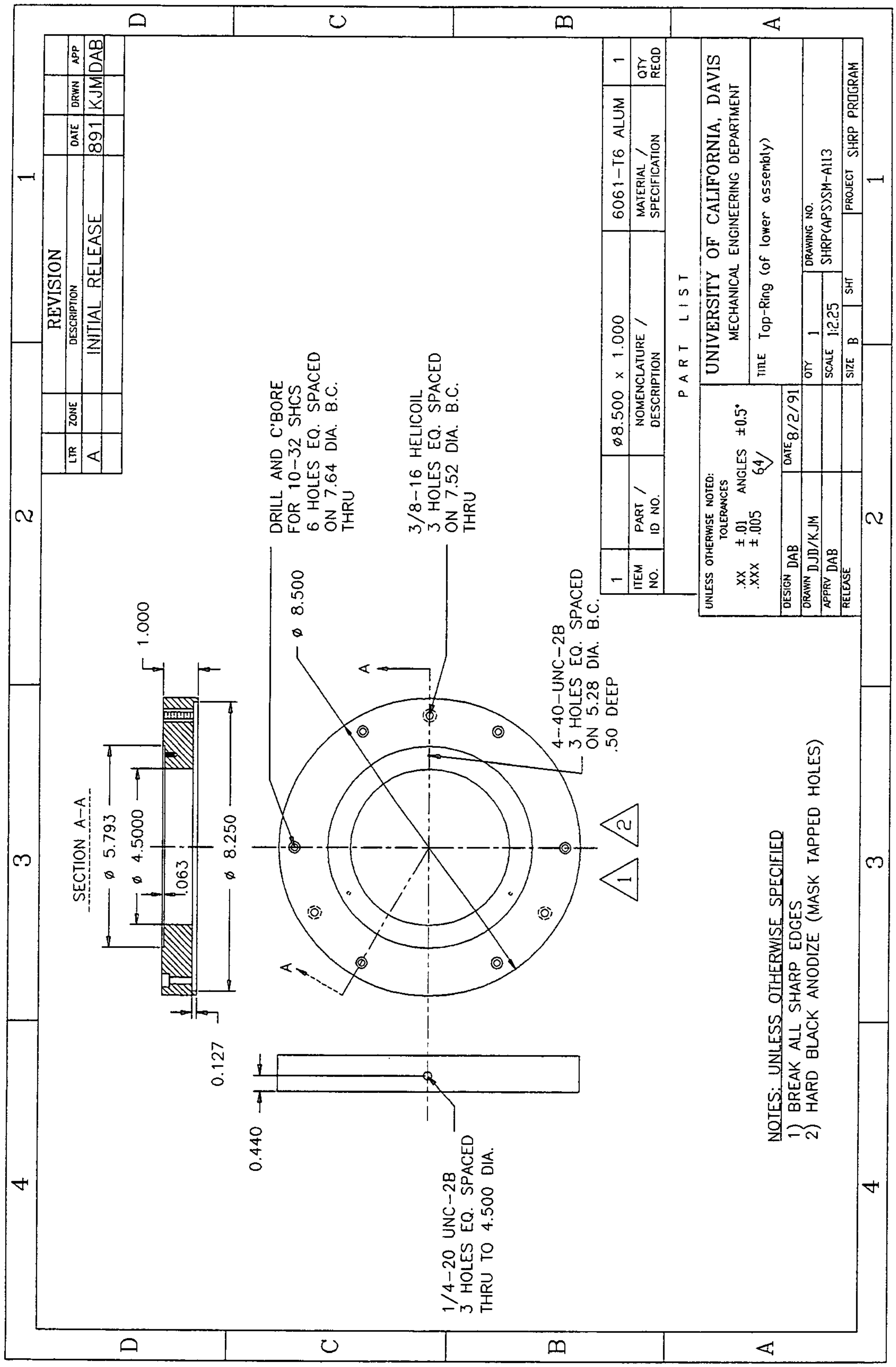
Drawing 1.5.11



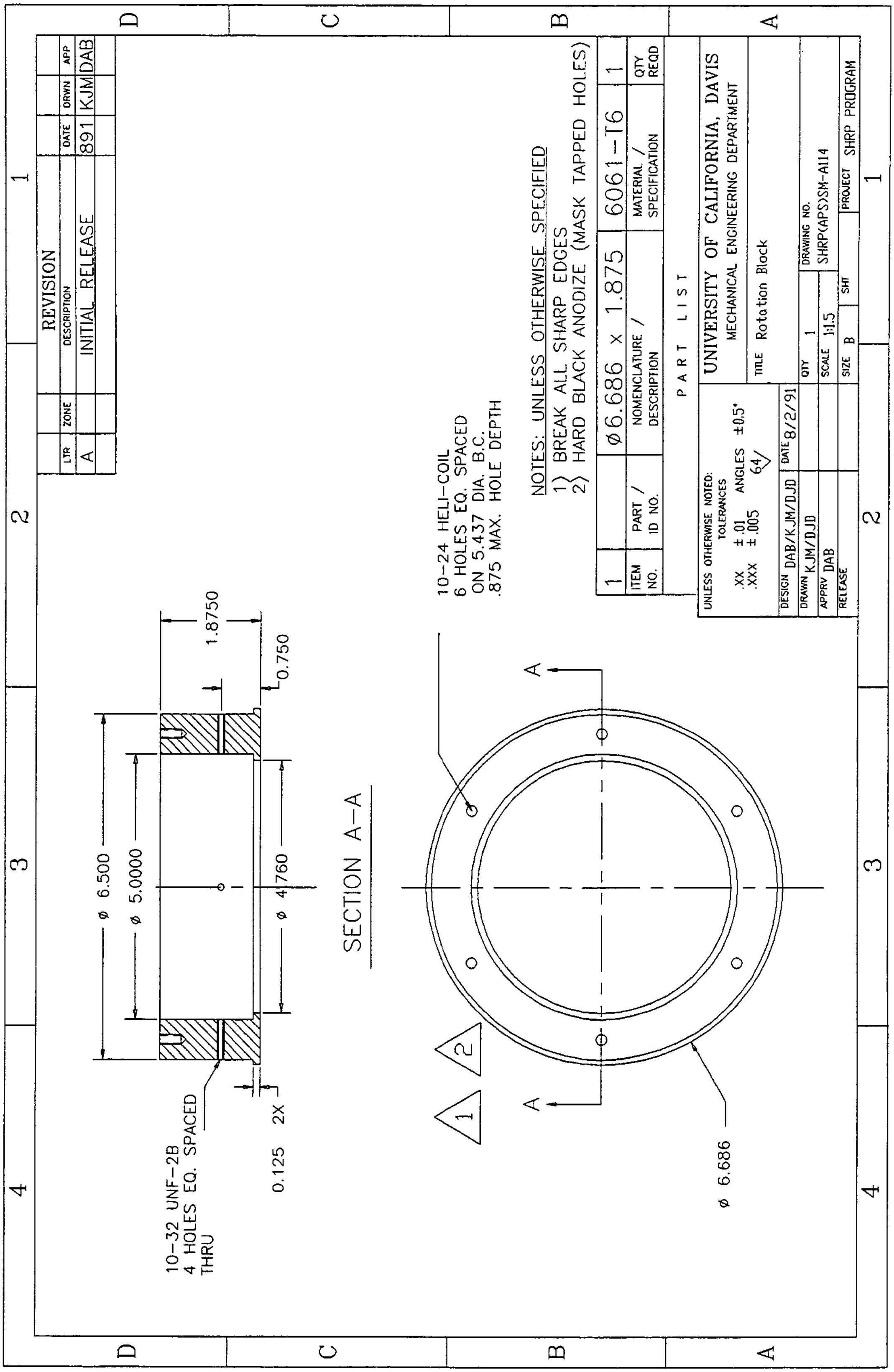
Drawing 1.5.12



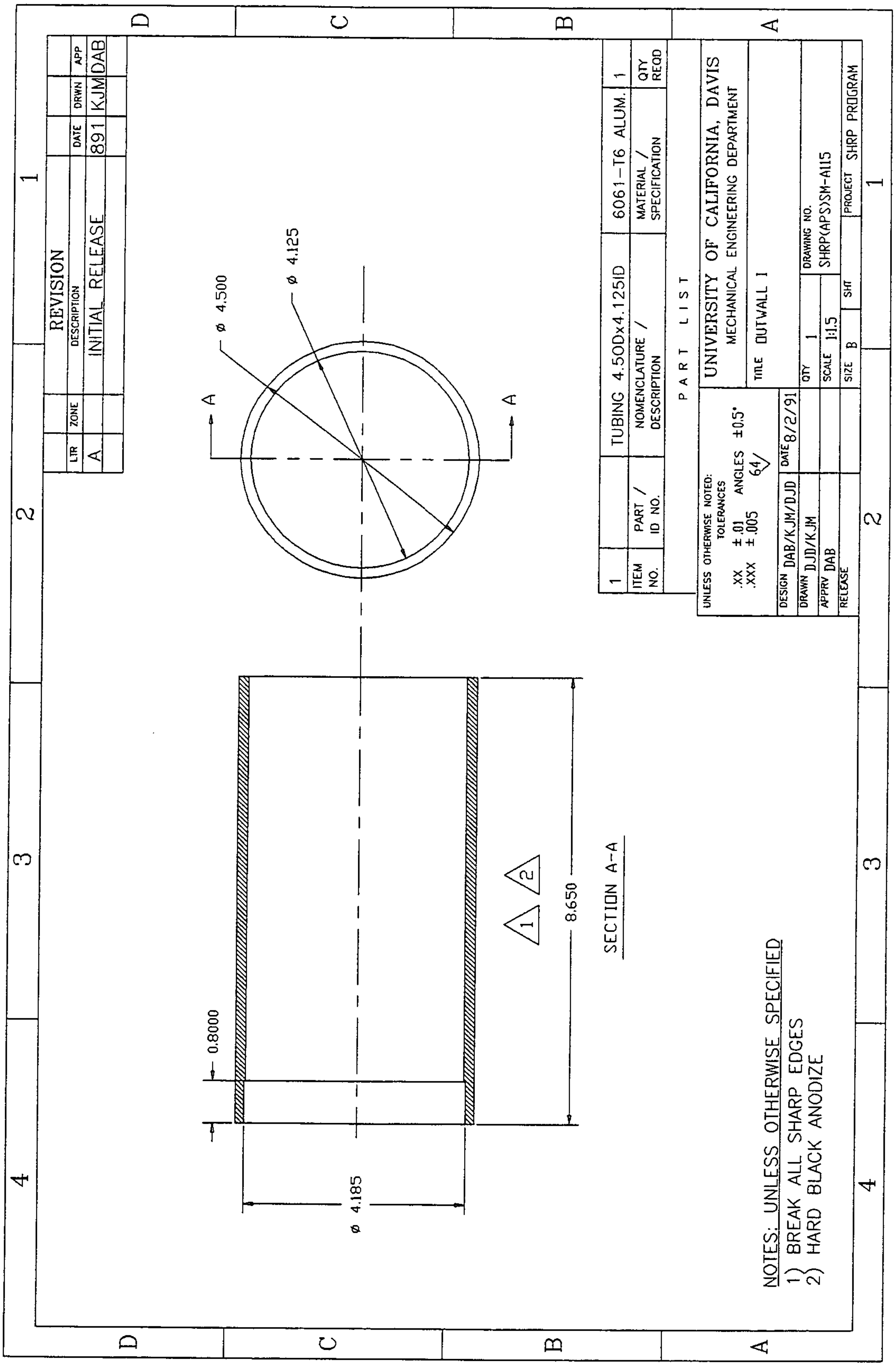
Drawing 1.5.13



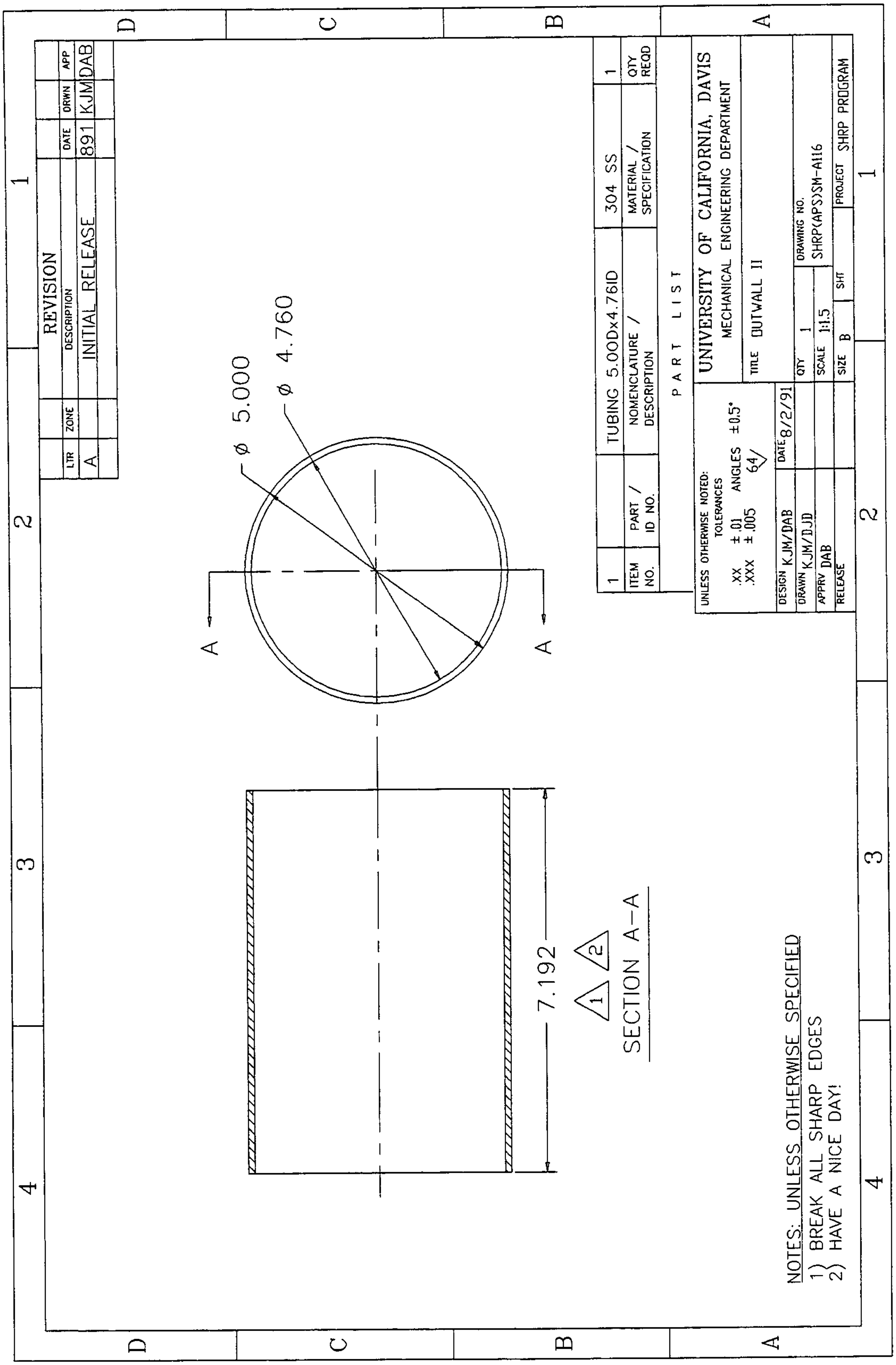
Drawing 1.5.14



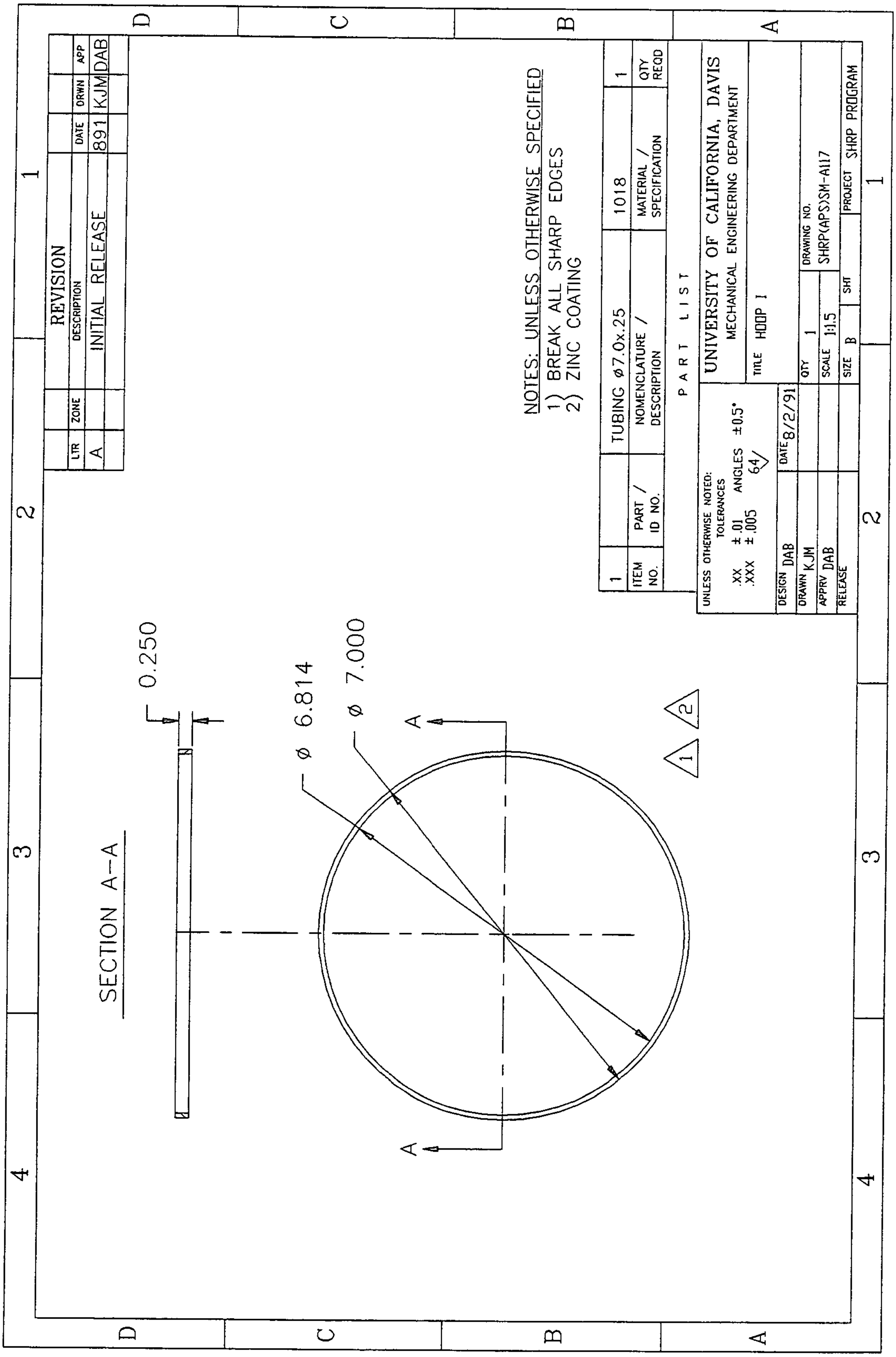
Drawing 1.5.15



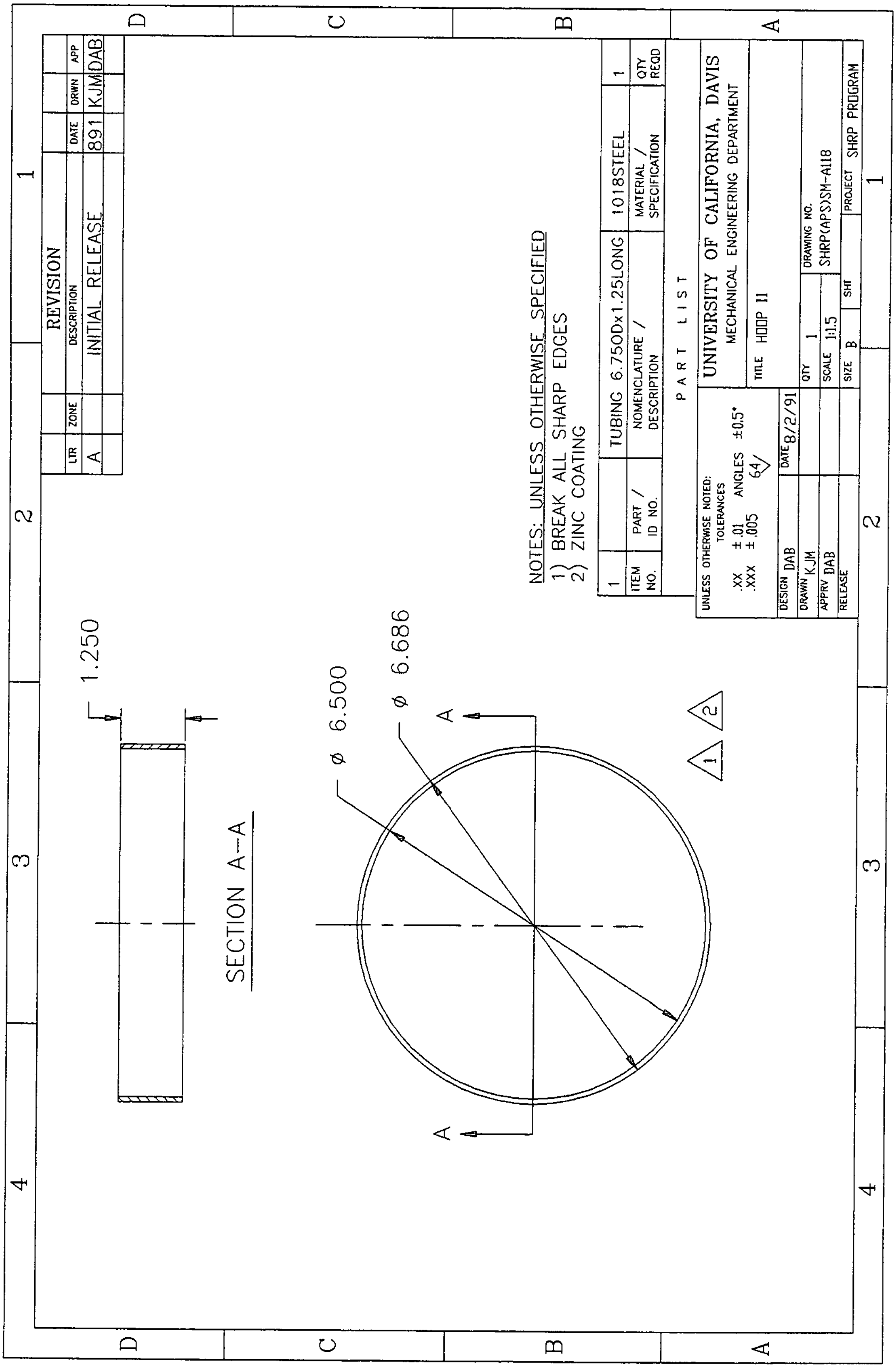
Drawing 1.5.16



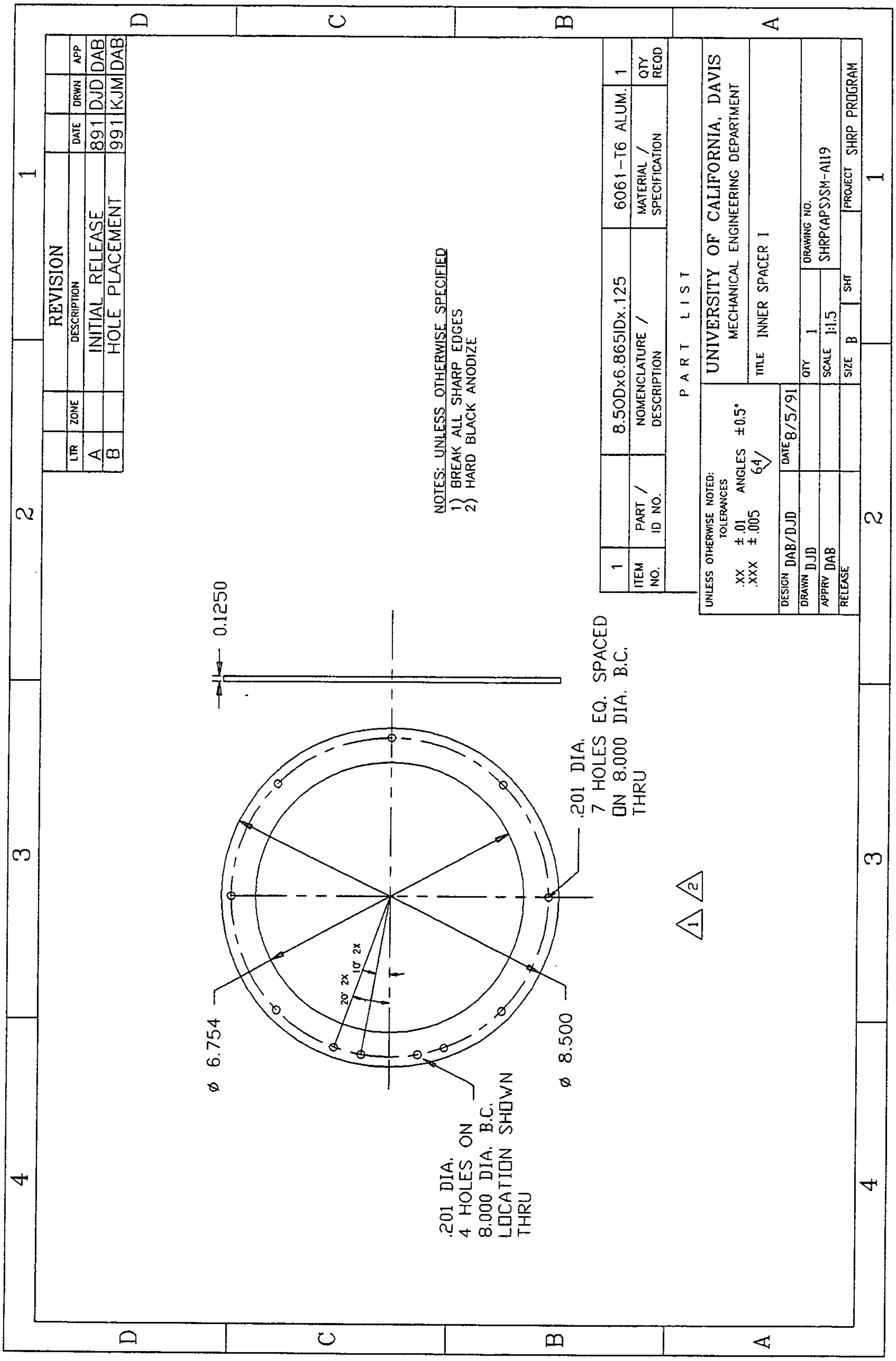
Drawing 1.5.17



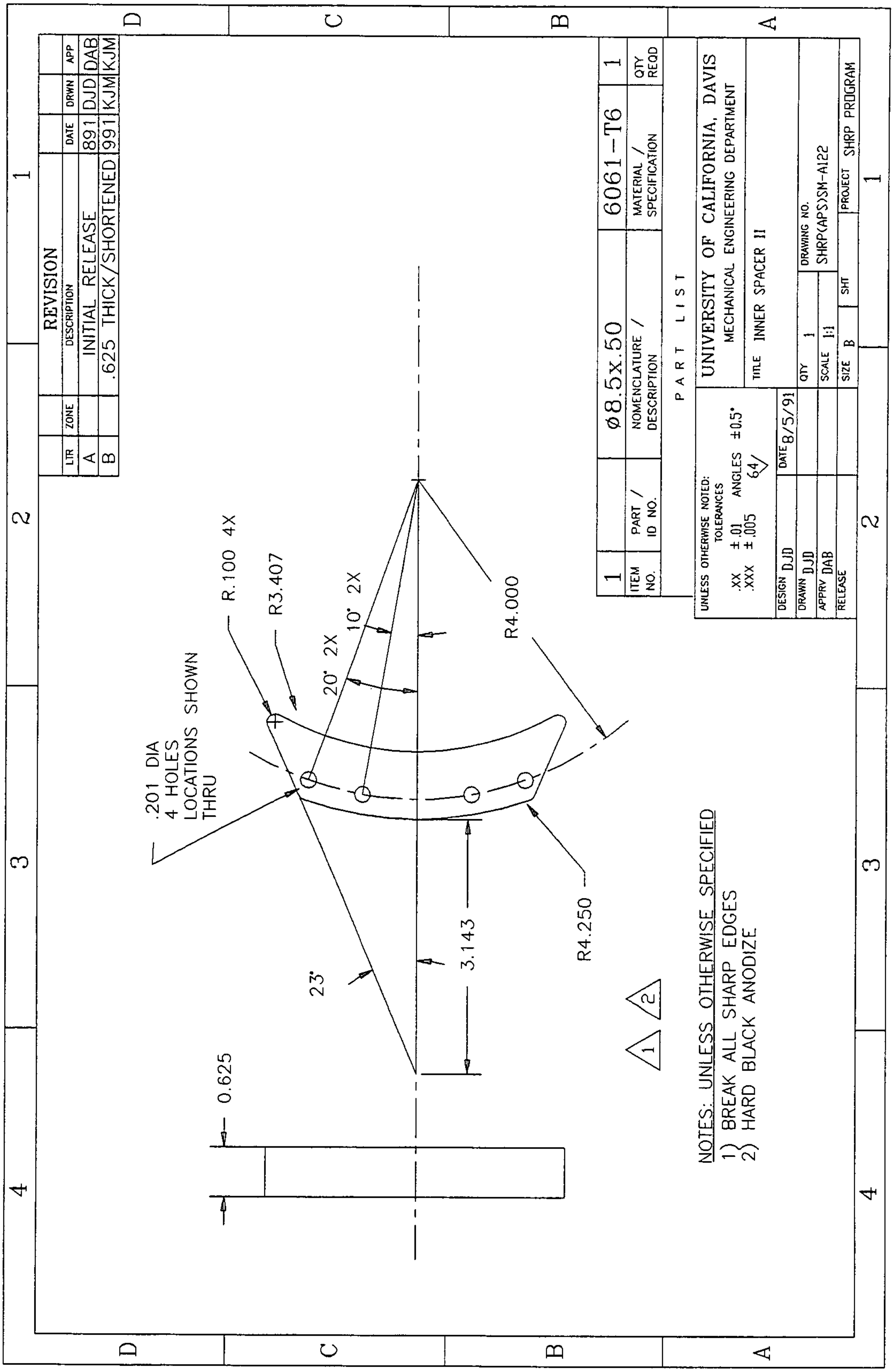
Drawing 1.5.18



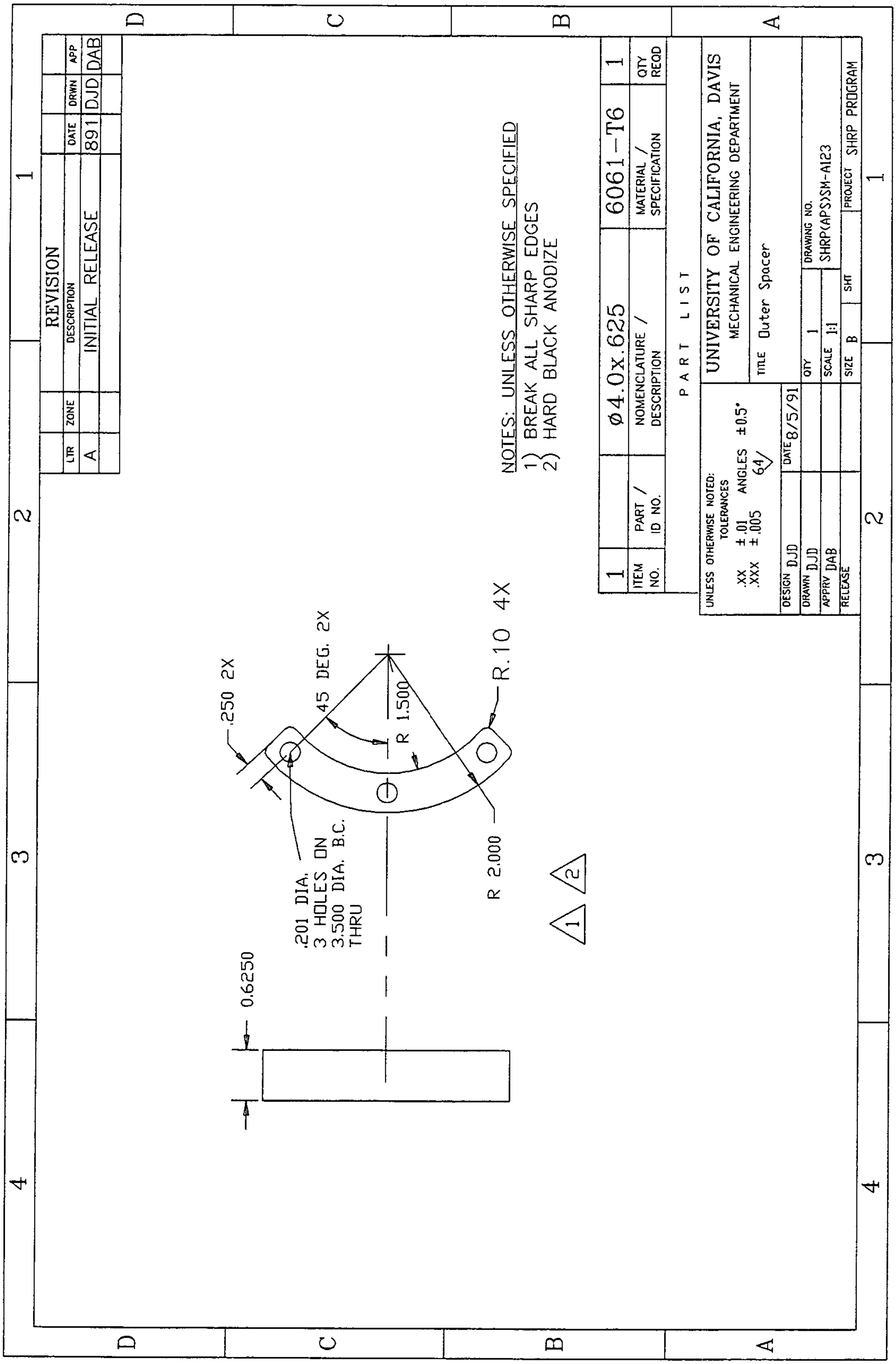
Drawing 1.5.19



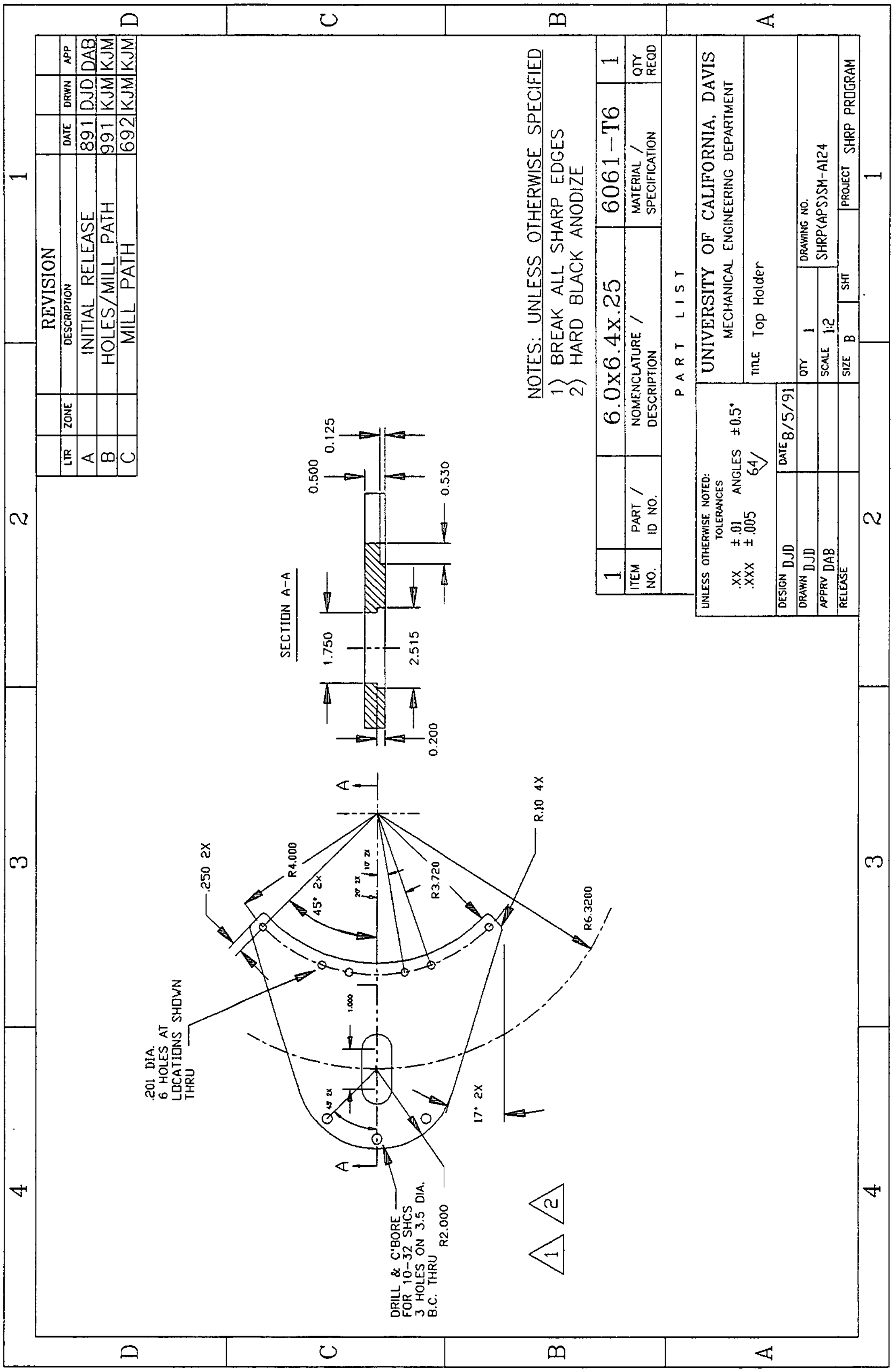
Drawing 1.5.20



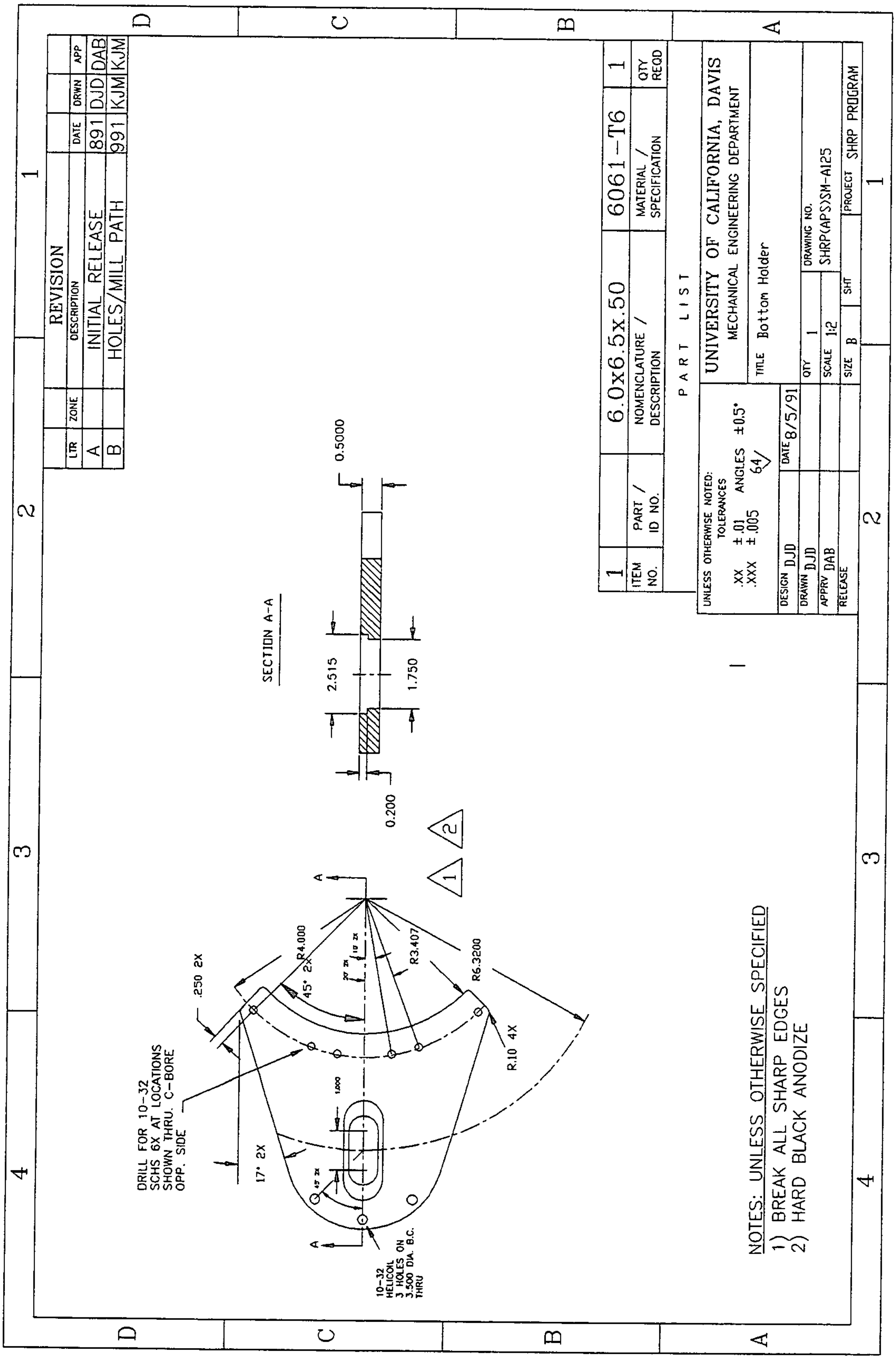
Drawing 1.5.21



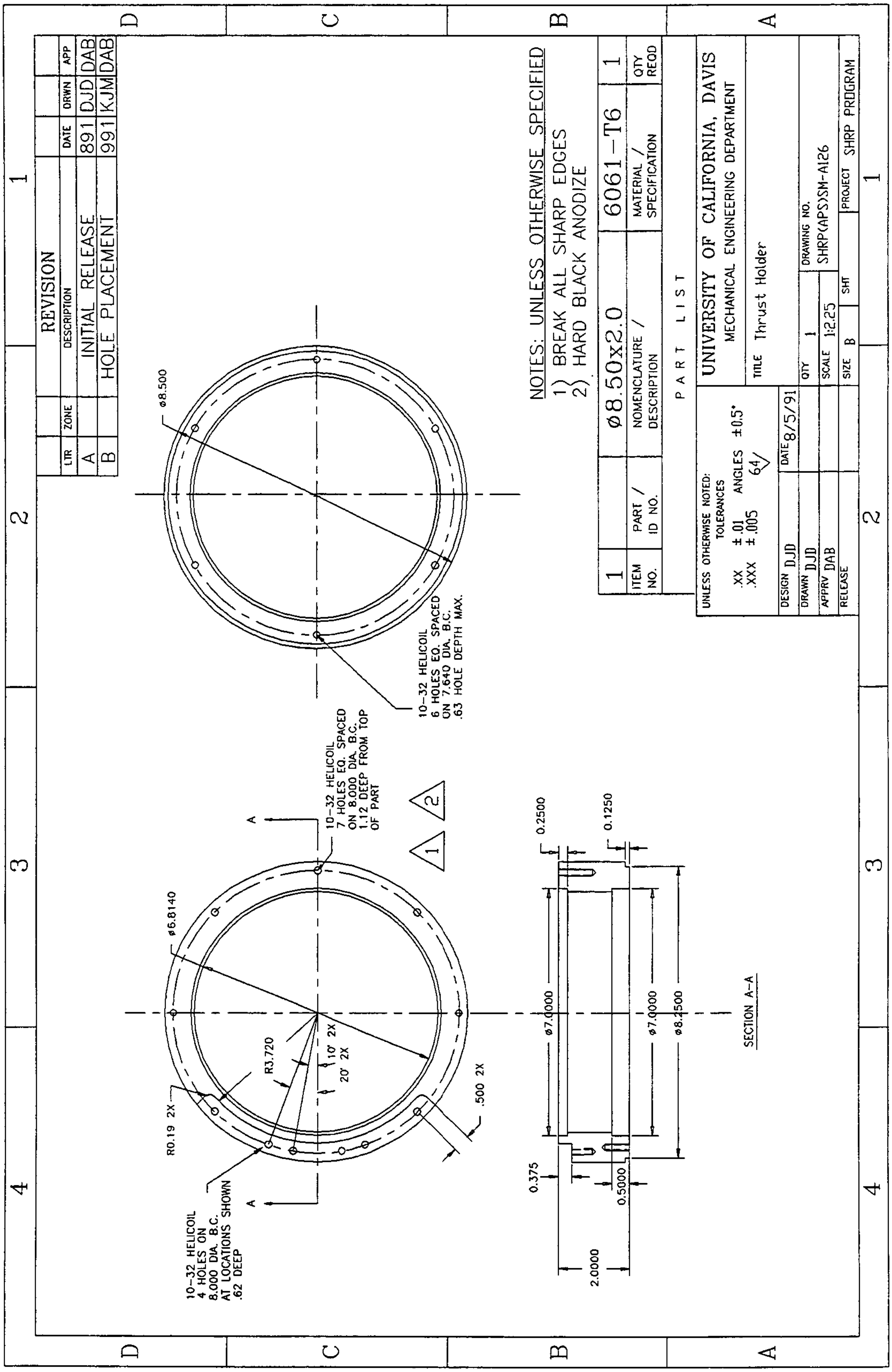
Drawing 1.5.22



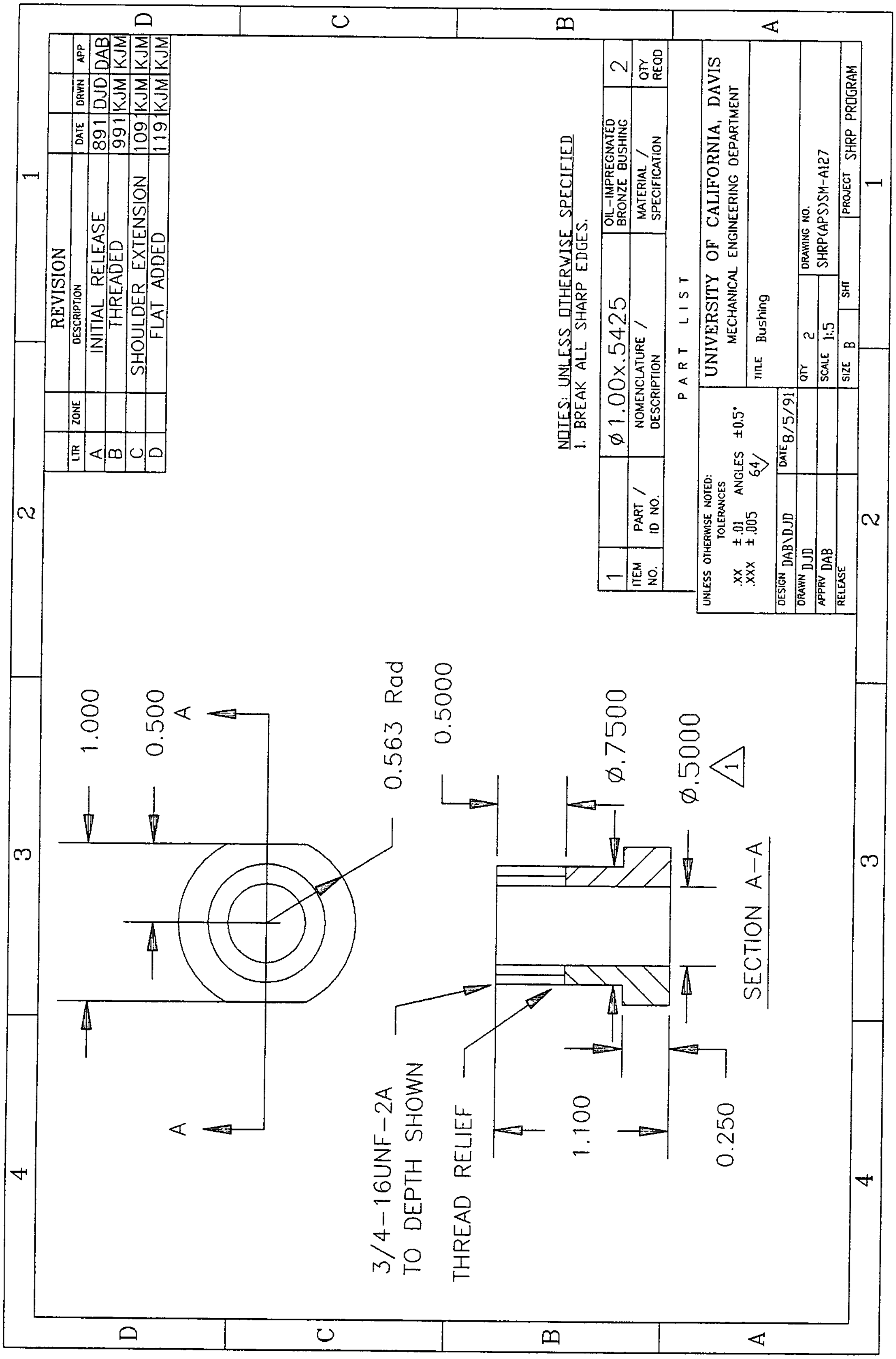
Drawing 1.5.23



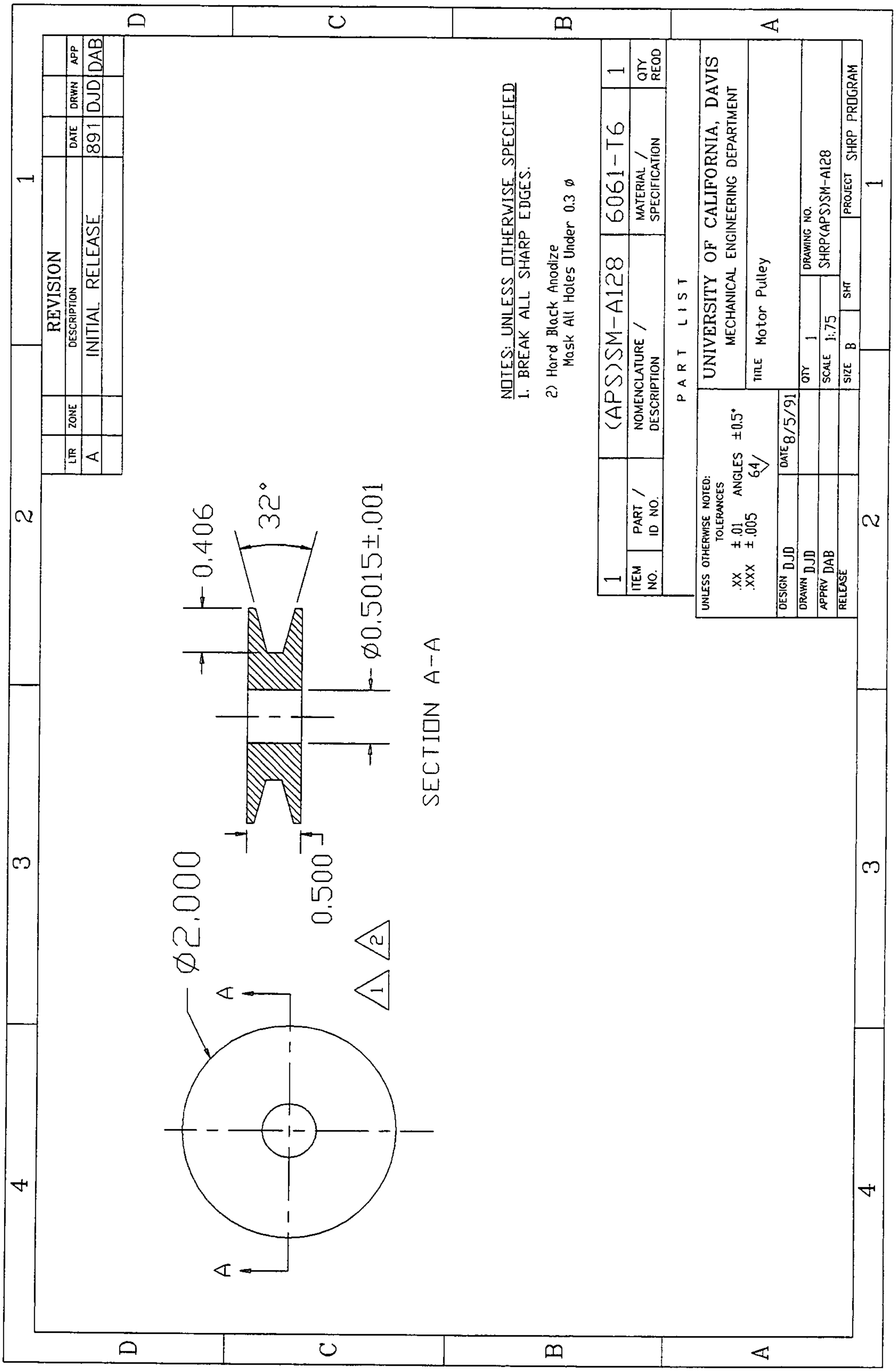
Drawing 1.5.24



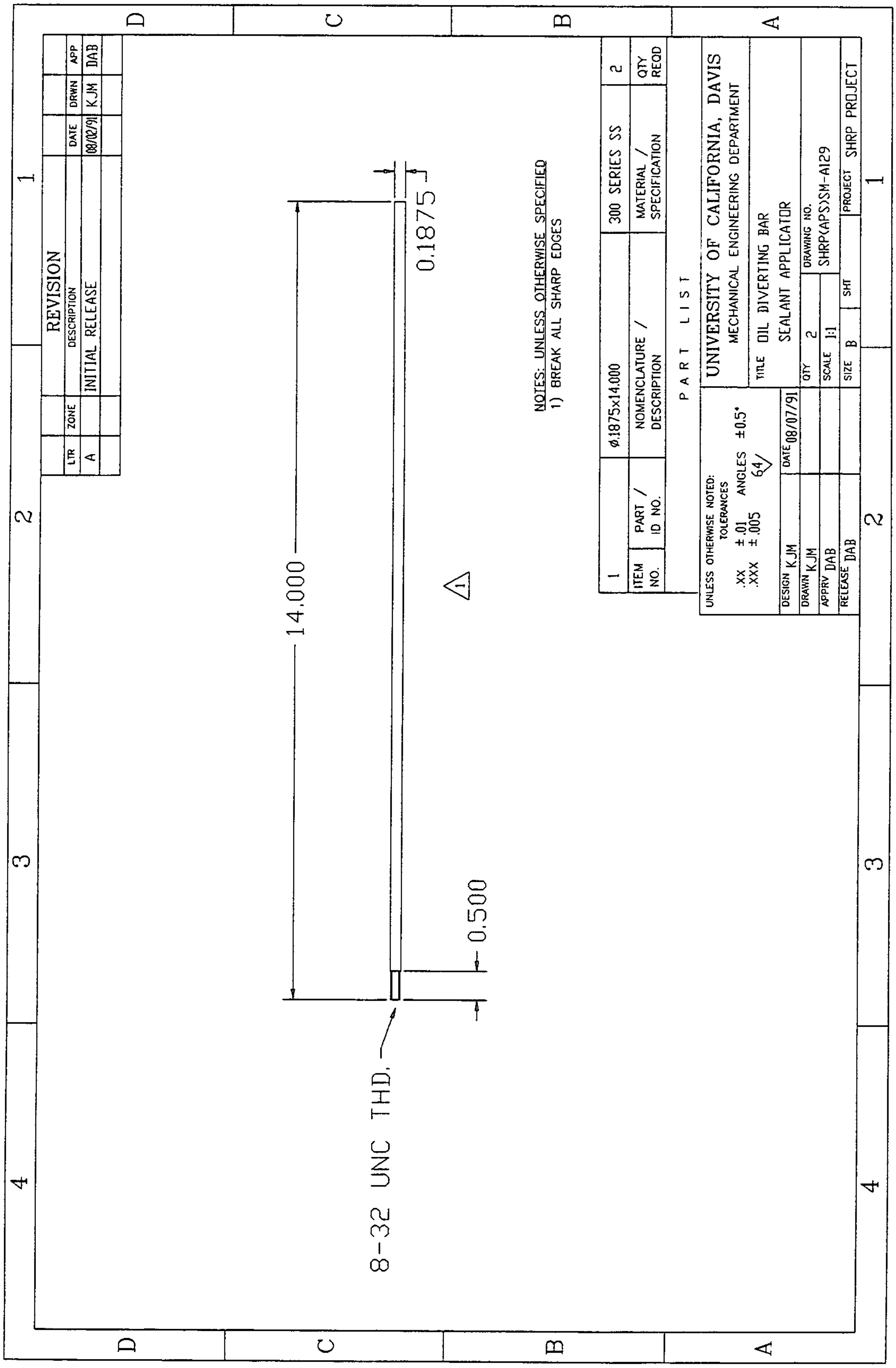
Drawing 1.5.25



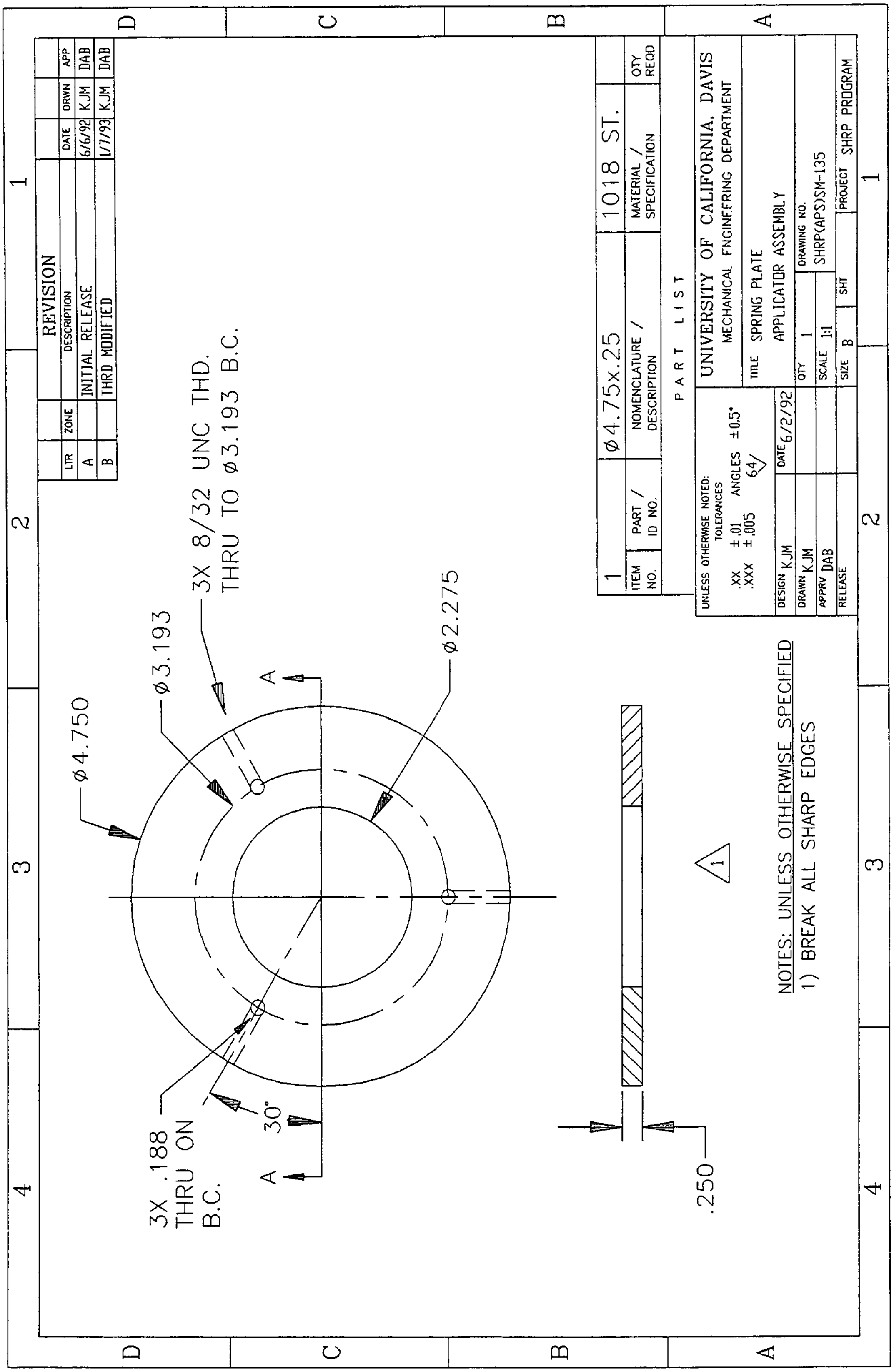
Drawing 1.5.26



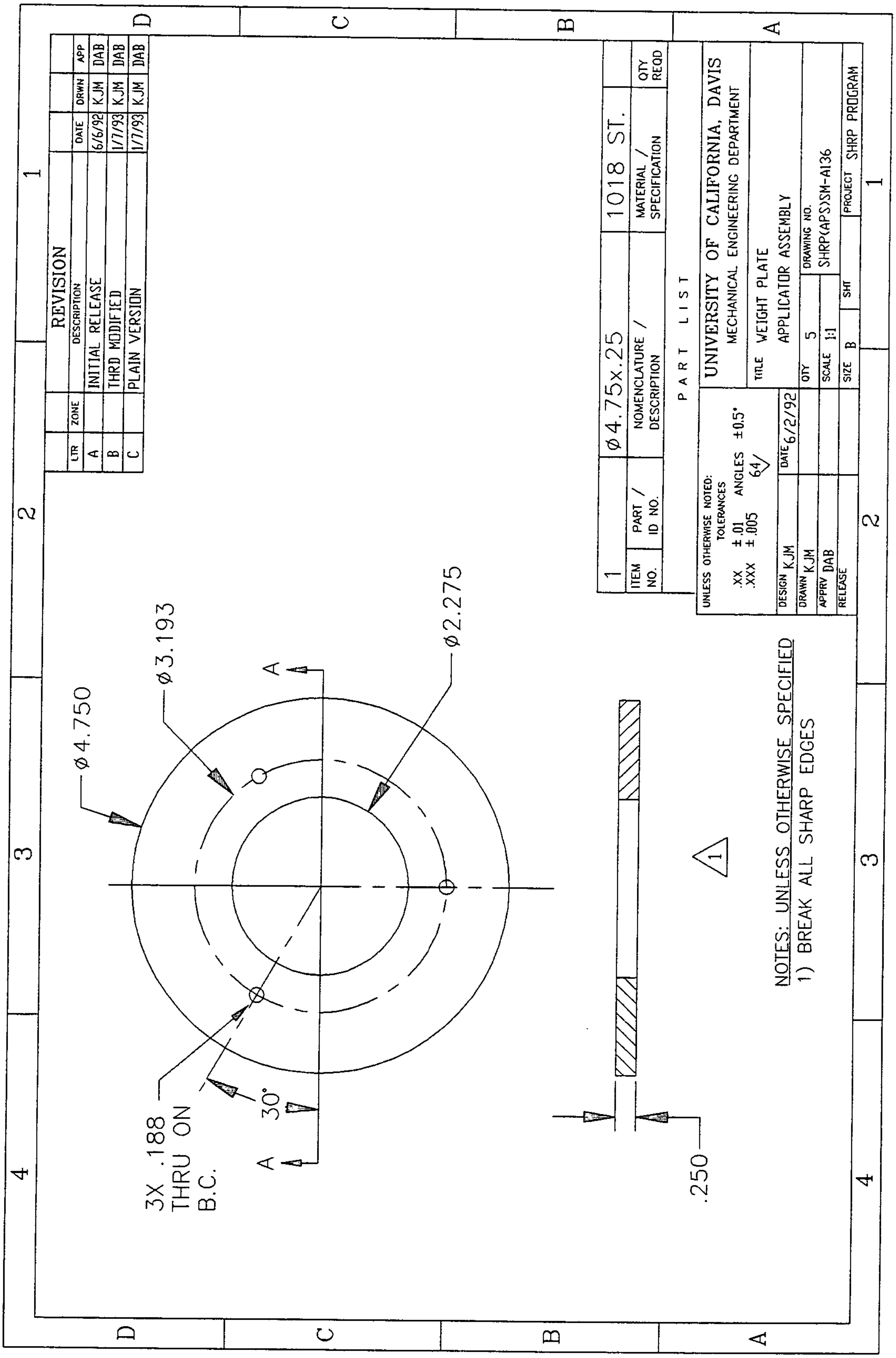
Drawing 1.5.27



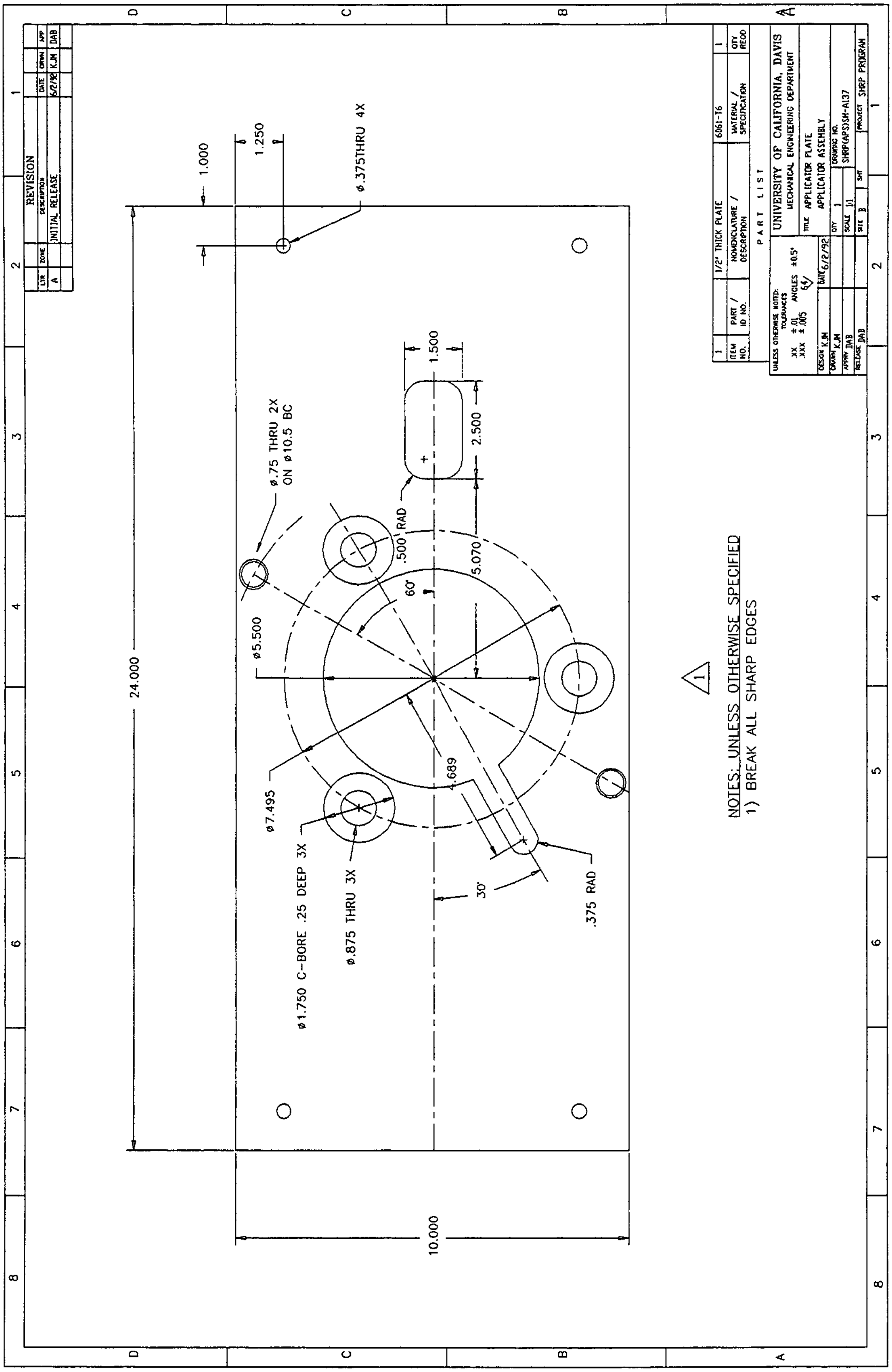
Drawing 1.5.28



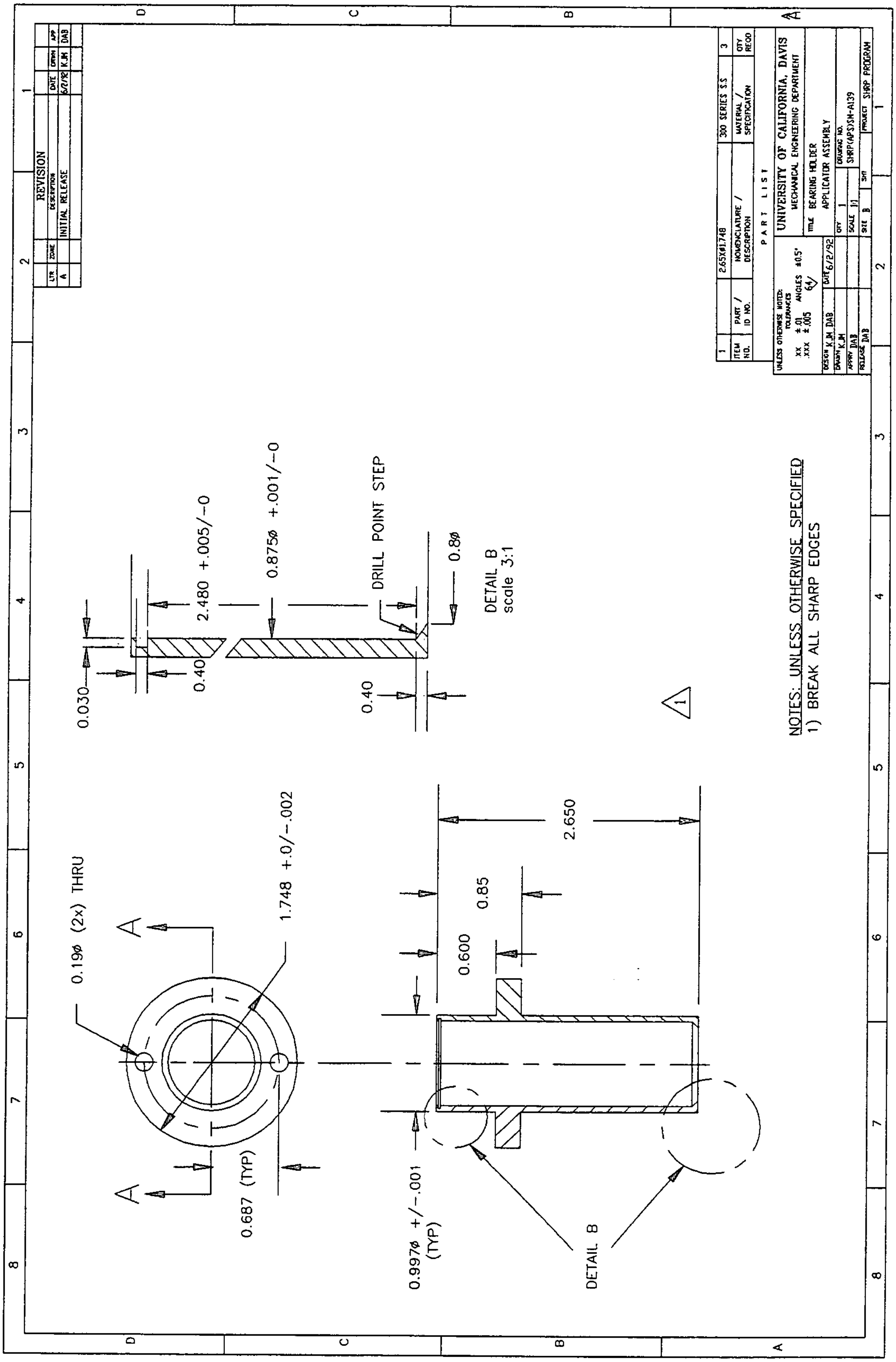
Drawing 1.5.29



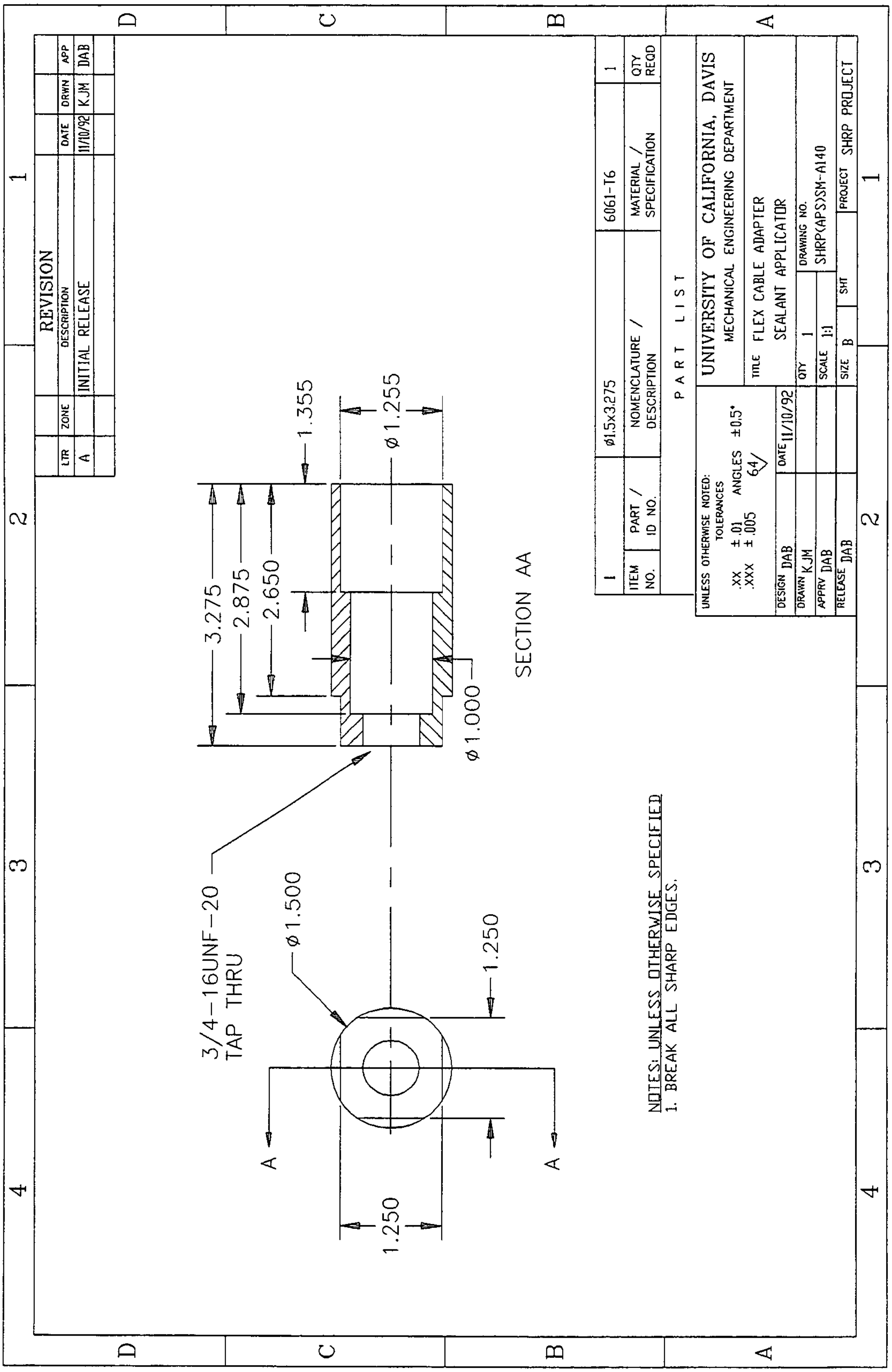
Drawing 1.5.30



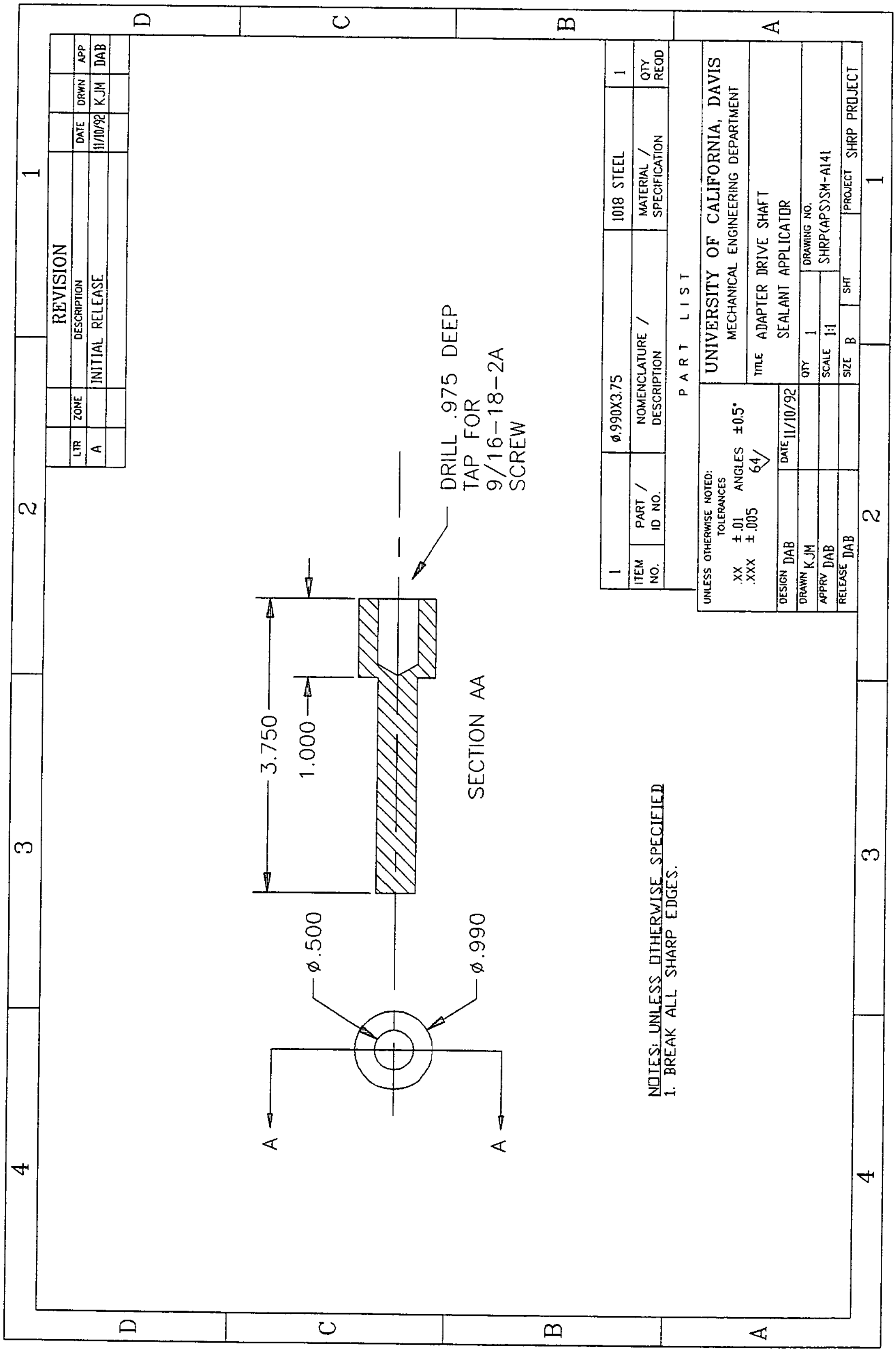
Drawing 1.5.31



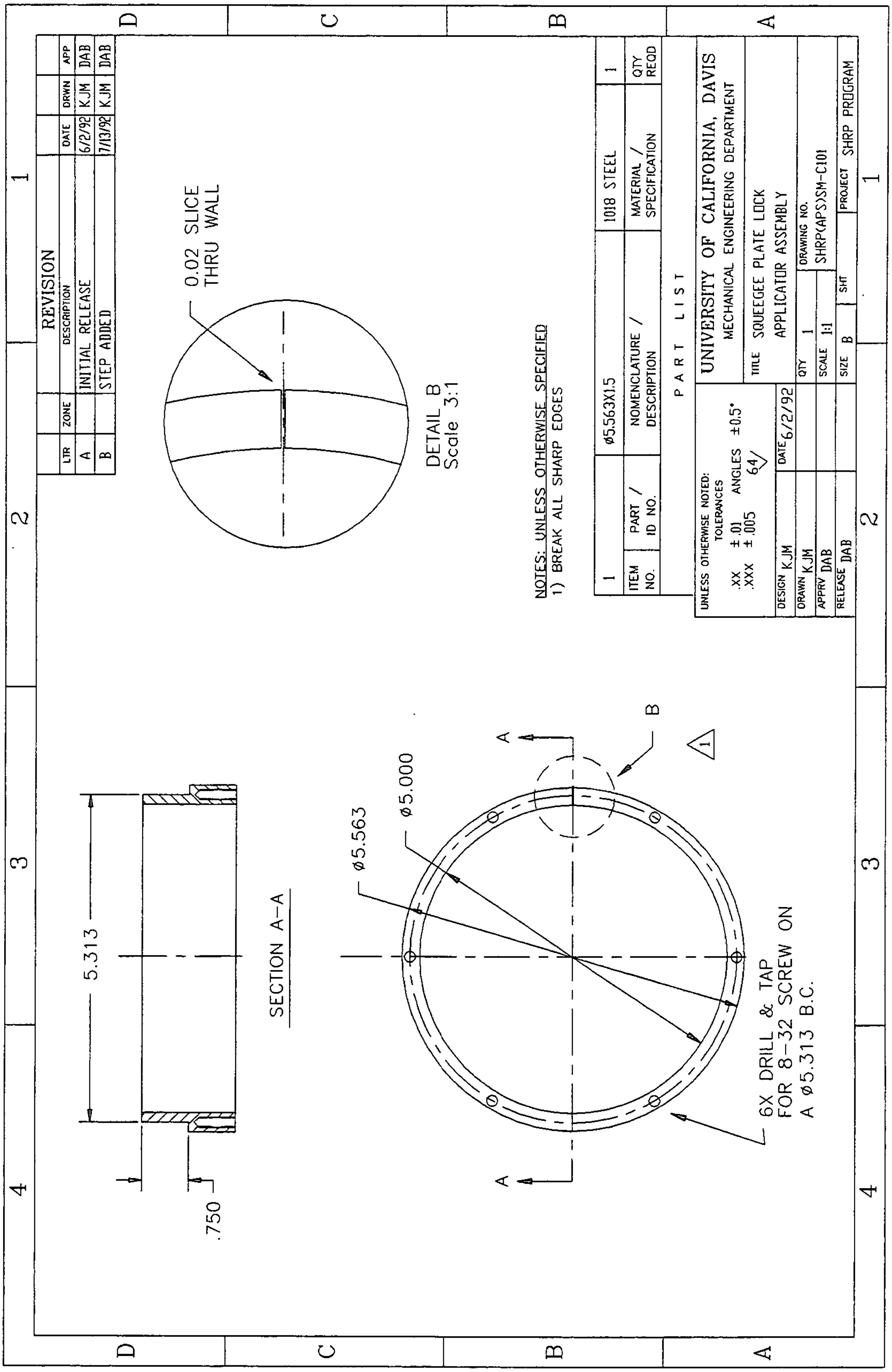
Drawing 1.5.32



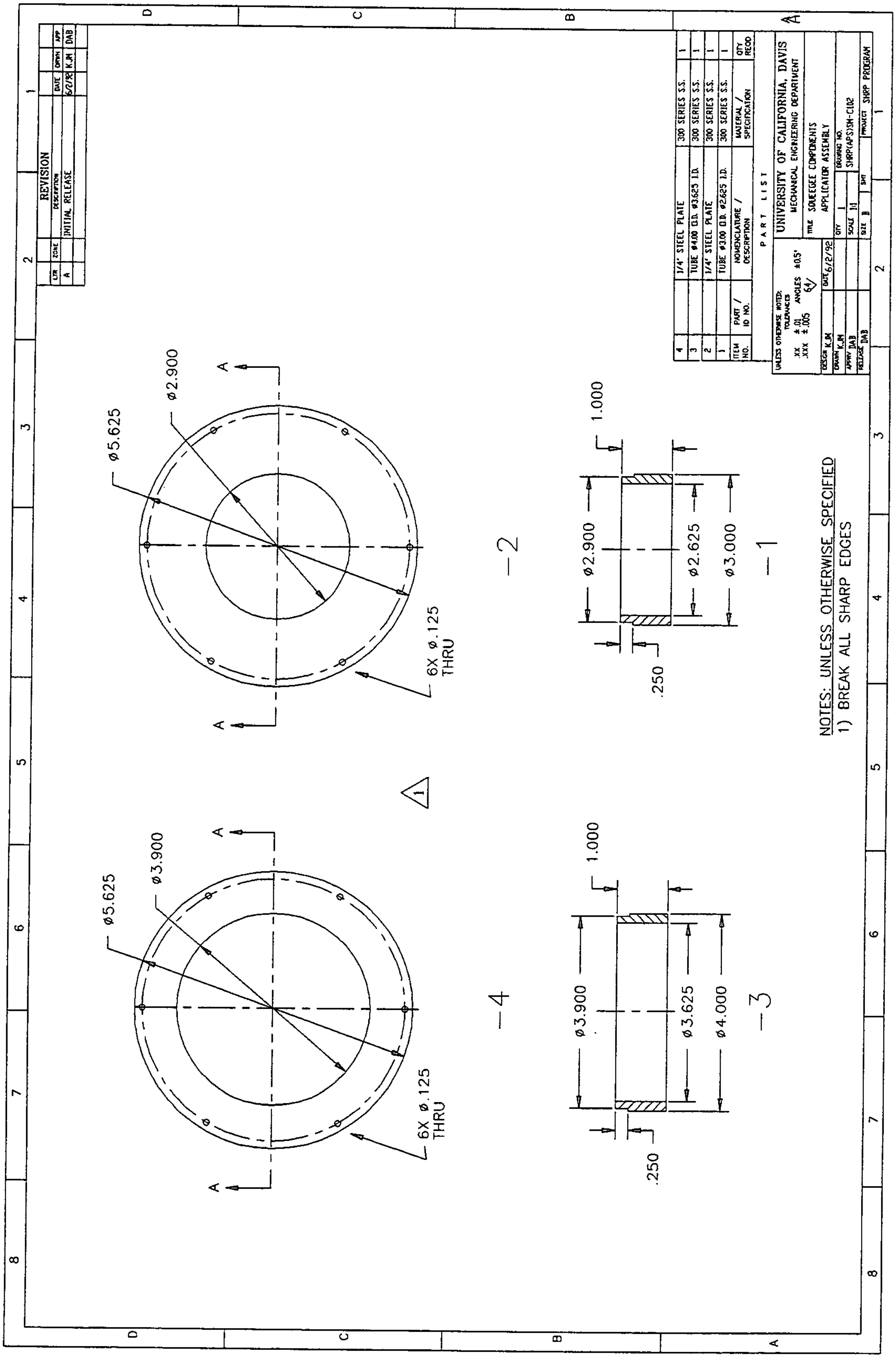
Drawing 1.5.33



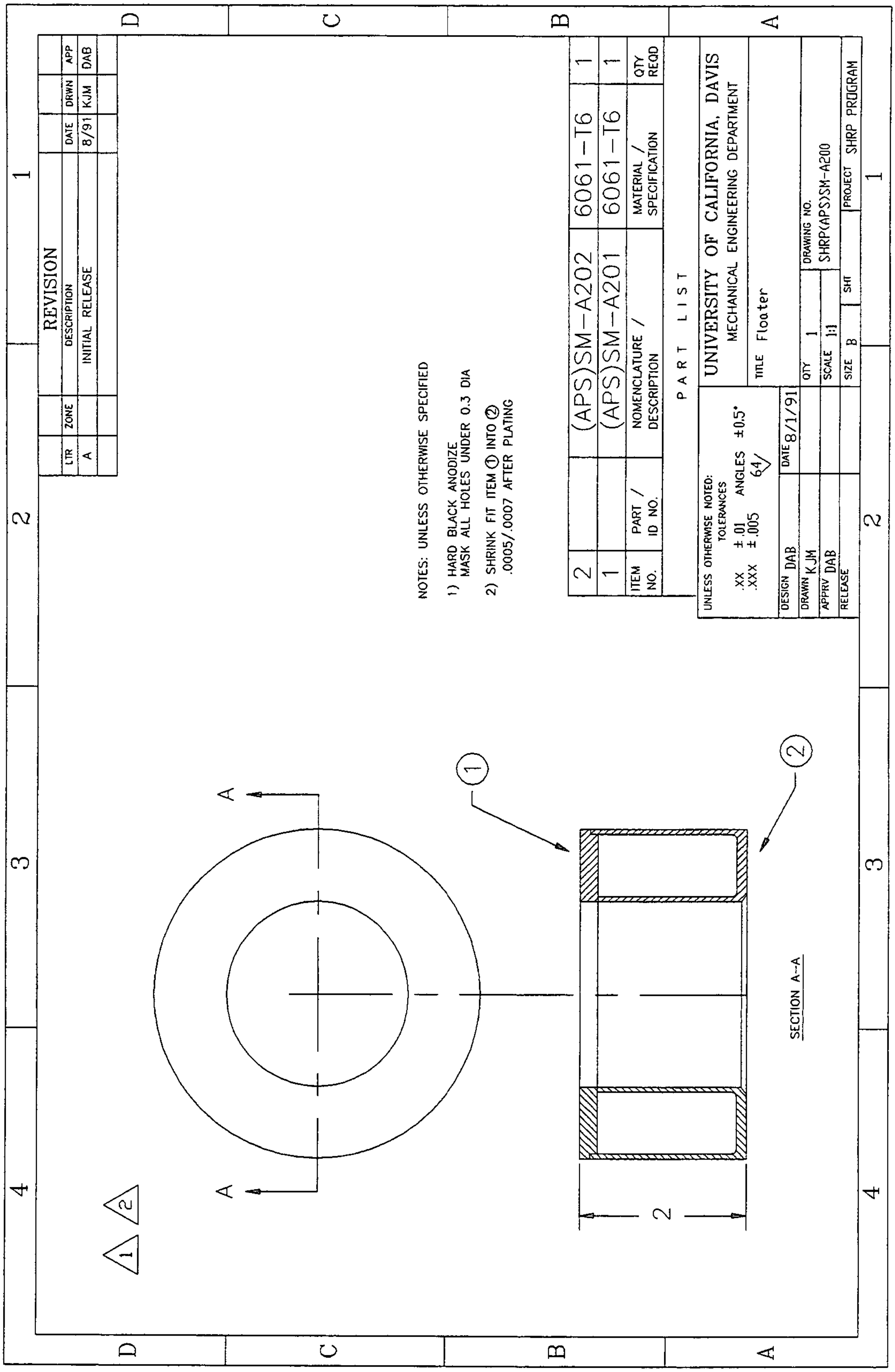
Drawing 1.5.34



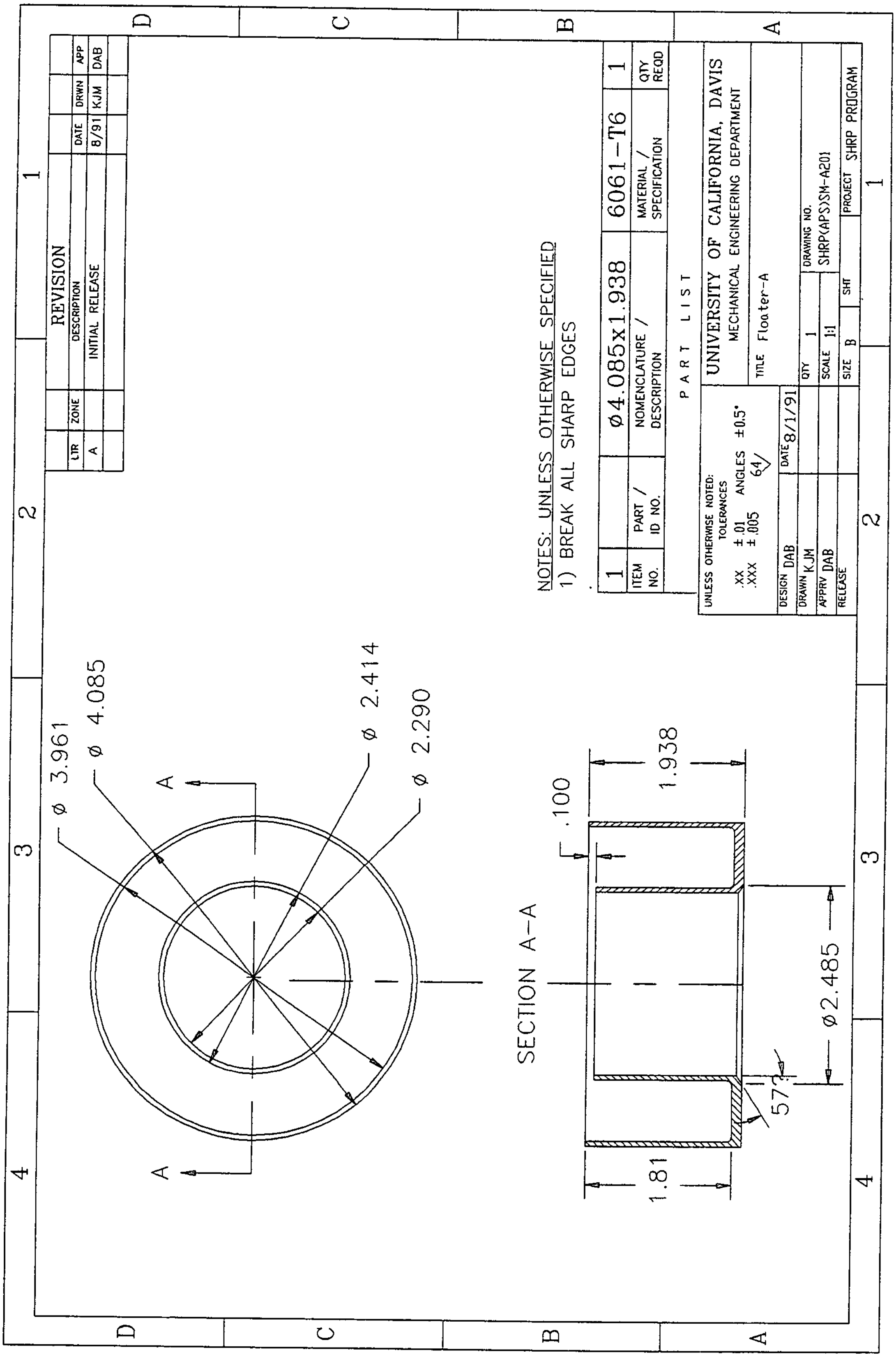
Drawing 1.5.35



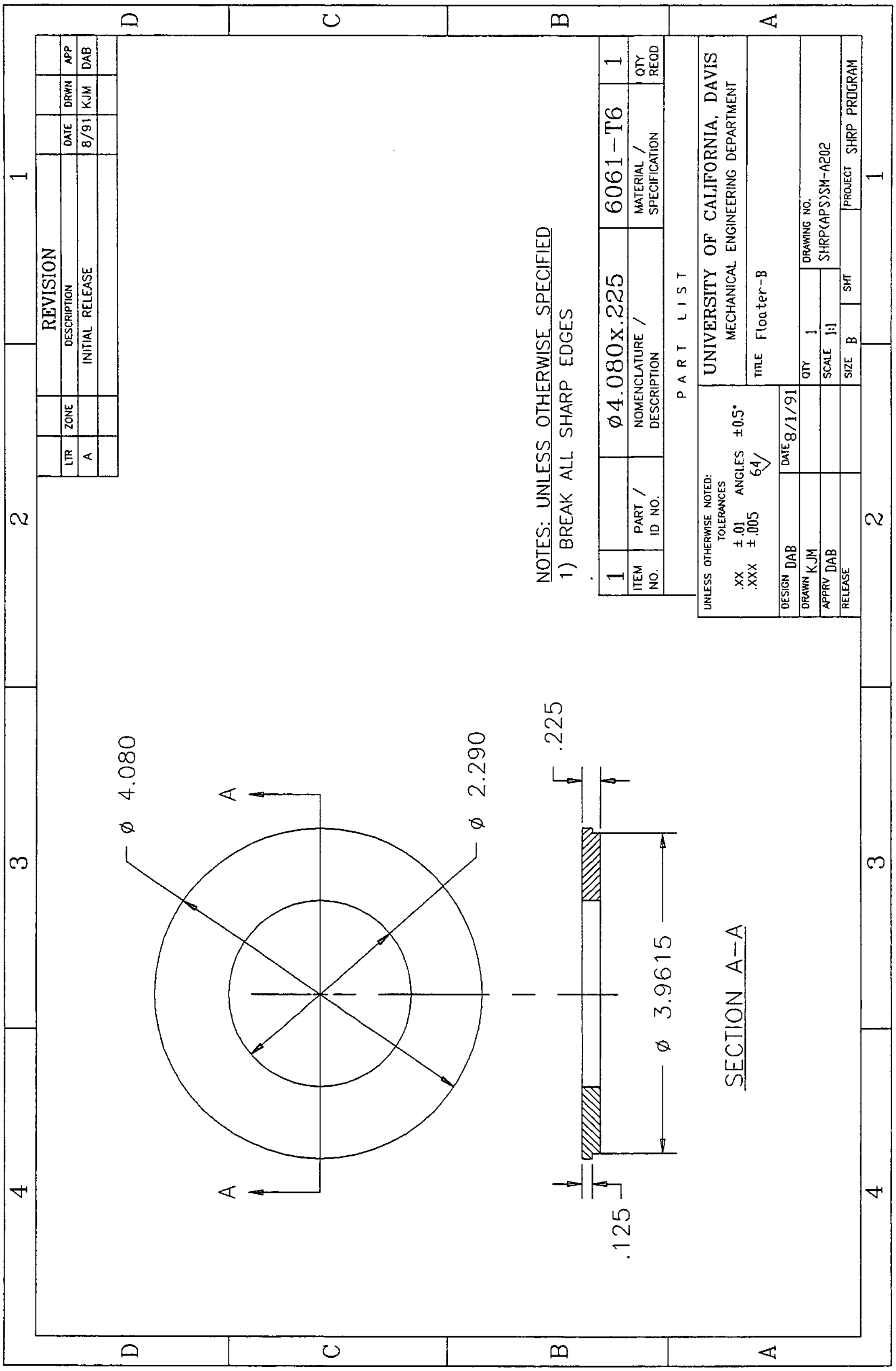
Drawing 1.5.36



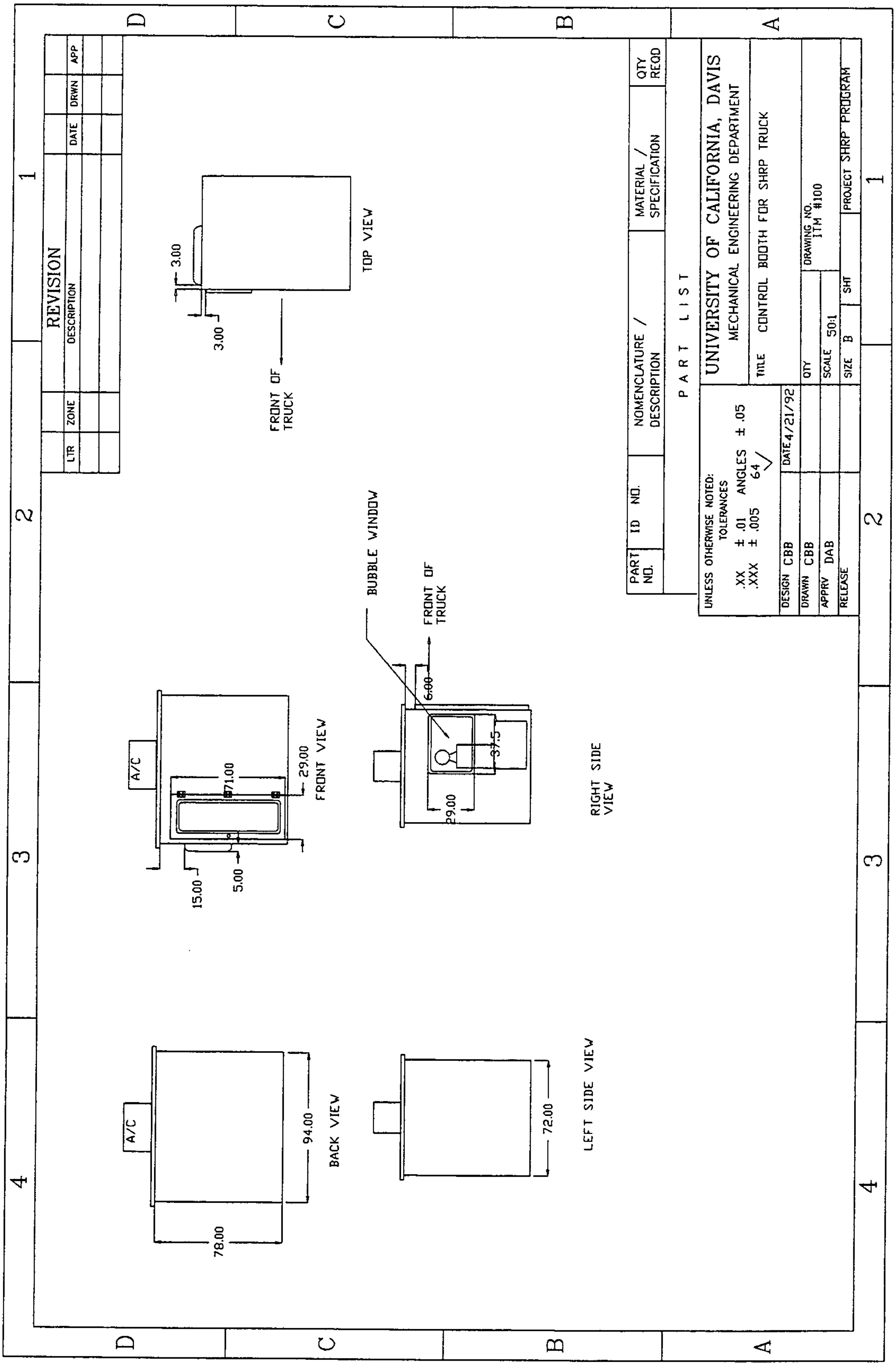
Drawing 1.5.37



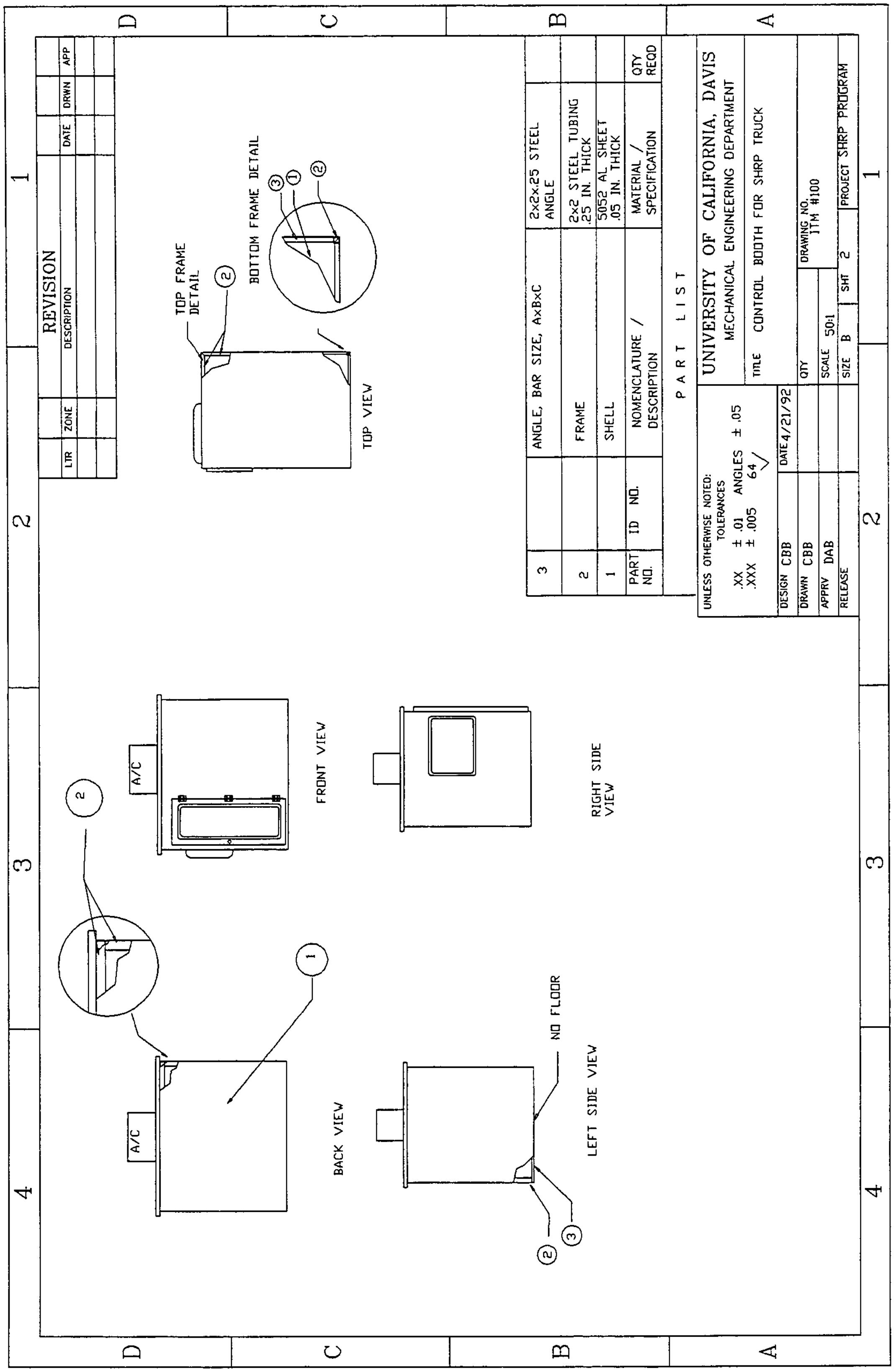
Drawing 1.5.38



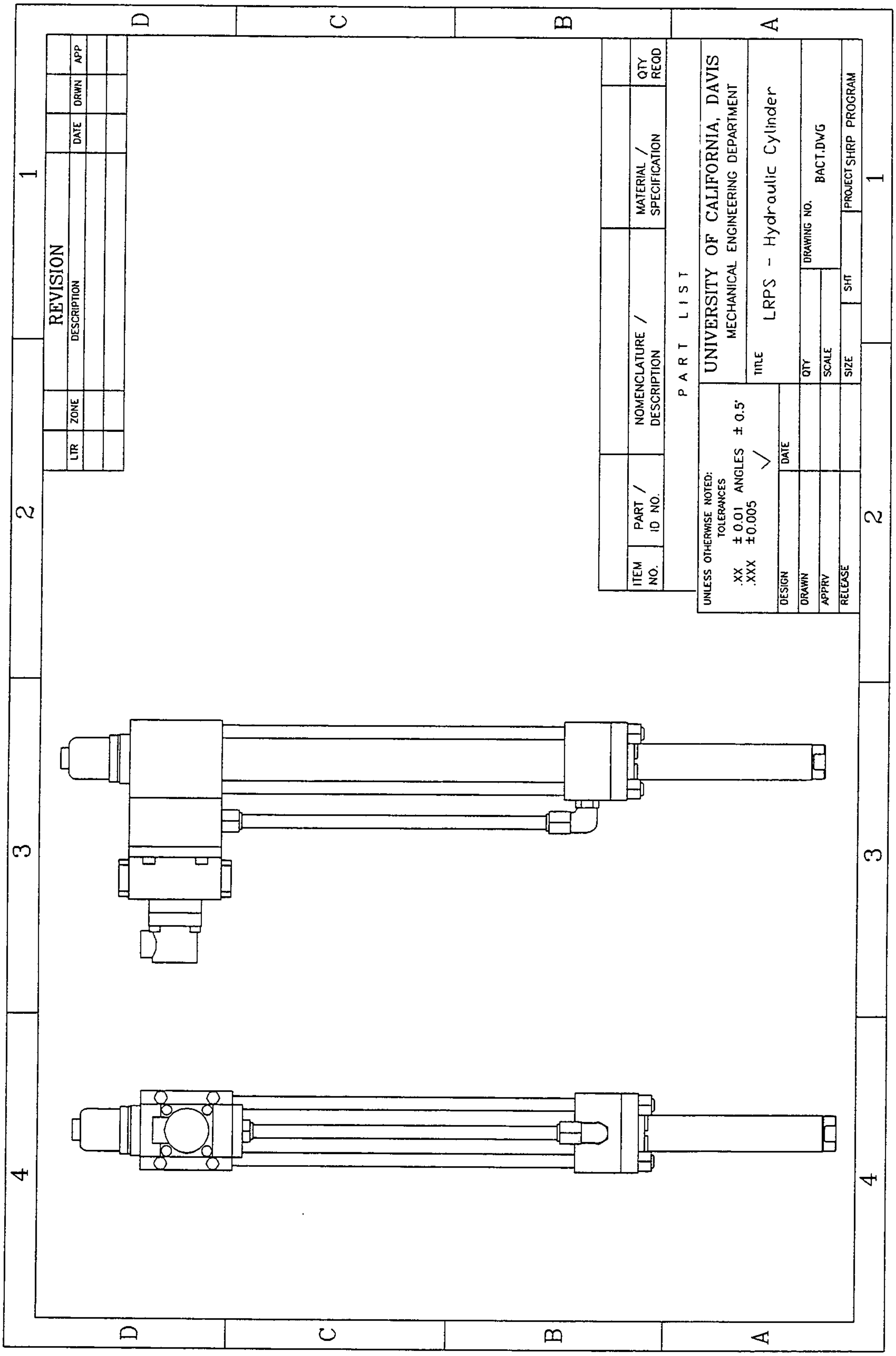
Drawing 1.5.39


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
3.00
3.00
TOP VIEW
FRONT OF TRUCK
BUBBLE WINDOW
FRONT OF TRUCK
A/C
71.00
29.00
FRONT VIEW
15.00
5.00
6.00
37.5
29.00
RIGHT SIDE VIEW
A/C
94.00
BACK VIEW
78.00
72.00
LEFT SIDE VIEW
PART NO.
ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01
.XXX ± .005
ANGLES ± .05
64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE CONTROL BOOTH FOR SHRP TRUCK
DESIGN CBB
DRAWN CBB
APPRV DAB
RELEASE
DATE 4/21/92
QTY
SCALE 50:1
SIZE B
SHT
DRAWING NO. ITM #100
PROJECT SHRP PROGRAM

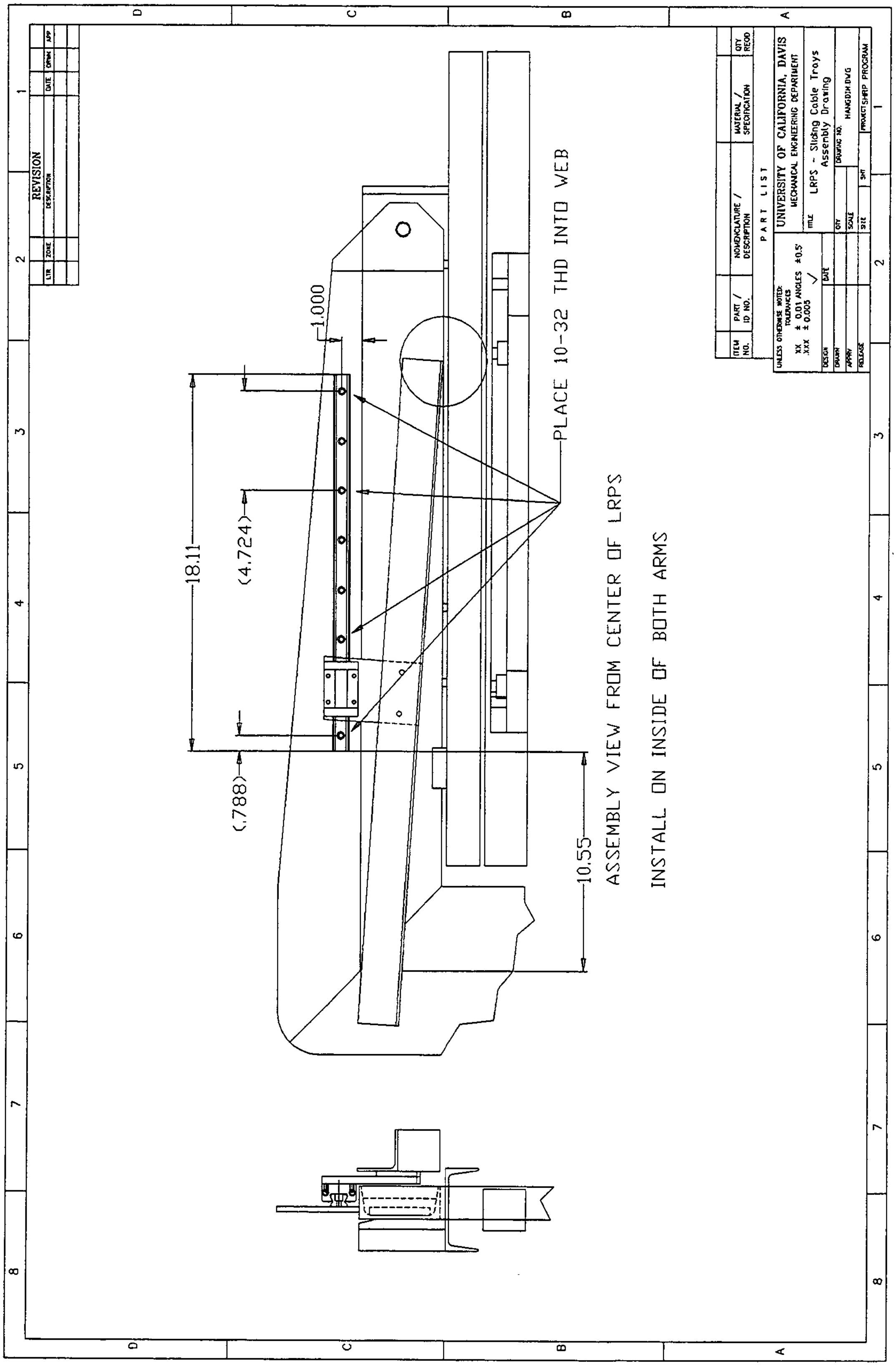
Drawing 2.1


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
TOP FRAME DETAIL
BOTTOM FRAME DETAIL
TOP VIEW
A/C
FRONT VIEW
RIGHT SIDE VIEW
BACK VIEW
LEFT SIDE VIEW
NO FLOOR
3
2
1
PART NO.
ID NO.
ANGLE, BAR SIZE, AxBxC
FRAME
SHELL
NOMENCLATURE / DESCRIPTION
2x2x.25 STEEL ANGLE
2x2 STEEL TUBING .25 IN. THICK
5052 AL SHEET .05 IN. THICK
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .01
.XXX ± .005
ANGLES ± .05
64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE CONTROL BOOTH FOR SHRP TRUCK
DESIGN CBB
DRAWN CBB
APPRV DAB
RELEASE
DATE 4/21/92
QTY
SCALE 50:1
SIZE B
SHT 2
DRAWING NO. ITM #100
PROJECT SHRP PROGRAM

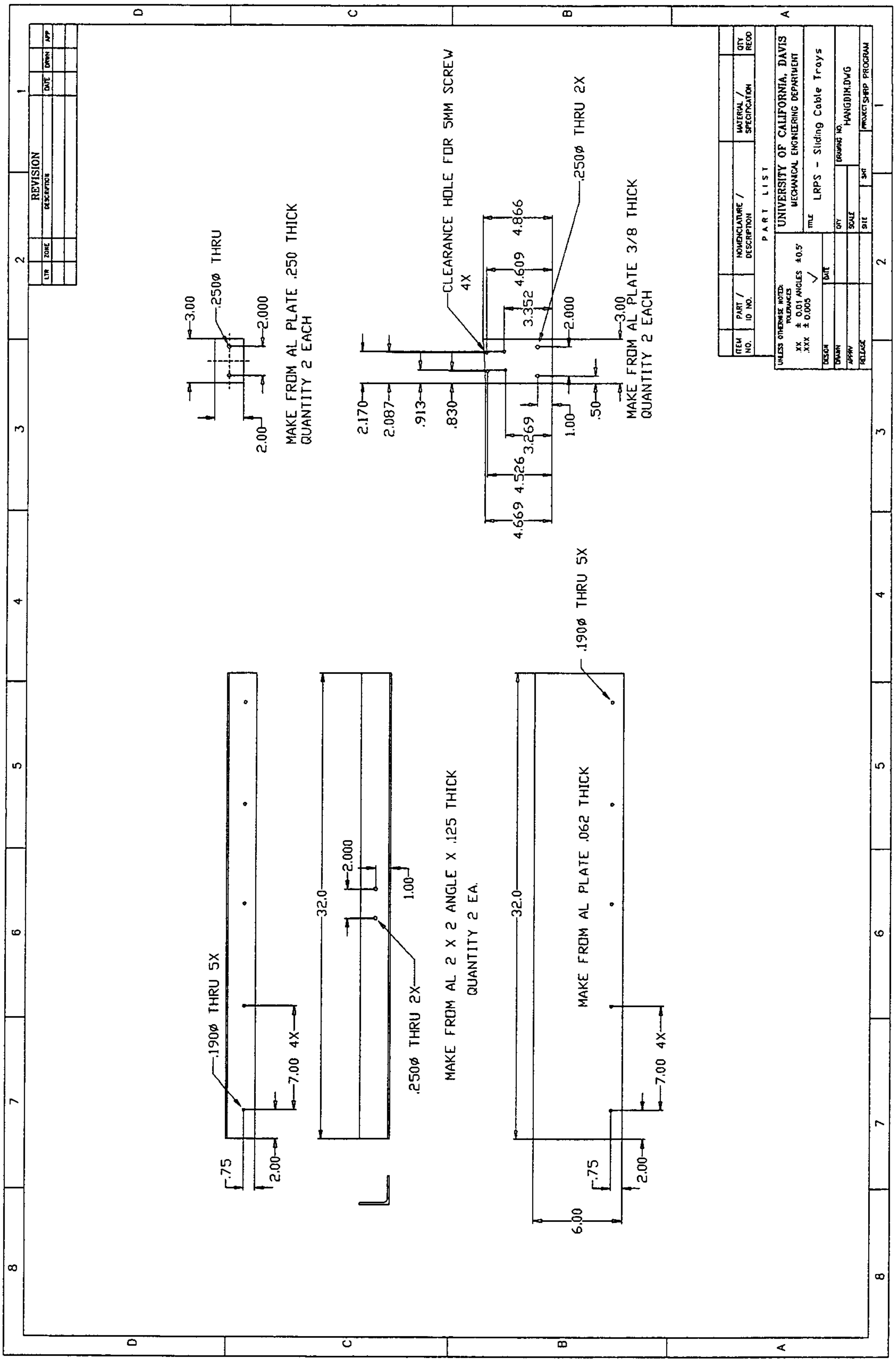
Drawing 2.2


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
P A R T   L I S T
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± 0.01 ANGLES ± 0.5°
.XXX ±0.005
DESIGN
DRAWN
APPRV
RELEASE
DATE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
LRPS - Hydraulic Cylinder
QTY
SCALE
SIZE
DRAWING NO.
BACT.DWG
SHT
PROJECT SHRP PROGRAM

Drawing 3.1.1

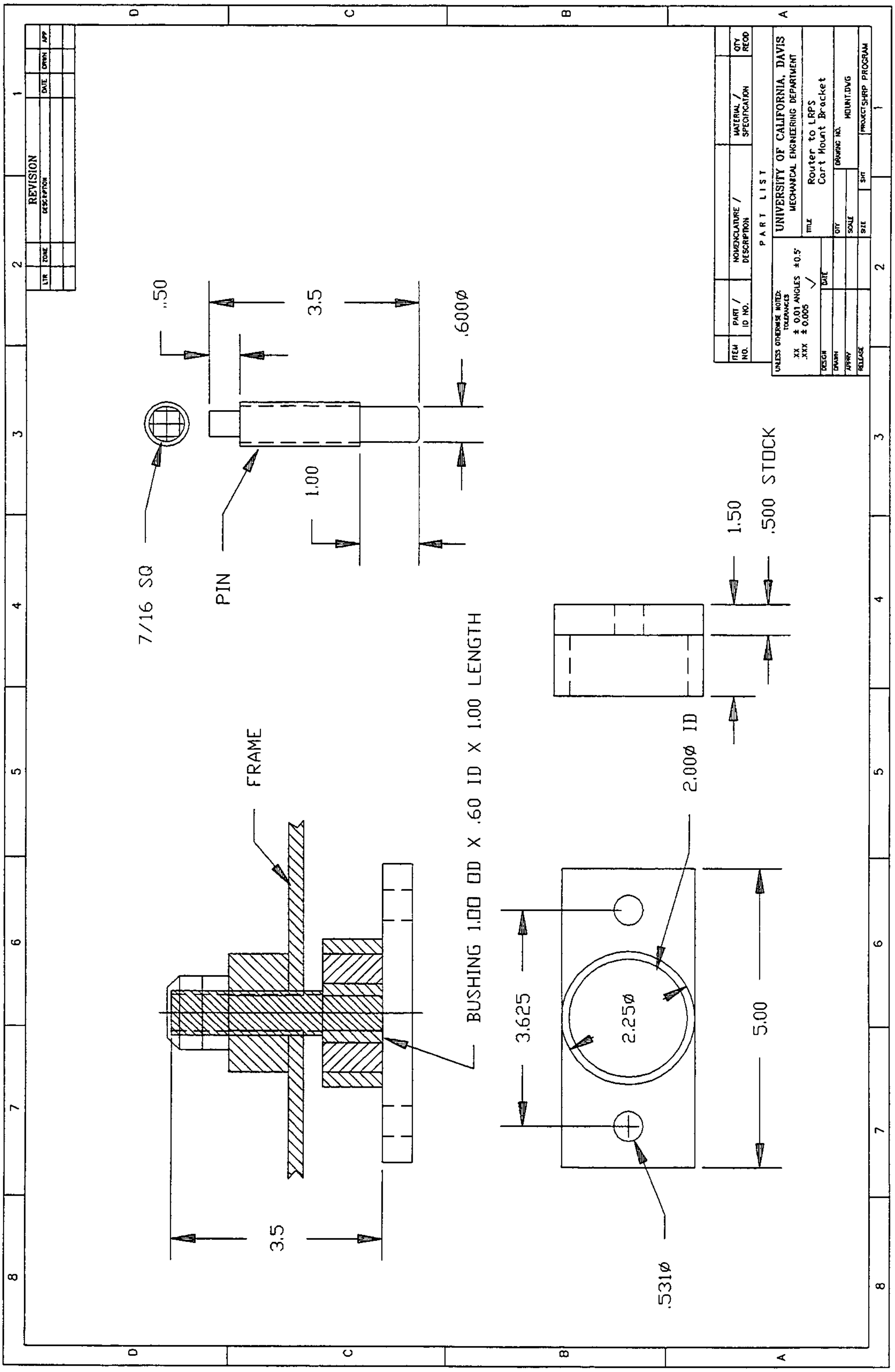

PLACE 10-32 THD INTO WEB
ASSEMBLY VIEW FROM CENTER OF LRPS
INSTALL ON INSIDE OF BOTH ARMS
1.000
18.11
(4.724)
(.788)
10.55
REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
LRPS - Sliding Cable Trays Assembly Drawing
HANGDIM.DWG
PROJECT SHRP PROGRAM

Drawing 3.1.2

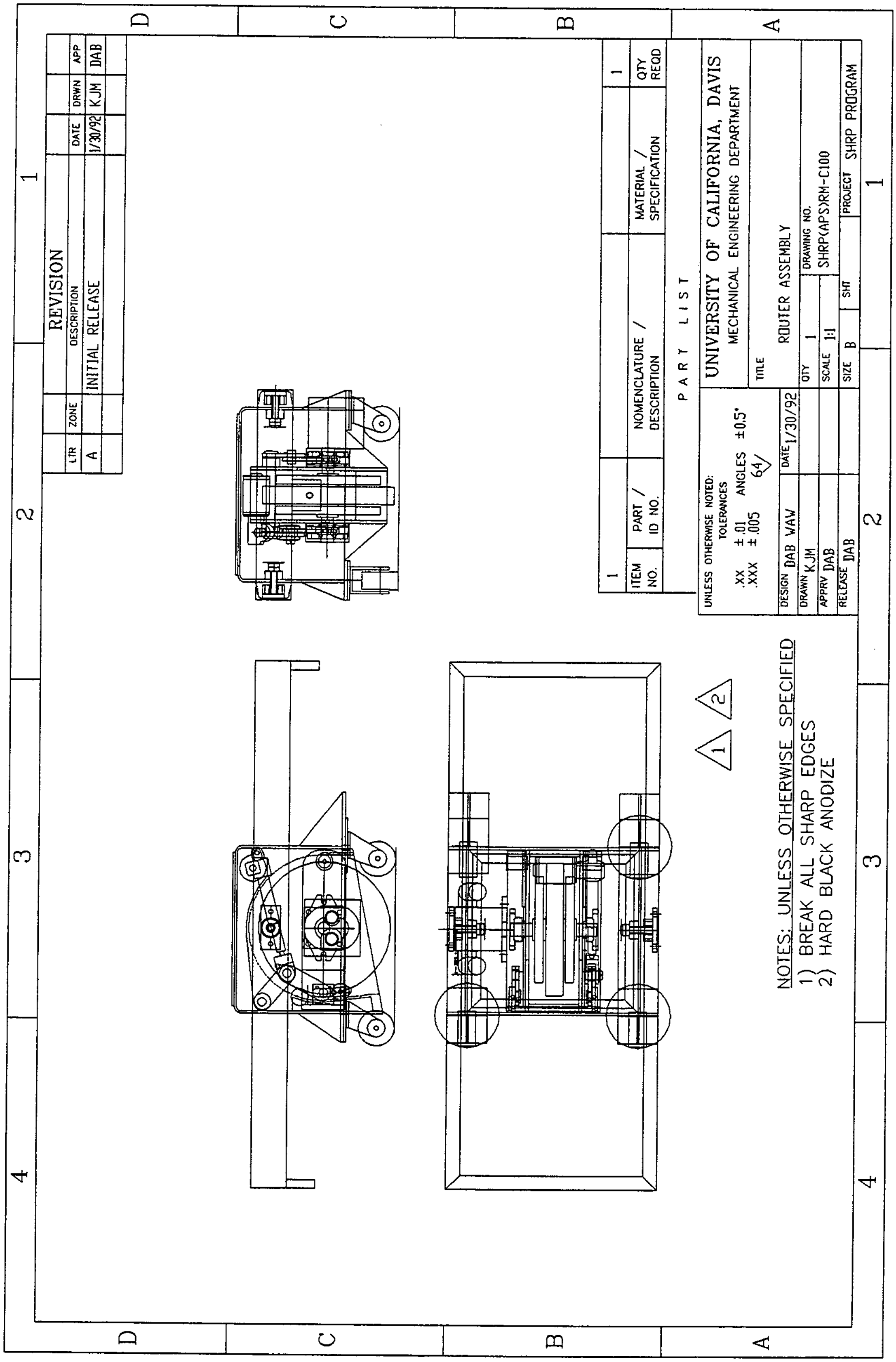


REVISION
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
LRPS - Sliding Cable Trays
HANGDIM.DWG
PART LIST
.250Ø THRU
MAKE FROM AL PLATE .250 THICK
QUANTITY 2 EACH
CLEARANCE HOLE FOR 5MM SCREW
4X
.250Ø THRU 2X
MAKE FROM AL PLATE 3/8 THICK
QUANTITY 2 EACH
.190Ø THRU 5X
.250Ø THRU 2X
MAKE FROM AL 2 X 2 ANGLE X .125 THICK
QUANTITY 2 EA.
MAKE FROM AL PLATE .062 THICK

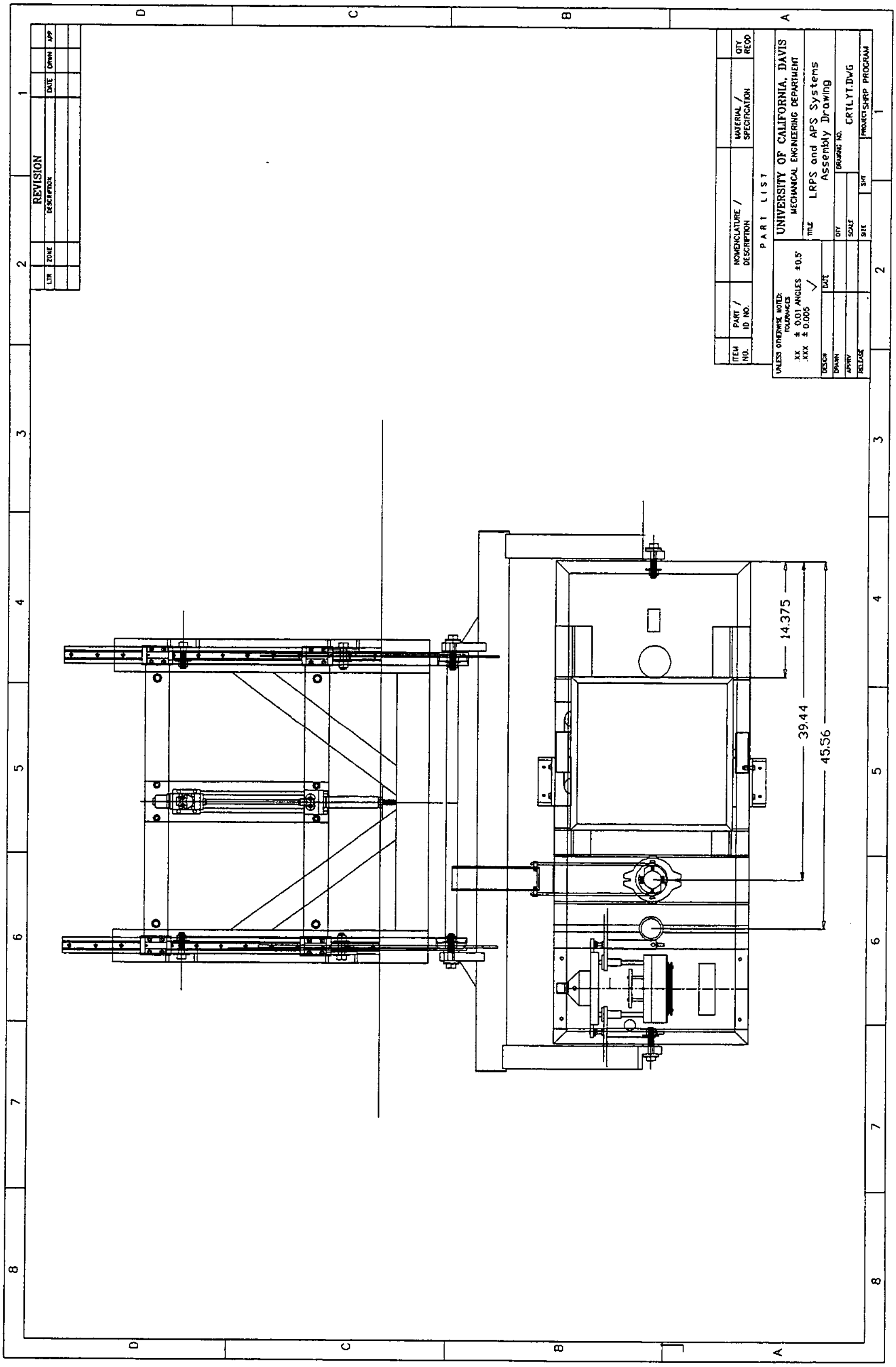
Drawing 3.1.3


REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Router to LRPS
Cart Mount Bracket
MOUNT.DWG
7/16 SQ
PIN
.50
3.5
.600Ø
1.00
FRAME
BUSHING 1.00 OD X .60 ID X 1.00 LENGTH
1.50
.500 STOCK
2.00Ø ID
3.625
2.25Ø
5.00
3.5
.531Ø

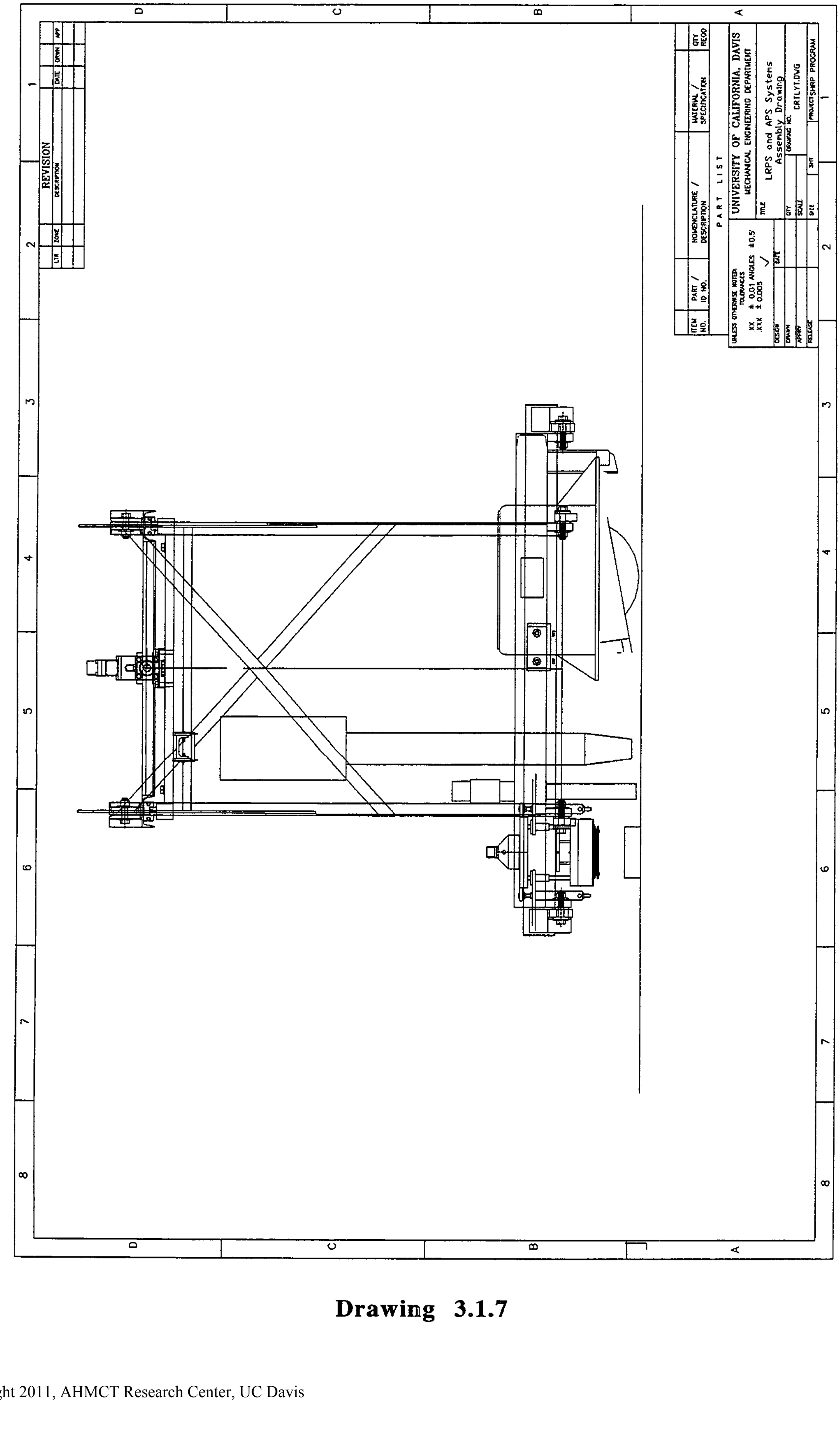
Drawing 3.1.4


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
A
INITIAL RELEASE
1/30/92
KJM
DAB
1
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
1
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± .01
.XXX ± .005
ANGLES ±0.5°
64
TITLE
ROUTER ASSEMBLY
DESIGN DAB WAW
DATE 1/30/92
DRAWN KJM
APPRV DAB
RELEASE DAB
QTY 1
SCALE 1:1
SIZE B
SHT
DRAWING NO.
SHRP(APS)RM-C100
PROJECT SHRP PROGRAM
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) HARD BLACK ANODIZE

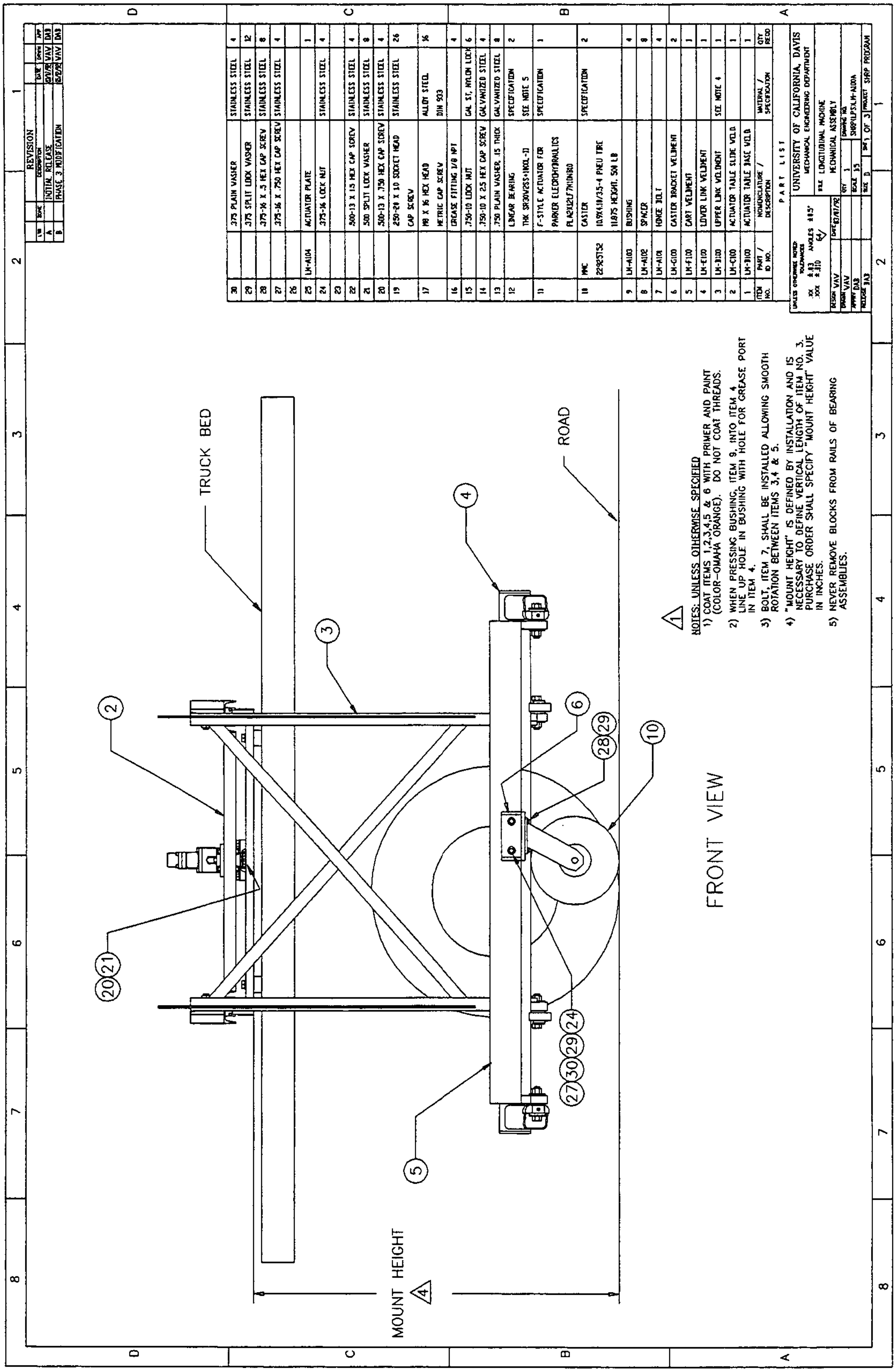
Drawing 3.1.5


REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
LRPS and APS Systems
Assembly Drawing
CRTLYT.DWG
14.375
39.44
45.56

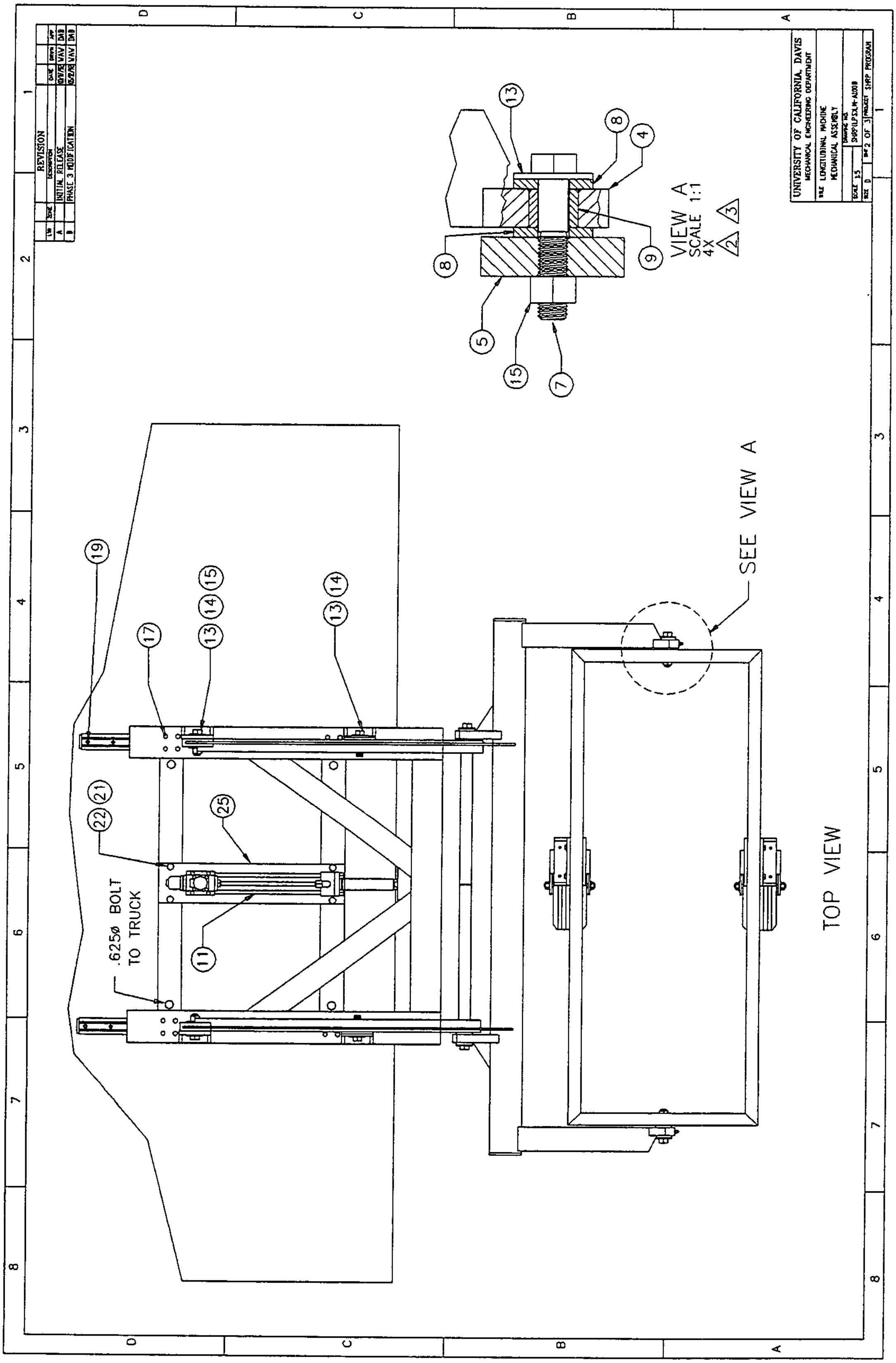
Drawing 3.1.6


REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
LRPS and APS Systems
Assembly Drawing
CRILYT.DWG
PROJECT:SHRP PROGRAM

Drawing 3.1.7

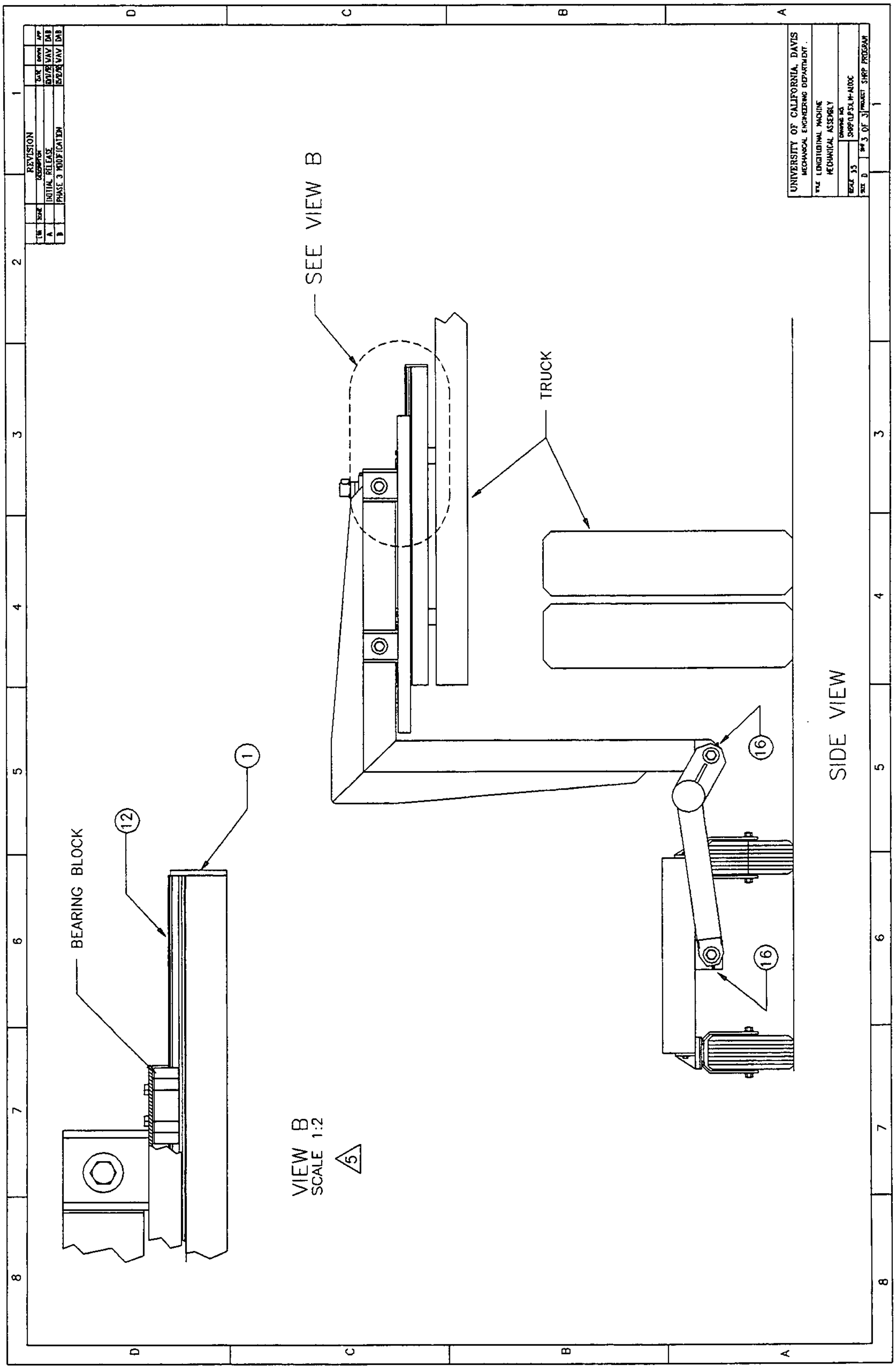

TRUCK BED
ROAD
MOUNT HEIGHT 4
FRONT VIEW
2
3
4
5
6
10
20 21
27 30 29 24
28 29
NOTES: UNLESS OTHERWISE SPECIFIED
1) COAT ITEMS 1,2,3,4,5 & 6 WITH PRIMER AND PAINT (COLOR-OMAHA ORANGE). DO NOT COAT THREADS.
2) WHEN PRESSING BUSHING, ITEM 9, INTO ITEM 4 LINE UP HOLE IN BUSHING WITH HOLE FOR GREASE PORT IN ITEM 4.
3) BOLT, ITEM 7, SHALL BE INSTALLED ALLOWING SMOOTH ROTATION BETWEEN ITEMS 3,4 & 5.
4) "MOUNT HEIGHT" IS DEFINED BY INSTALLATION AND IS NECESSARY TO DEFINE VERTICAL LENGTH OF ITEM NO. 3. PURCHASE ORDER SHALL SPECIFY "MOUNT HEIGHT" VALUE IN INCHES.
5) NEVER REMOVE BLOCKS FROM RAILS OF BEARING ASSEMBLIES.
REVISION
A INITIAL RELEASE
B PHASE 3 MODIFICATION
30 .375 PLAIN WASHER STAINLESS STEEL 4
29 .375 SPLIT LOCK WASHER STAINLESS STEEL 12
28 .375-16 X .5 HEX CAP SCREW STAINLESS STEEL 8
27 .375-16 X .750 HEX CAP SCREW STAINLESS STEEL 4
26
25 LH-A104 ACTUATOR PLATE 1
24 .375-16 LOCK NUT STAINLESS STEEL 4
23
22 .500-13 X 1.5 HEX CAP SCREW STAINLESS STEEL 4
21 .500 SPLIT LOCK WASHER STAINLESS STEEL 8
20 .500-13 X .750 HEX CAP SCREW STAINLESS STEEL 4
19 .250-20 X 1.0 SOCKET HEAD CAP SCREW STAINLESS STEEL 26
17 M8 X 16 HEX HEAD METRIC CAP SCREW ALLOY STEEL DIN 933 16
16 GREASE FITTING 1/8 NPT 4
15 .750-10 LOCK NUT GAL ST, NYLON LOCK 6
14 .750-10 X 2.5 HEX CAP SCREW GALVANIZED STEEL 4
13 .750 PLAIN WASHER, .15 THICK GALVANIZED STEEL 8
12 LINEAR BEARING THK SR30V2SS+1800L-II SPECIFICATION SEE NOTE 5 2
11 F-STYLE ACTUATOR FOR PARKER ELECROHYDRAULICS FLA2X12LF7M1DN80 SPECIFICATION 1
10 MMC 22925T52 CASTER 10.9X4.10/3.5-4 PNEU TIRE 11.875 HEIGHT, 500 LB SPECIFICATION 2
9 LH-A103 BUSHING 4
8 LH-A102 SPACER 8
7 LH-A101 HINGE BOLT 4
6 LH-G100 CASTER BRACKET WELDMENT 2
5 LH-F100 CART WELDMENT 1
4 LH-E100 LOWER LINK WELDMENT 1
3 LH-D100 UPPER LINK WELDMENT SEE NOTE 4 1
2 LH-C100 ACTUATOR TABLE SLIDE WELD 1
1 LH-B100 ACTUATOR TABLE BASE WELD 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
LONGITUDINAL MACHINE MECHANICAL ASSEMBLY
SHRP-LPS-LH-A100A
SHT 1 OF 3
SHRP PROGRAM

Drawing 3.2.1

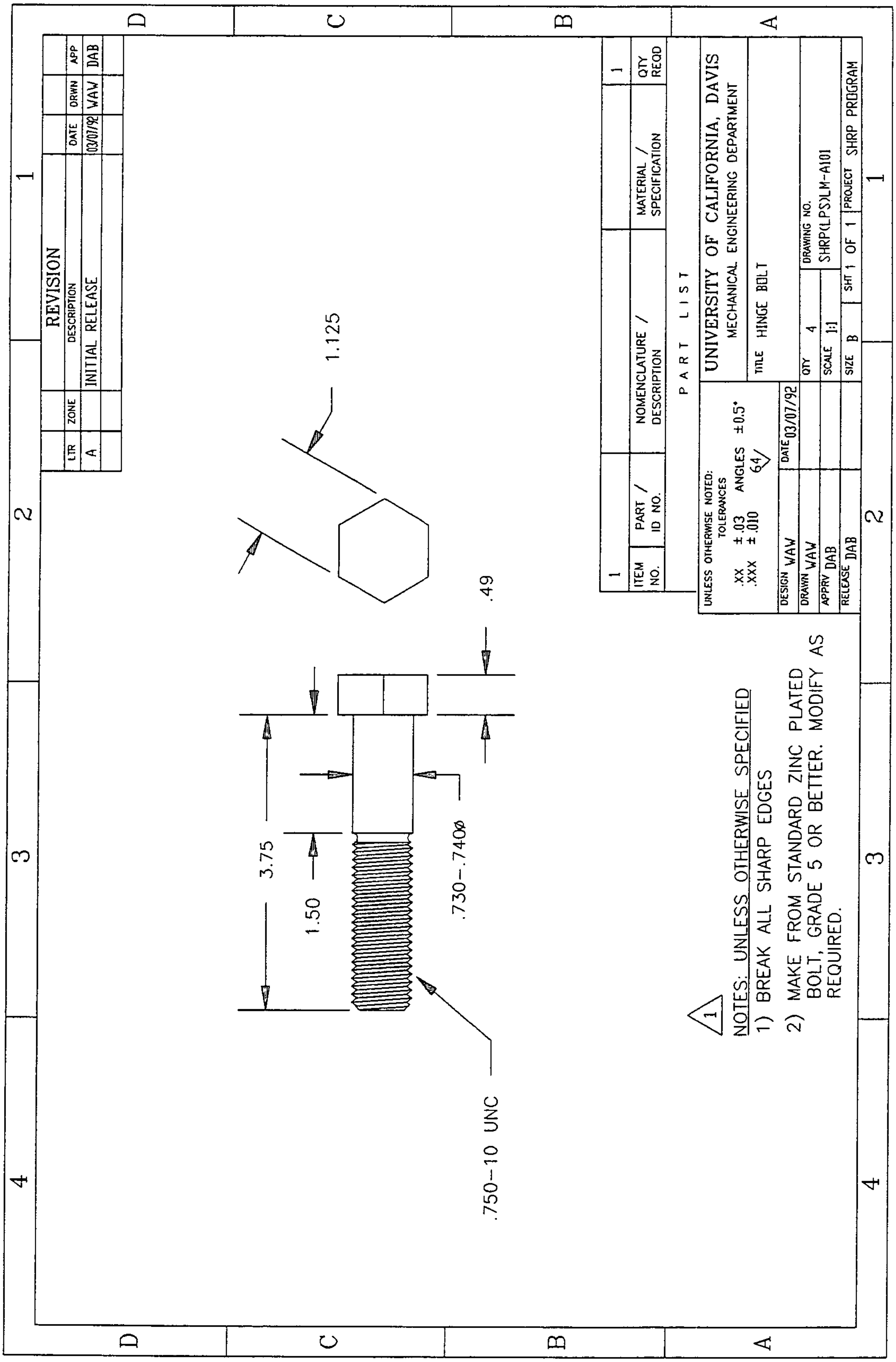


REVISION
INITIAL RELEASE
PHASE 3 MODIFICATION
VIEW A
SCALE 1:1
4X
SEE VIEW A
.625Ø BOLT
TO TRUCK
TOP VIEW
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
LONGITUDINAL MACHINE
MECHANICAL ASSEMBLY
SHRP PROGRAM

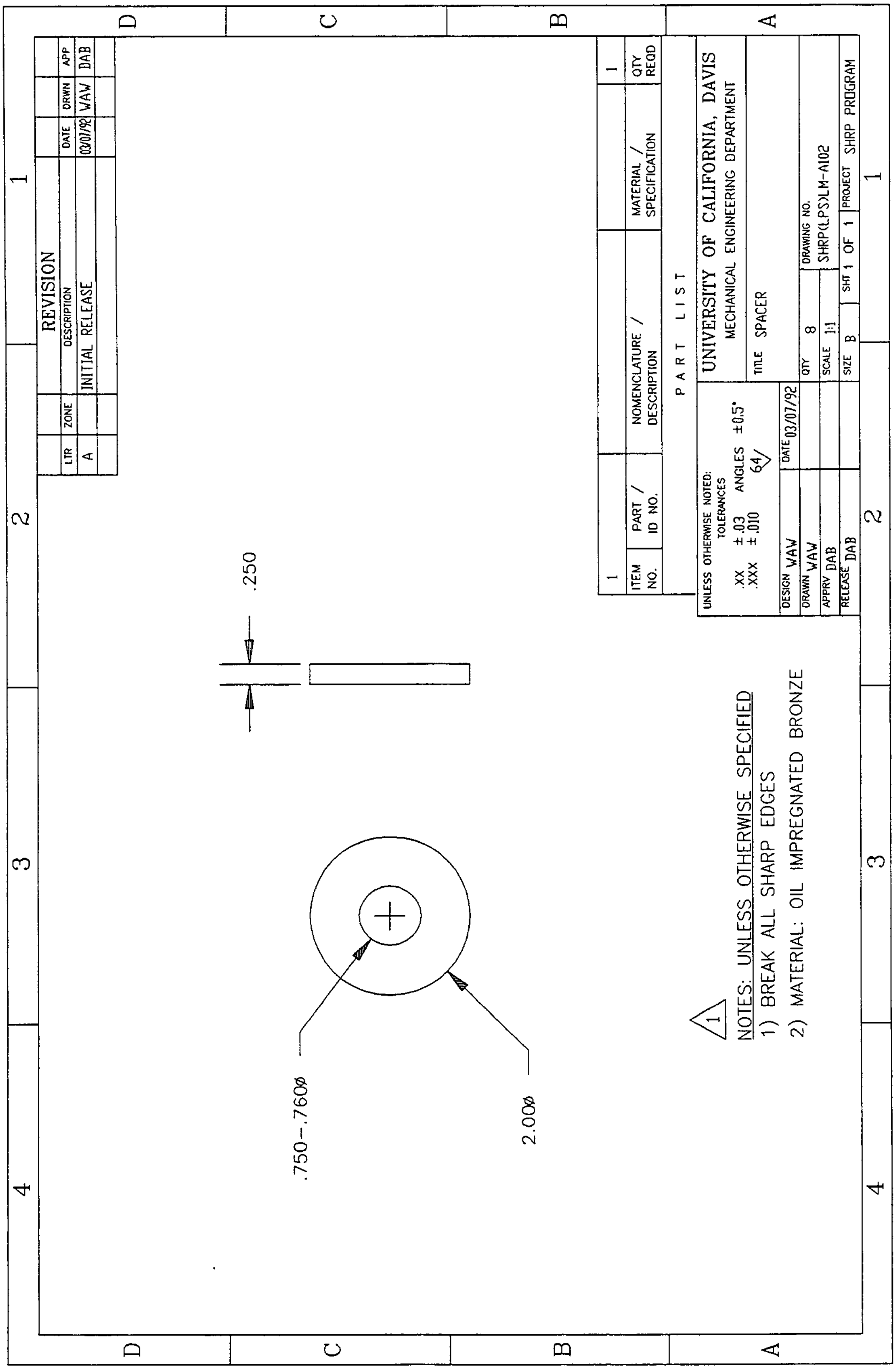
Drawing 3.2.2


SEE VIEW B
TRUCK
BEARING BLOCK
VIEW B
SCALE 1:2
SIDE VIEW
REVISION
INITIAL RELEASE
PHASE 3 MODIFICATION
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
LONGITUDINAL MACHINE
MECHANICAL ASSEMBLY
SHRP PROGRAM

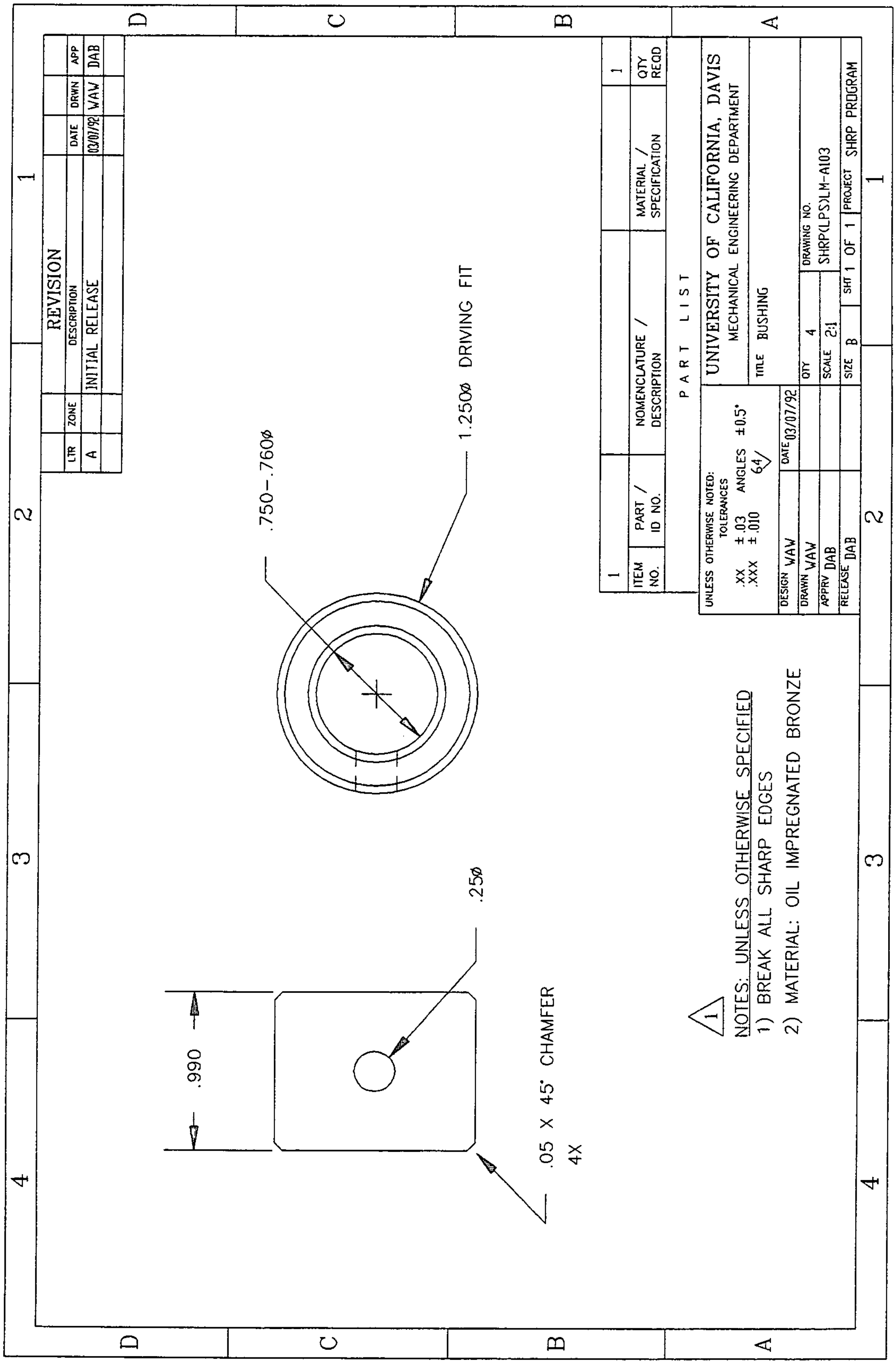
Drawing 3.2.3


REVISION
LTR | ZONE | DESCRIPTION | DATE | DRWN | APP
A | | INITIAL RELEASE | 03/07/92 | WAV | DAB
1.125
.49
3.75
1.50
.730-.740ø
.750-10 UNC
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) MAKE FROM STANDARD ZINC PLATED BOLT, GRADE 5 OR BETTER. MODIFY AS REQUIRED.
ITEM NO. | PART / ID NO. | NOMENCLATURE / DESCRIPTION | MATERIAL / SPECIFICATION | QTY REQD
1 | | | | 1
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .03
.XXX ± .010
ANGLES ±0.5°
64
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE HINGE BOLT
DESIGN WAW
DRAWN WAW
APPRV DAB
RELEASE DAB
DATE 03/07/92
QTY 4
SCALE 1:1
SIZE B
SHT 1 OF 1
DRAWING NO. SHRP(LPS)LM-A101
PROJECT SHRP PROGRAM

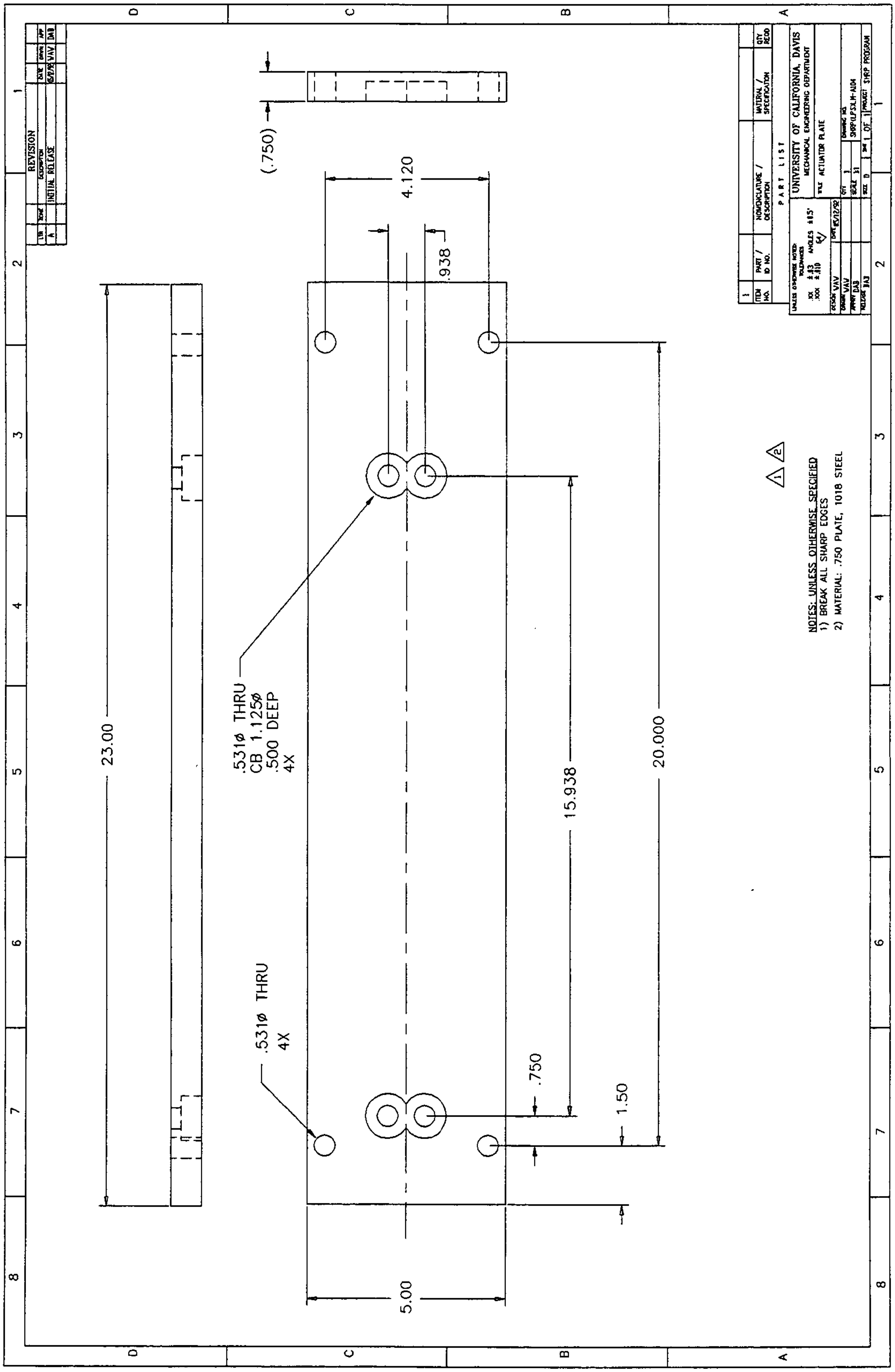
Drawing 3.2.4


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 03/07/92 WAW DAB
.250
.750-.760Ø
2.00Ø
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) MATERIAL: OIL IMPREGNATED BRONZE
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY. REQD
1 1
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ±.03 ANGLES ±0.5°
.XXX ±.010
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE SPACER
DESIGN WAW DATE 03/07/92
DRAWN WAW
APPRV DAB
RELEASE DAB
QTY 8
SCALE 1:1
SIZE B
DRAWING NO. SHRP(LPS)LM-A102
SHT 1 OF 1
PROJECT SHRP PROGRAM

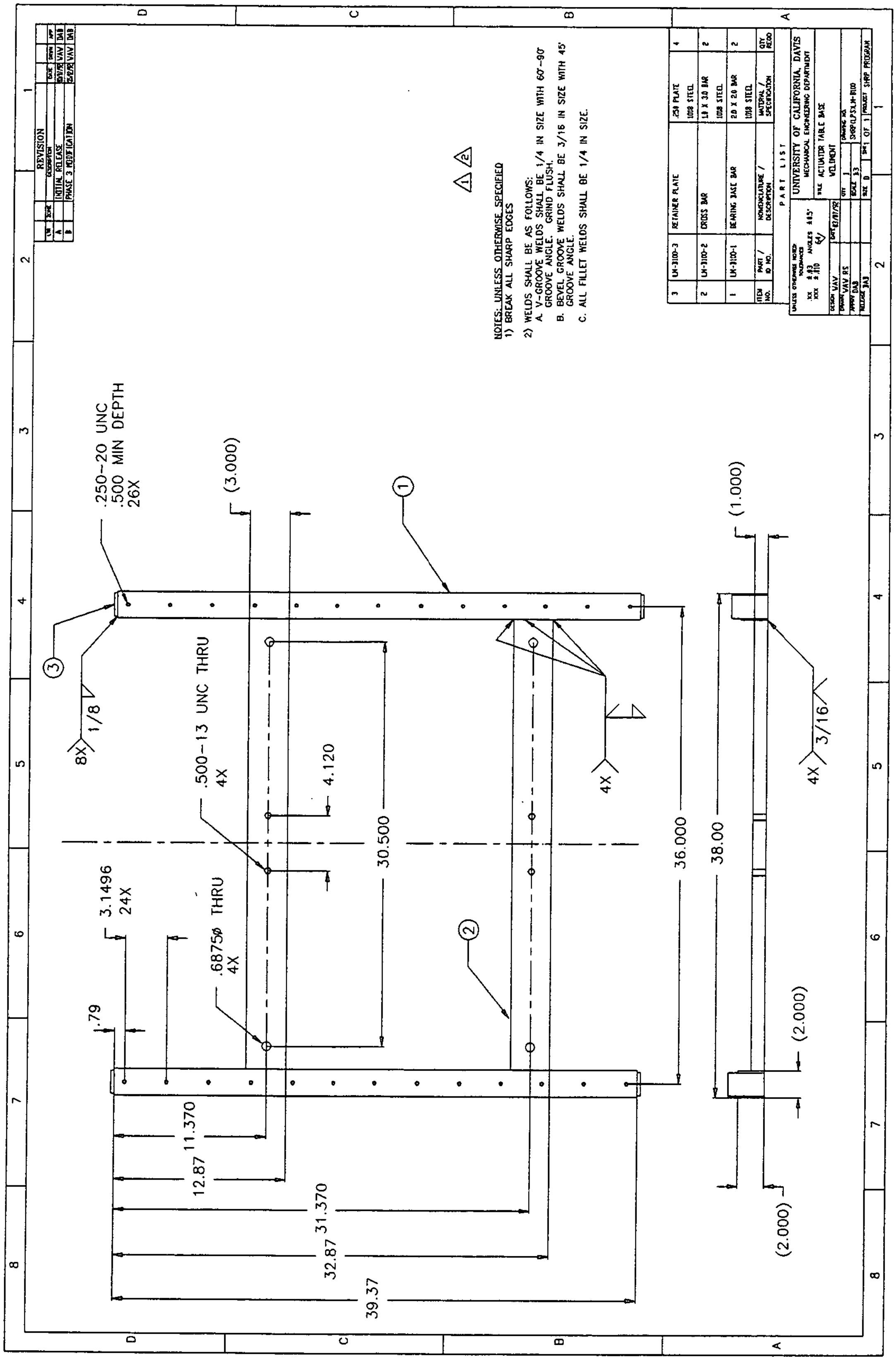
Drawing 3.2.5


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
A INITIAL RELEASE 03/07/92 WAW DAB
.750-.760ø
1.250ø DRIVING FIT
.25ø
.990
.05 X 45° CHAMFER
4X
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) MATERIAL: OIL IMPREGNATED BRONZE
1 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES
.XX ± .03
.XXX ± .010
ANGLES ±0.5°
64
DESIGN WAW DATE 03/07/92
DRAWN WAW
APPRV DAB
RELEASE DAB
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE BUSHING
QTY 4
SCALE 2:1
SIZE B
DRAWING NO. SHRP(LPS)LM-A103
SHT 1 OF 1
PROJECT SHRP PROGRAM
A B C D
1 2 3 4

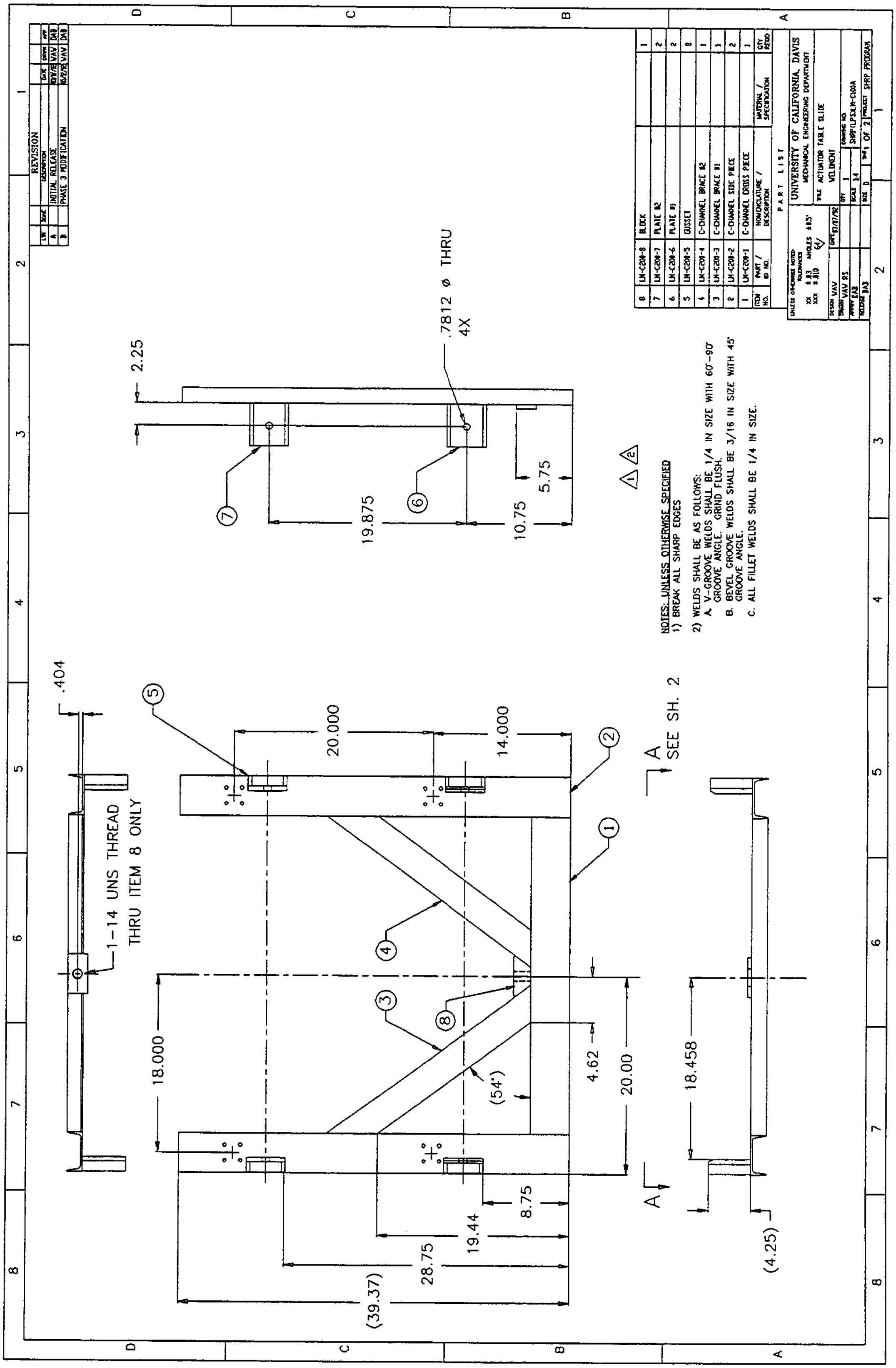
Drawing 3.2.6


(.750)
4.120
.938
23.00
.531⌀ THRU
CB 1.125⌀
.500 DEEP
4X
15.938
20.000
.531⌀ THRU
4X
.750
1.50
5.00
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) MATERIAL: .750 PLATE, 1018 STEEL
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
ACTUATOR PLATE
REVISION
INITIAL RELEASE
PART LIST

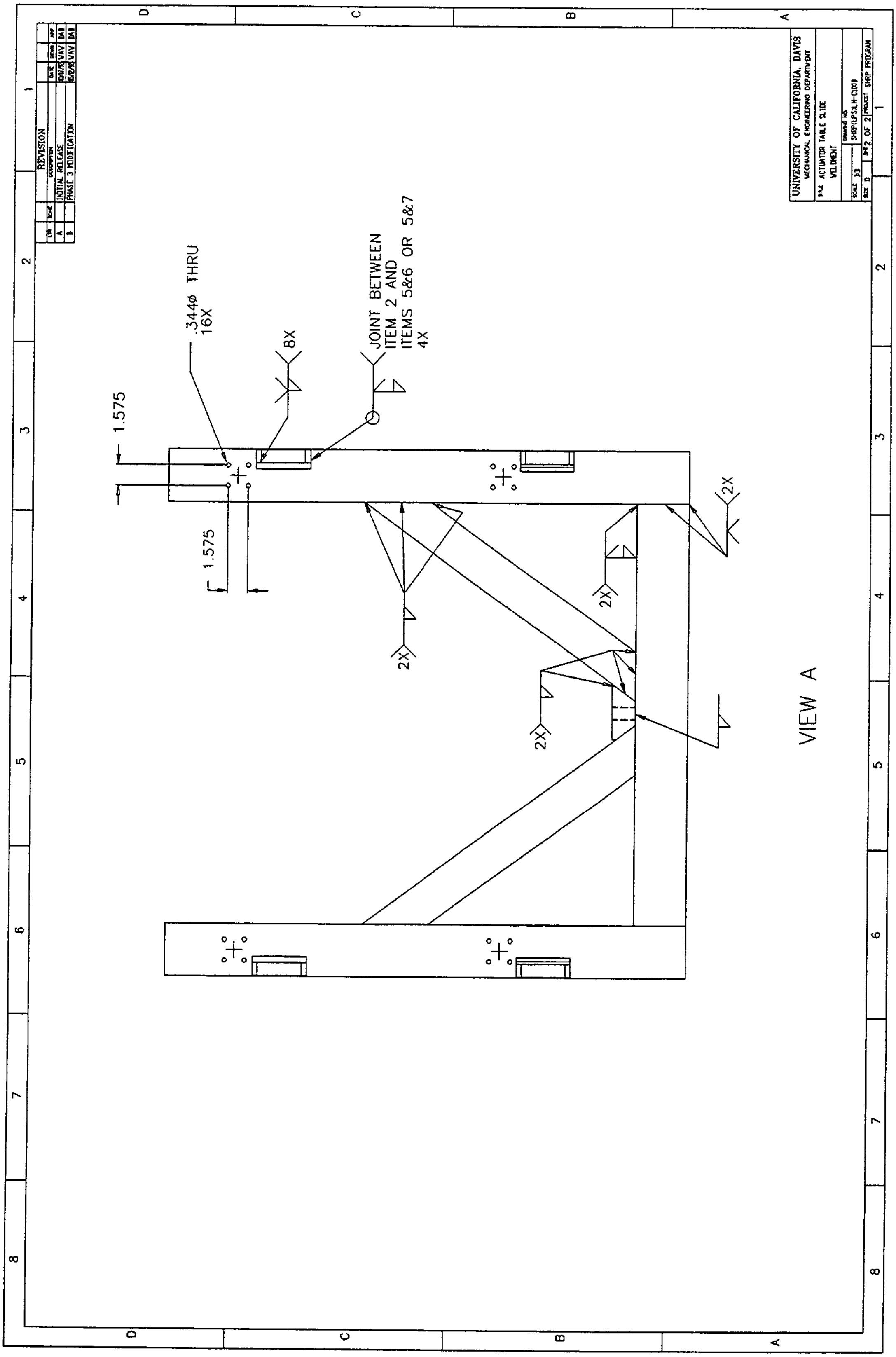
Drawing 3.2.7


REVISION
INITIAL RELEASE
PHASE 3 MODIFICATION
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) WELDS SHALL BE AS FOLLOWS:
A. V-GROOVE WELDS SHALL BE 1/4 IN SIZE WITH 60°-90° GROOVE ANGLE. GRIND FLUSH.
B. BEVEL GROOVE WELDS SHALL BE 3/16 IN SIZE WITH 45° GROOVE ANGLE.
C. ALL FILLET WELDS SHALL BE 1/4 IN SIZE.
LM-3100-3 RETAINER PLATE .250 PLATE 1018 STEEL 4
LM-3100-2 CROSS BAR 1.0 X 3.0 BAR 1018 STEEL 2
LM-3100-1 BEARING BASE BAR 2.0 X 2.0 BAR 1018 STEEL 2
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
ACTUATOR TABLE BASE
WELDMENT
.250-20 UNC
.500 MIN DEPTH
26X
(3.000)
(1.000)
.500-13 UNC THRU
4X
4.120
30.500
36.000
38.00
3.1496
24X
.6875Ø THRU
4X
.79
1/8
8X
3/16
4X
(2.000)
11.370
12.87
31.370
32.87
39.37

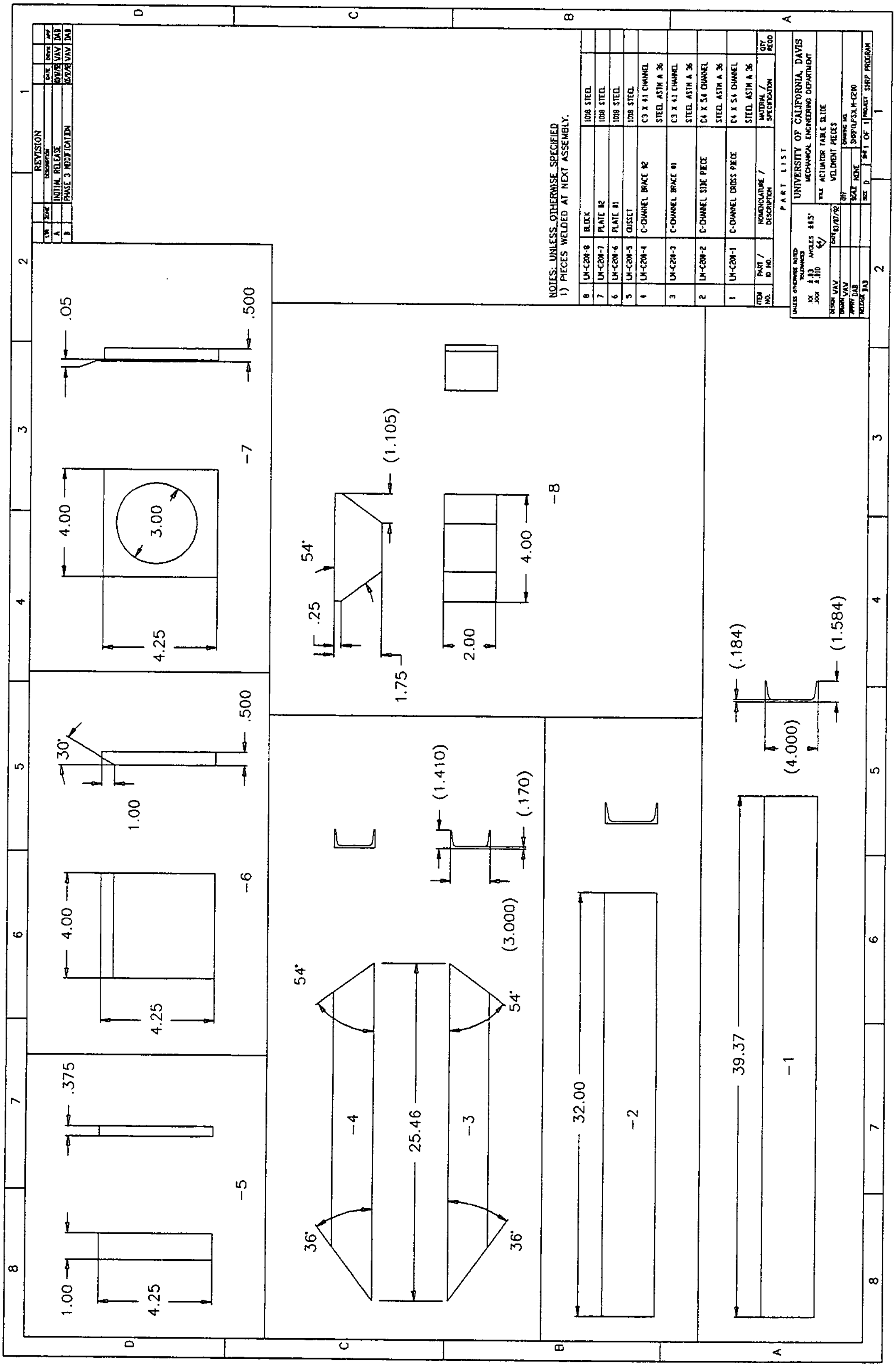
Drawing 3.2.8


NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) WELDS SHALL BE AS FOLLOWS:
A. V-GROOVE WELDS SHALL BE 1/4 IN SIZE WITH 60°-90° GROOVE ANGLE. GRIND FLUSH.
B. BEVEL GROOVE WELDS SHALL BE 3/16 IN SIZE WITH 45° GROOVE ANGLE.
C. ALL FILLET WELDS SHALL BE 1/4 IN SIZE.
1-14 UNS THREAD THRU ITEM 8 ONLY
.7812 ⌀ THRU 4X
A SEE SH. 2
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
PART LIST
REVISION

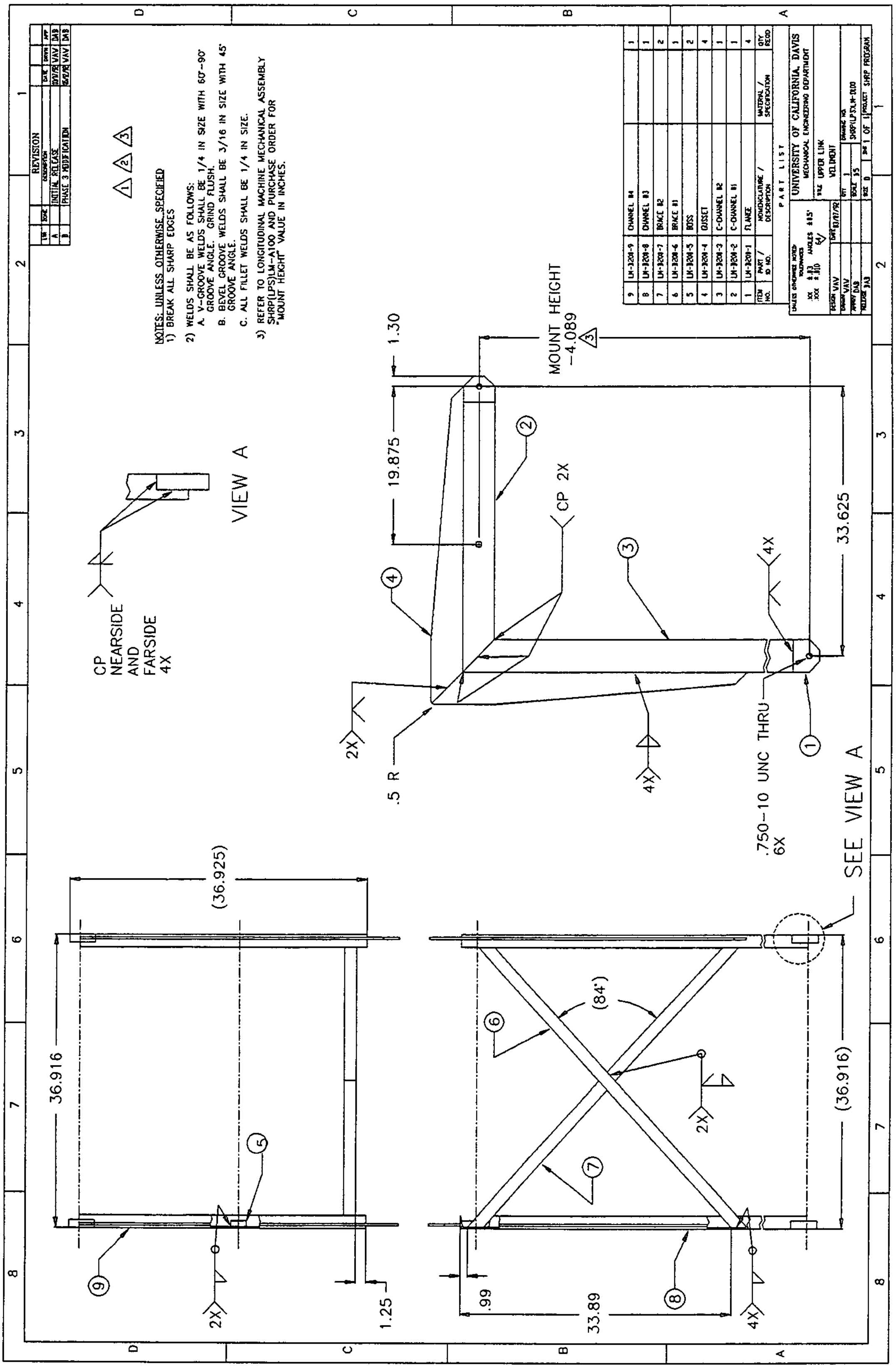
Drawing 3.2.9



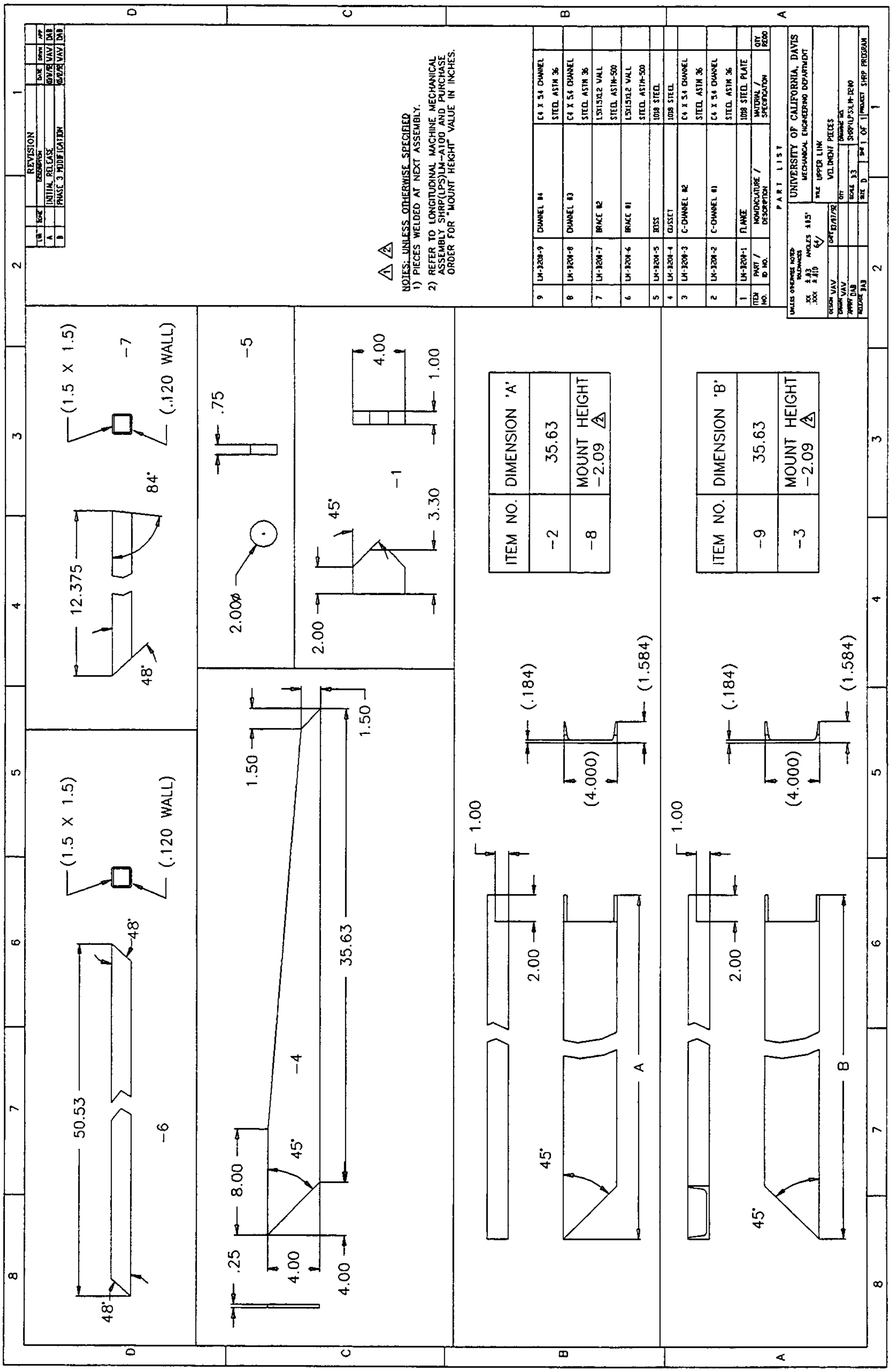
Drawing 3.2.10



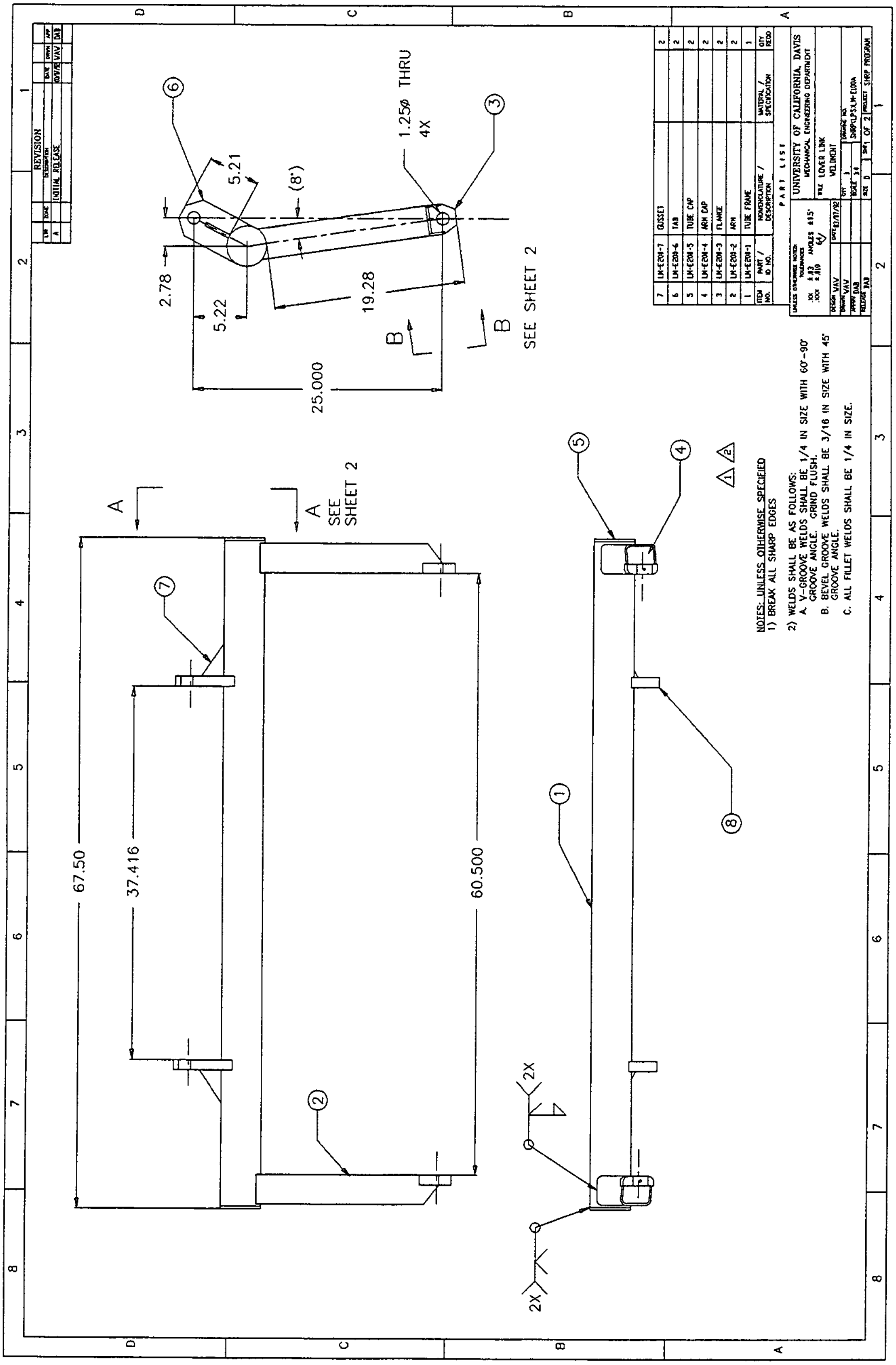
Drawing 3.2.11



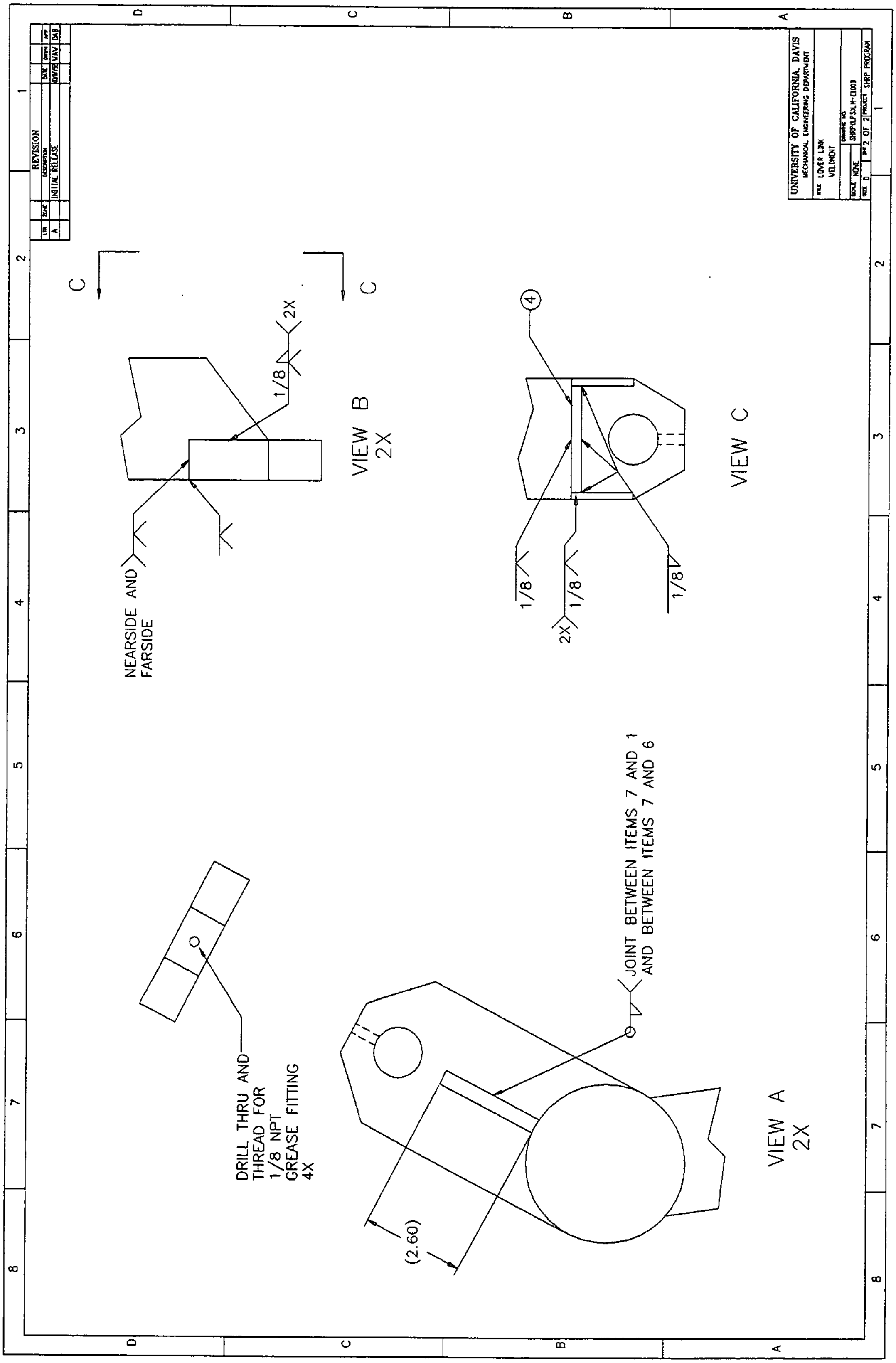
Drawing 3.2.12



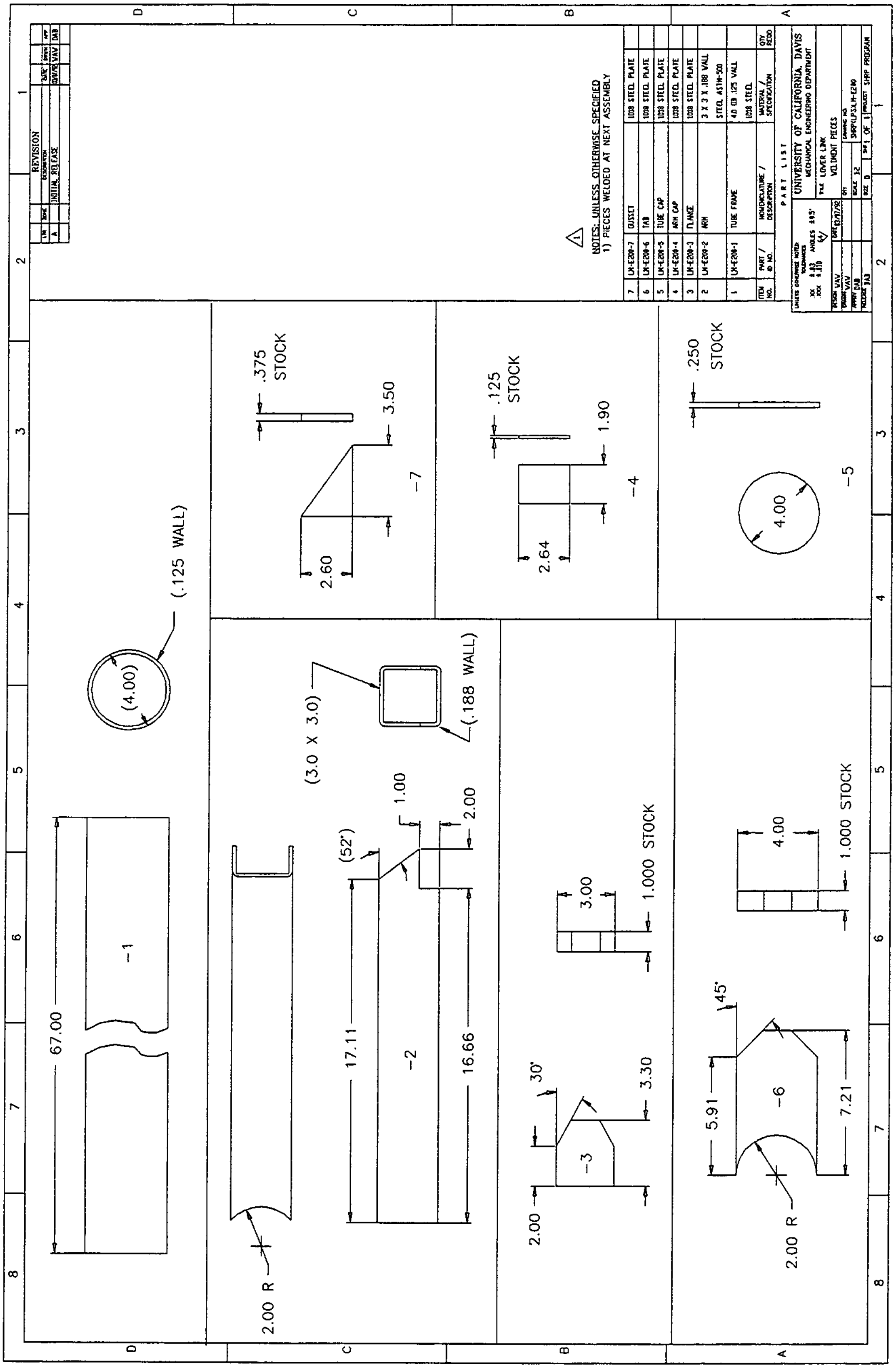
Drawing 3.2.13



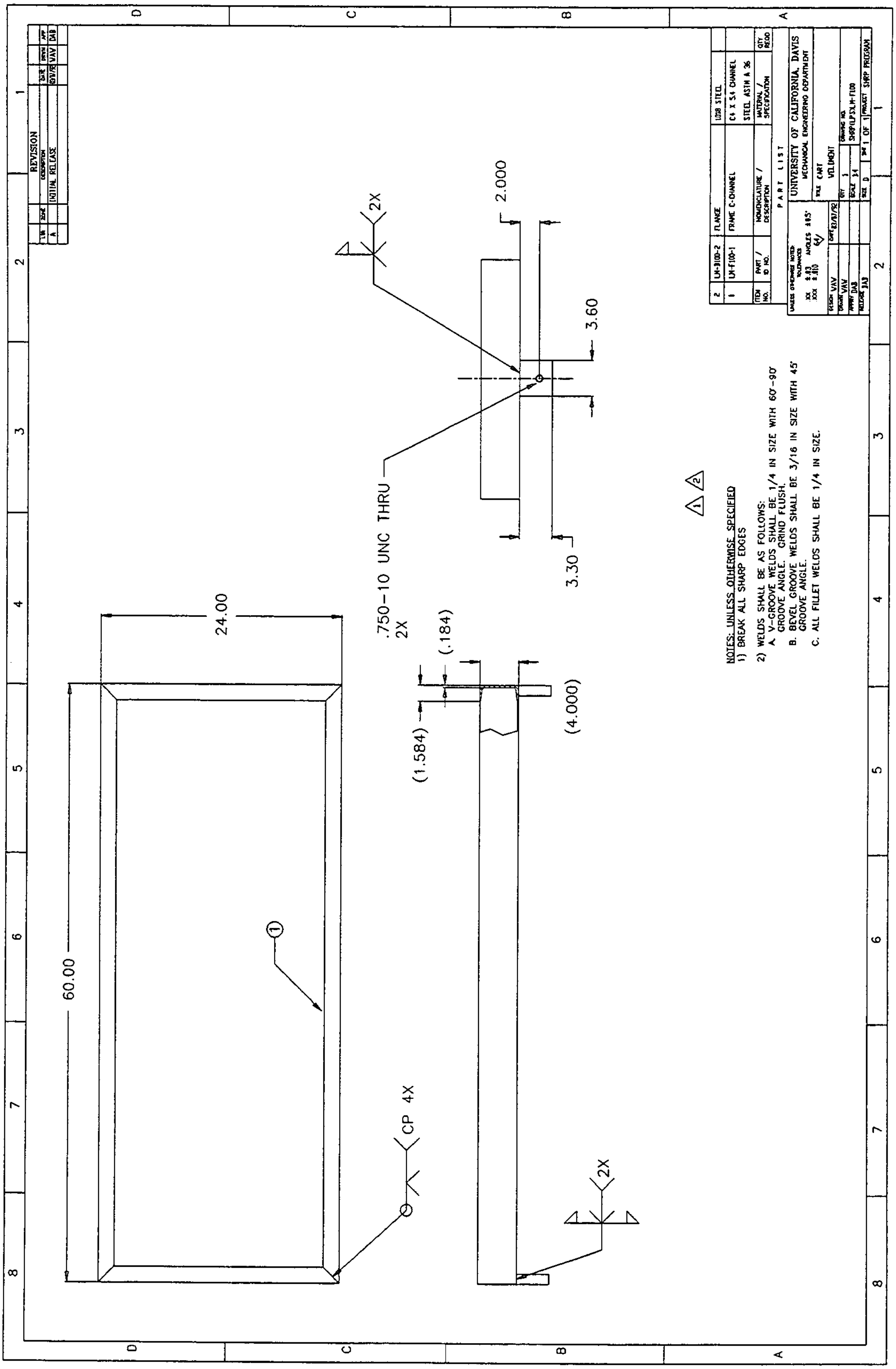
Drawing 3.2.14



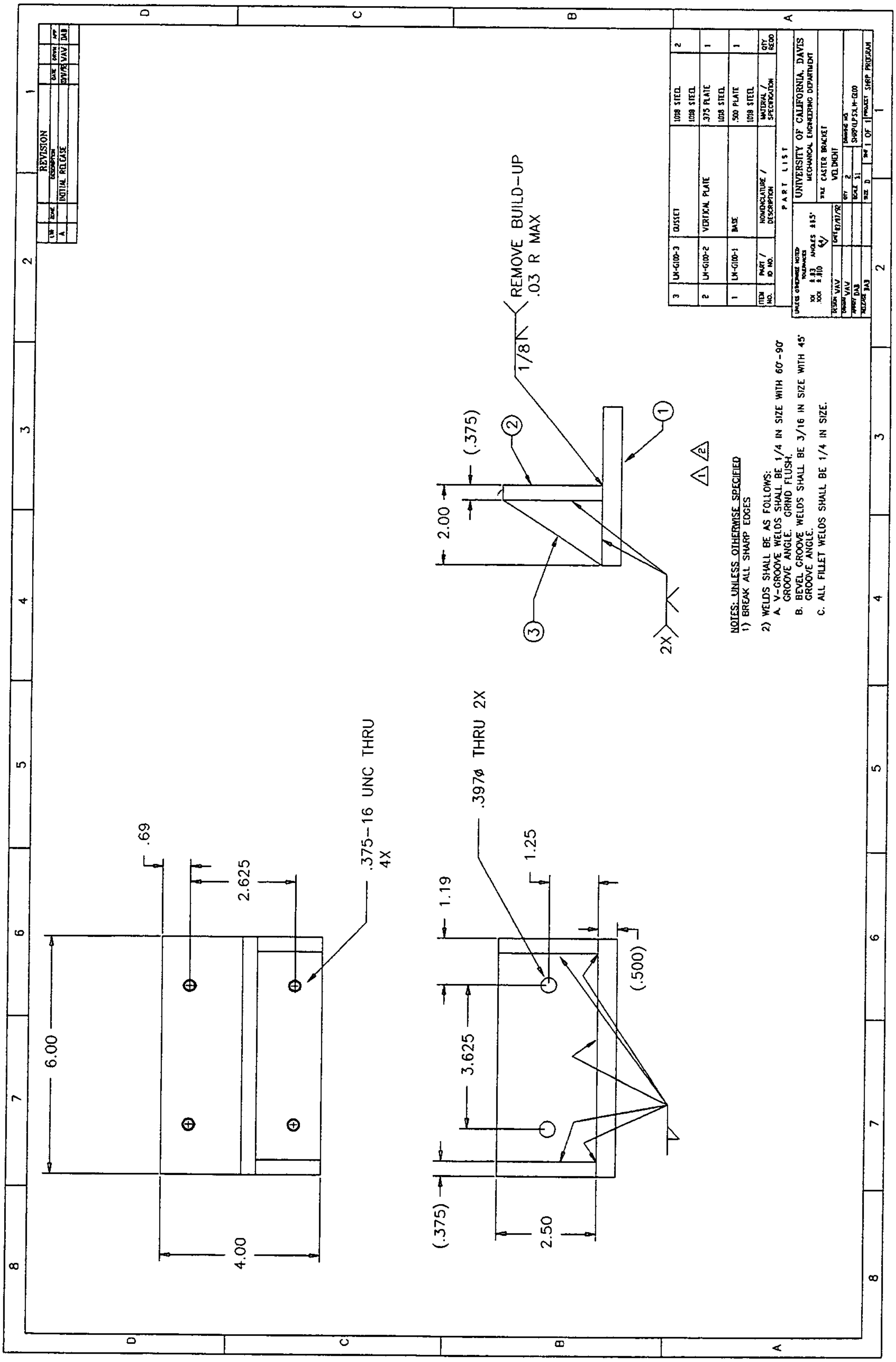
Drawing 3.2.15



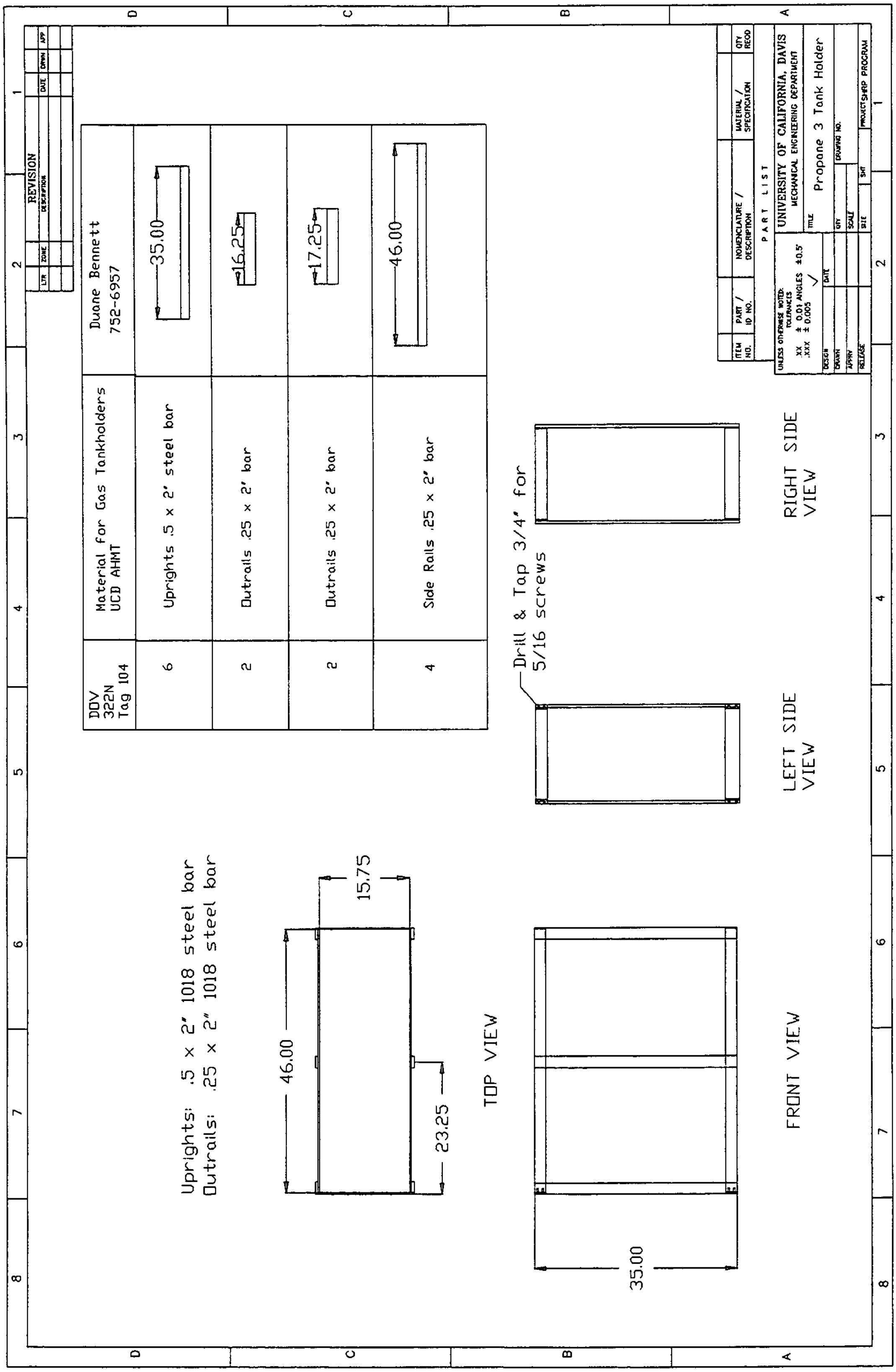
Drawing 3.2.16



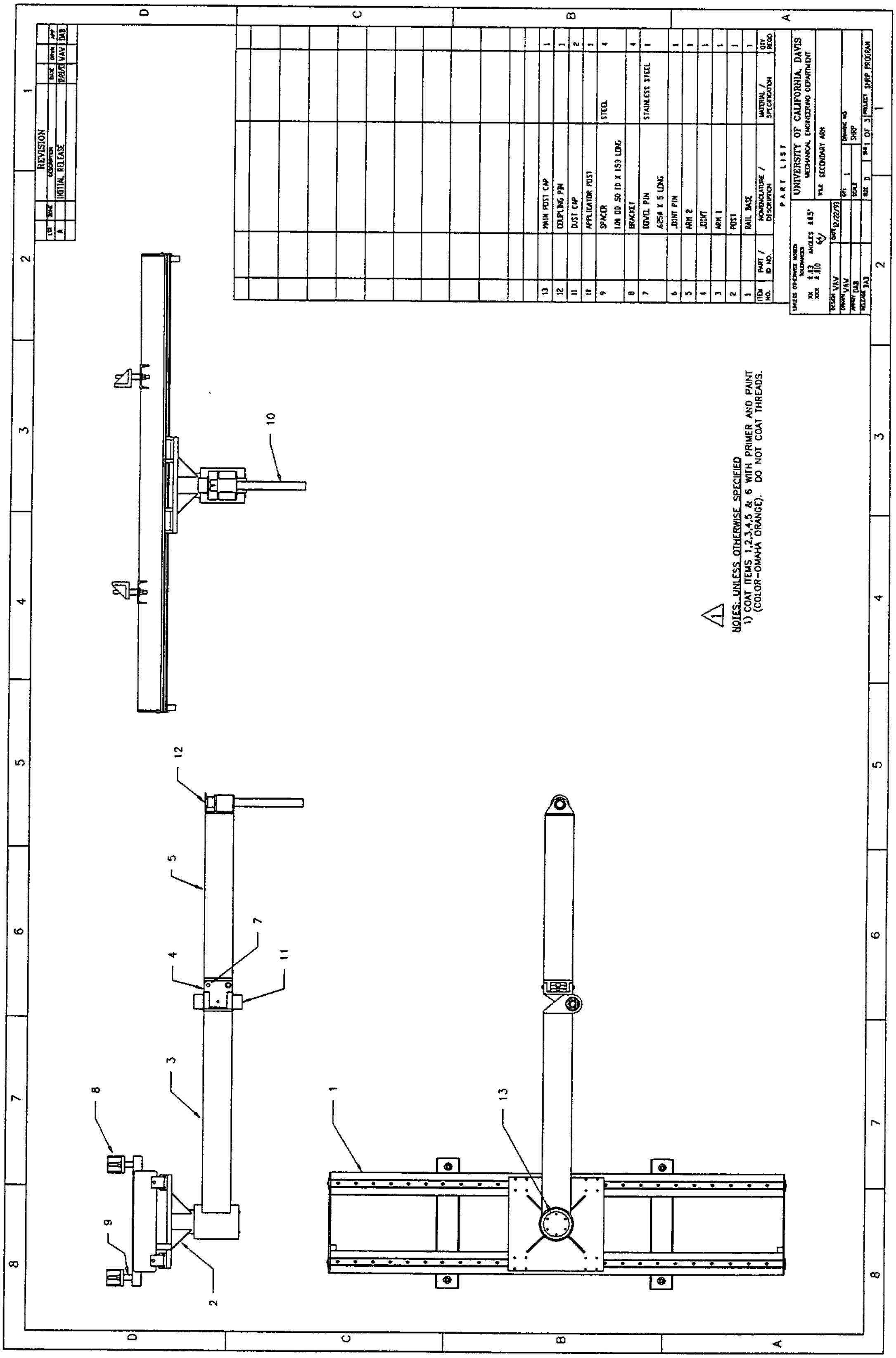
Drawing 3.2.17



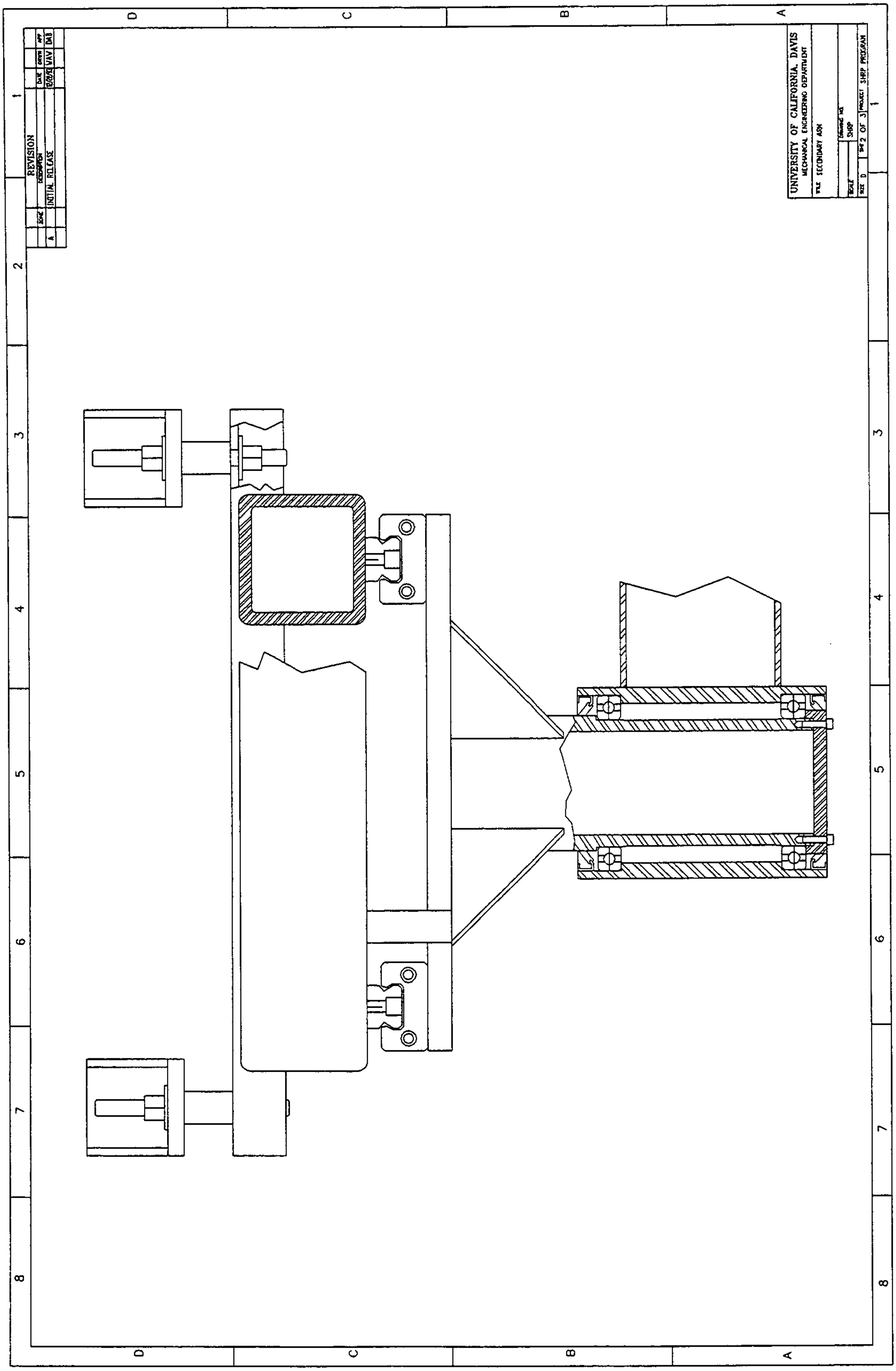
Drawing 3.2.18


REVISION
Duane Bennett
752-6957
Material for Gas Tankholders
UCD AHMT
DDV
322N
Tag 104
Uprights .5 x 2" steel bar
6
35.00
Outrails .25 x 2" bar
2
16.25
Outrails .25 x 2" bar
2
17.25
Side Rails .25 x 2" bar
4
46.00
Uprights: .5 x 2" 1018 steel bar
Outrails: .25 x 2" 1018 steel bar
46.00
15.75
23.25
TOP VIEW
Drill & Tap 3/4" for 5/16 screws
LEFT SIDE VIEW
RIGHT SIDE VIEW
FRONT VIEW
35.00
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Propane 3 Tank Holder

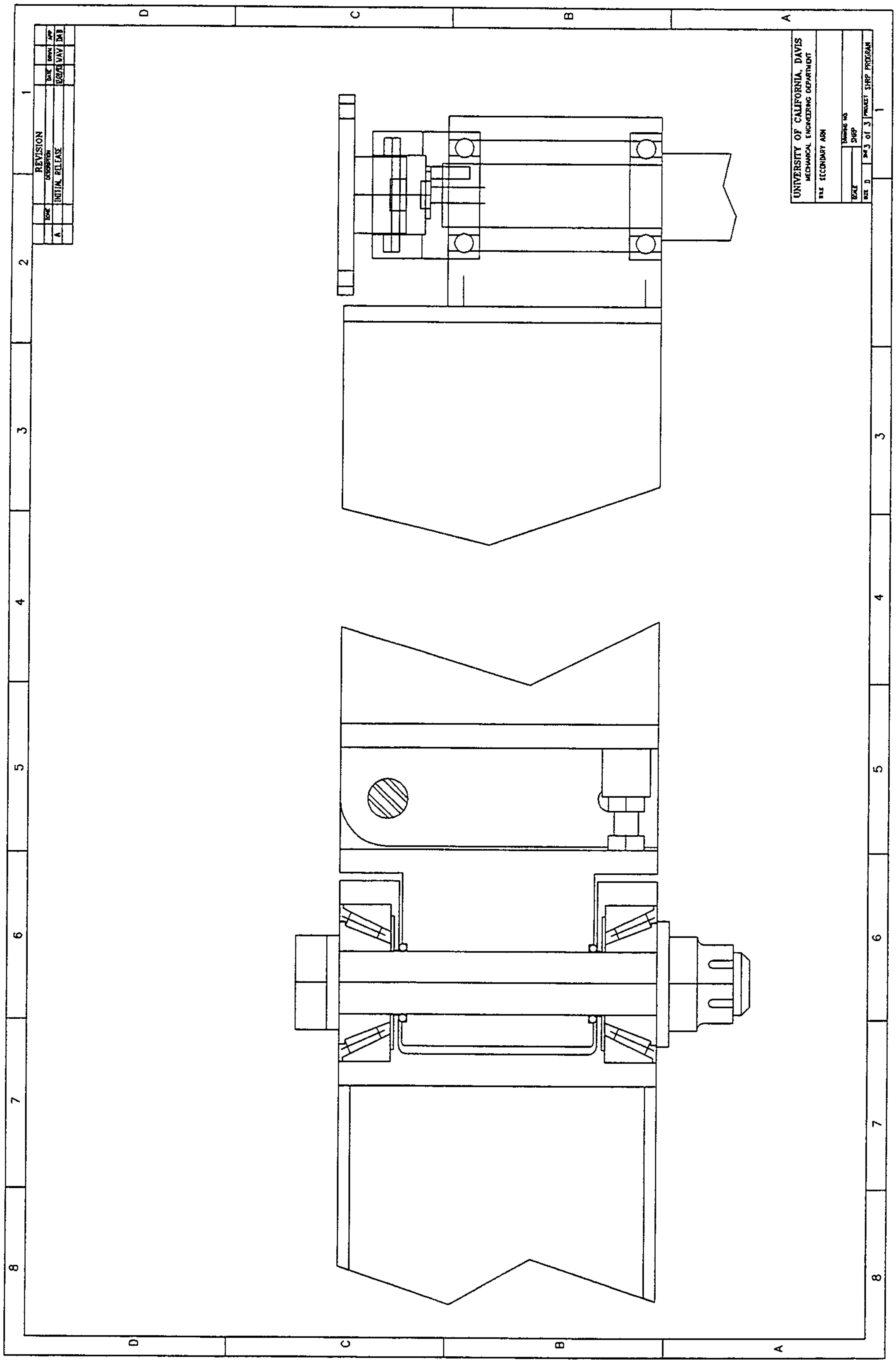
Drawing 4.1


REVISION
INITIAL RELEASE
VAV
DAB
NOTES: UNLESS OTHERWISE SPECIFIED
1) COAT ITEMS 1,2,3,4,5 & 6 WITH PRIMER AND PAINT (COLOR-OMAHA ORANGE). DO NOT COAT THREADS.
13 MAIN POST CAP 1
12 COUPLING PIN 1
11 DUST CAP 2
10 APPLICATOR POST 1
9 SPACER 1.00 OD .50 ID X 1.53 LONG STEEL 4
8 BRACKET 4
7 DOWEL PIN .625 X 5 LONG STAINLESS STEEL 1
6 JOINT PIN 1
5 ARM 2 1
4 JOINT 1
3 ARM 1 1
2 POST 1
1 RAIL BASE 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
SECONDARY ARM
SHRP
SHRP PROGRAM

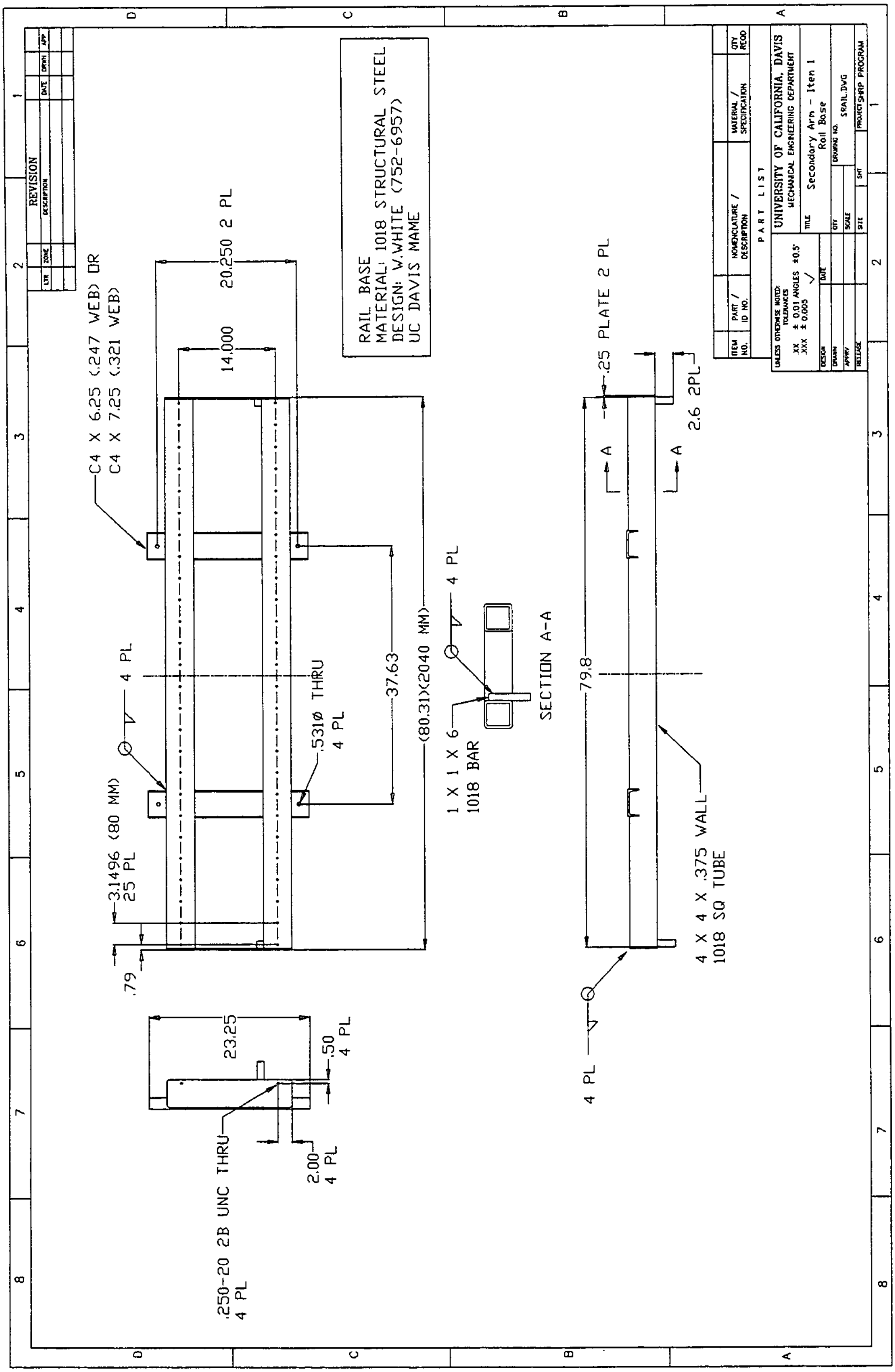
Drawing 5.1.1


UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
SECONDARY ASM
REVISION
INITIAL RELEASE

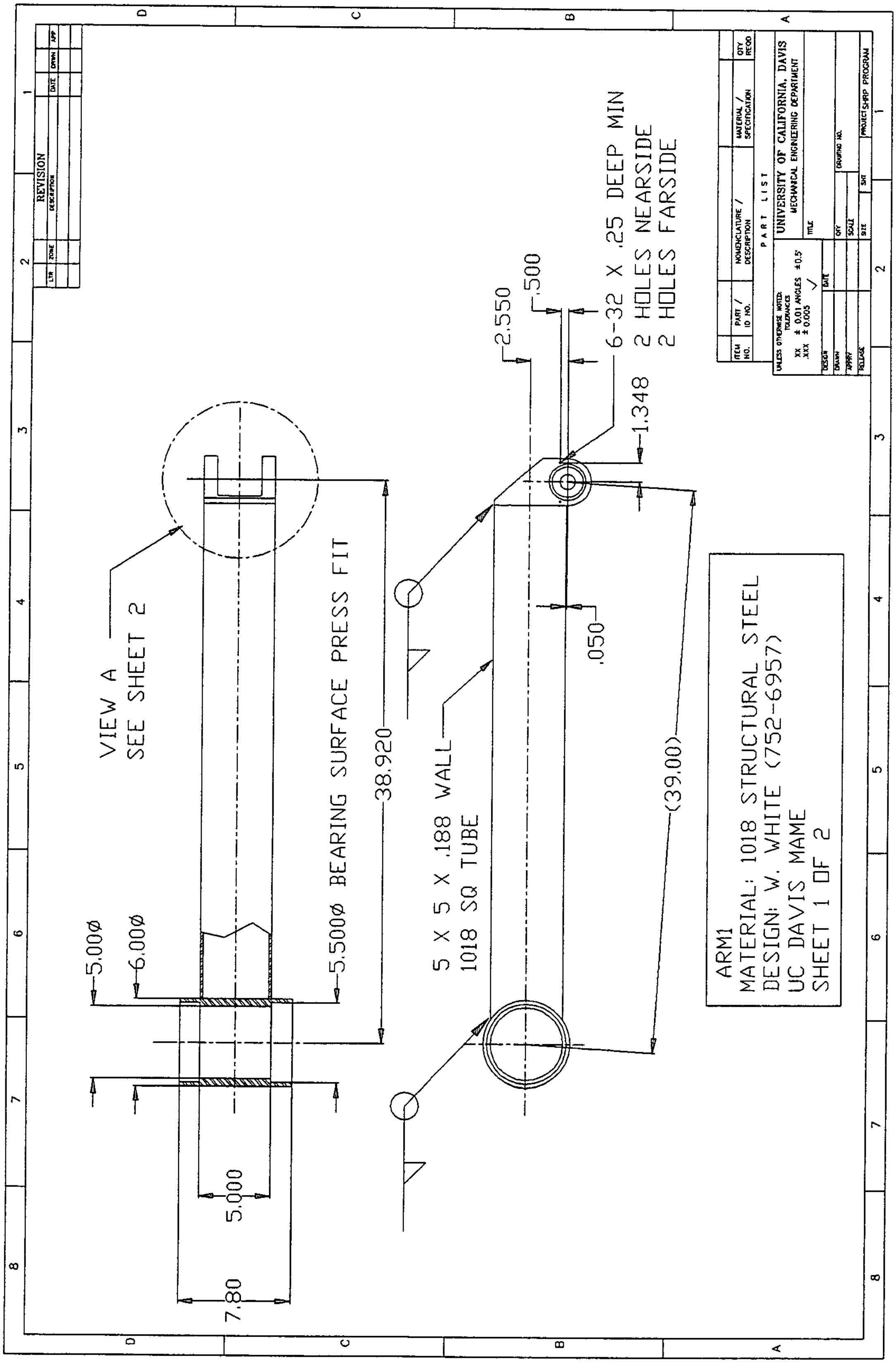
Drawing 5.1.2


UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE SECONDARY ARM
SHRP
3 of 3
PROJECT SHRP PROGRAM
SIZE D
REVISION
INITIAL RELEASE

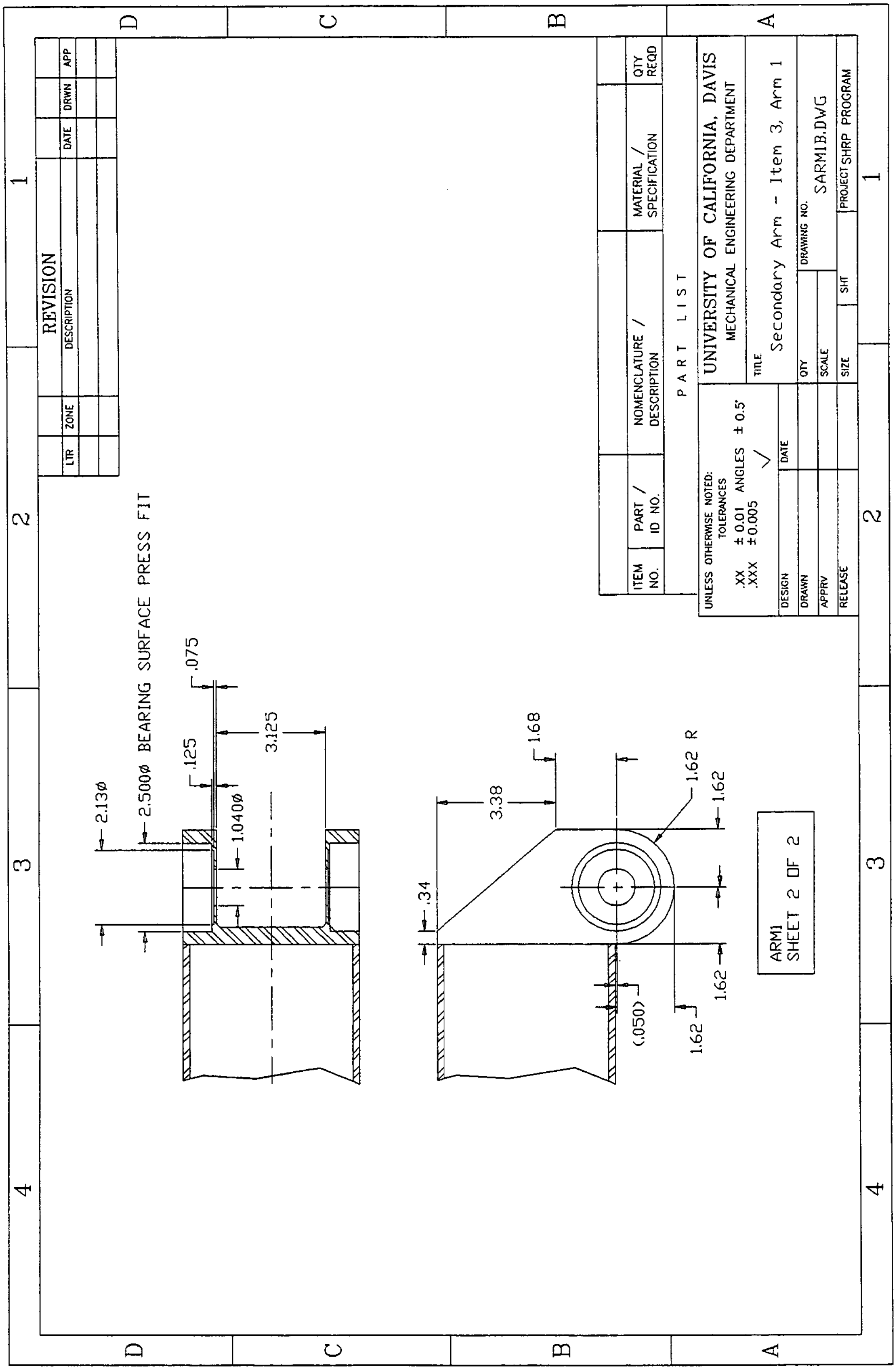
Drawing 5.1.3


RAIL BASE
MATERIAL: 1018 STRUCTURAL STEEL
DESIGN: W.WHITE (752-6957)
UC DAVIS MAME
C4 X 6.25 (.247 WEB) OR
C4 X 7.25 (.321 WEB)
14.000
20.250 2 PL
.5310 THRU
4 PL
37.63
(80.31)(2040 MM)
3.1496 (80 MM)
25 PL
.79
4 PL
1 X 1 X 6
1018 BAR
SECTION A-A
.25 PLATE 2 PL
2.6 2PL
79.8
4 X 4 X .375 WALL
1018 SQ TUBE
23.25
.50
4 PL
2.00
4 PL
.250-20 2B UNC THRU
4 PL
REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Secondary Arm - Item 1
Rail Base
SRAIL.DVG

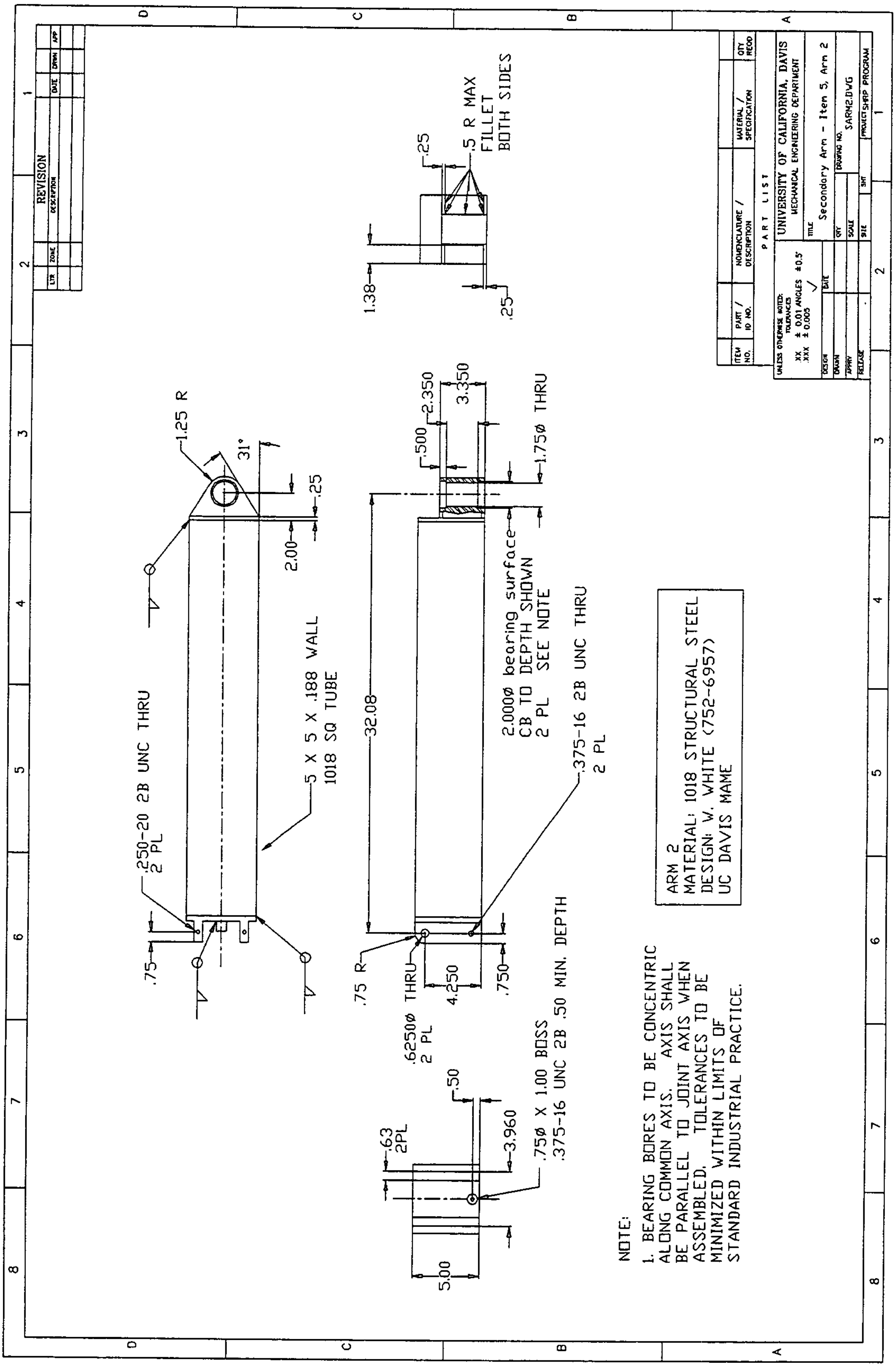
Drawing 5.1.4


REVISION
VIEW A
SEE SHEET 2
5.500Ø BEARING SURFACE PRESS FIT
38.920
5.00Ø
6.00Ø
5.000
7.80
5 X 5 X .188 WALL
1018 SQ TUBE
.050
(39.00)
1.348
2.550
.500
6-32 X .25 DEEP MIN
2 HOLES NEARSIDE
2 HOLES FARSIDE
ARM1
MATERIAL: 1018 STRUCTURAL STEEL
DESIGN: W. WHITE (752-6957)
UC DAVIS MAME
SHEET 1 OF 2
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
SHRP PROGRAM

Drawing 5.1.5

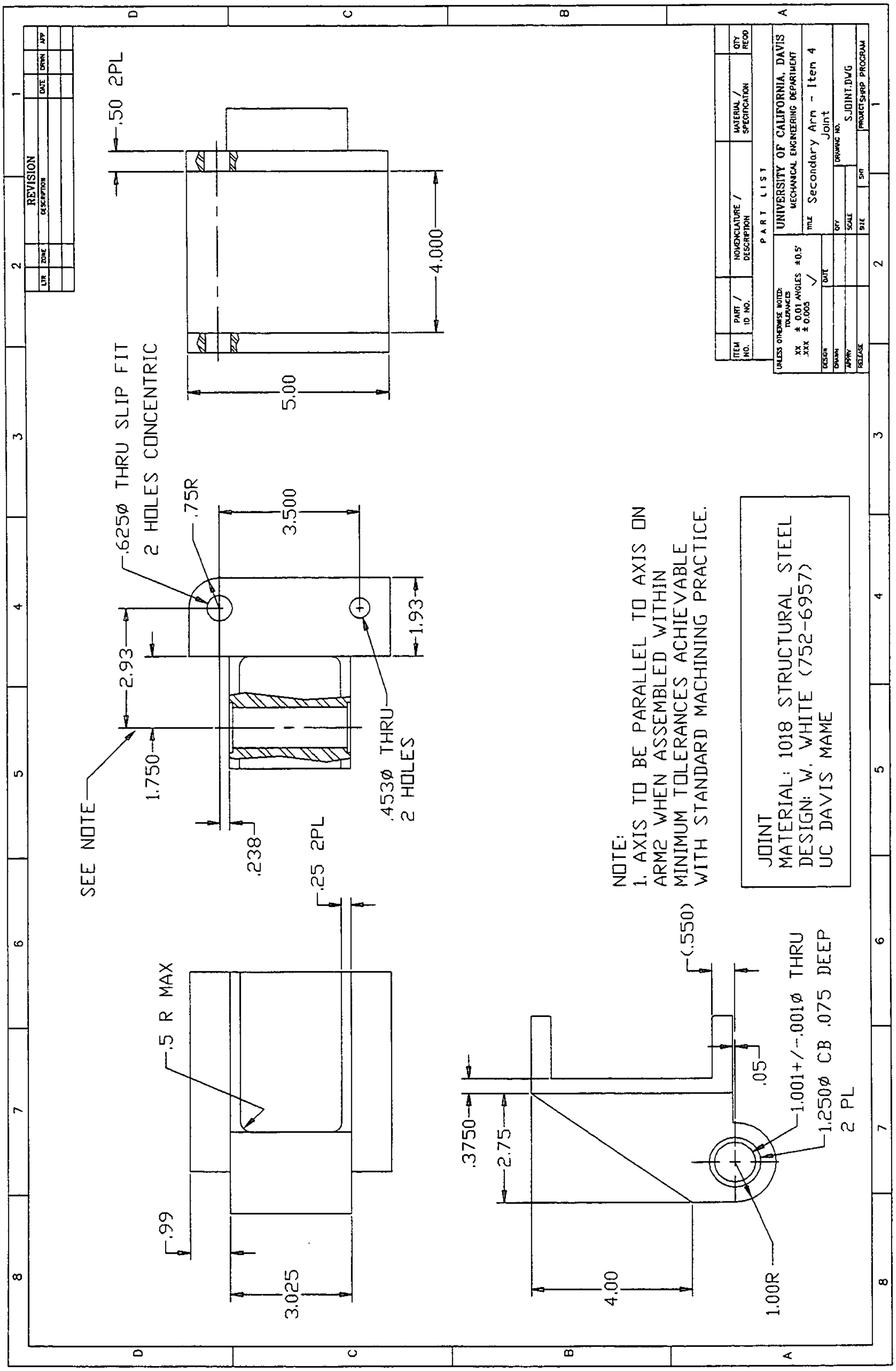

REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
2.500ø BEARING SURFACE PRESS FIT
2.13ø
.125
1.040ø
.075
3.125
3.38
1.68
1.62 R
1.62
.34
(.050)
1.62
ARM1
SHEET 2 OF 2
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± 0.01 ANGLES ± 0.5°
.XXX ± 0.005
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
Secondary Arm - Item 3, Arm 1
DESIGN
DRAWN
APPRV
RELEASE
DATE
QTY
SCALE
SIZE
SHT
DRAWING NO.
SARM1B.DWG
PROJECT SHRP PROGRAM

Drawing 5.1.6

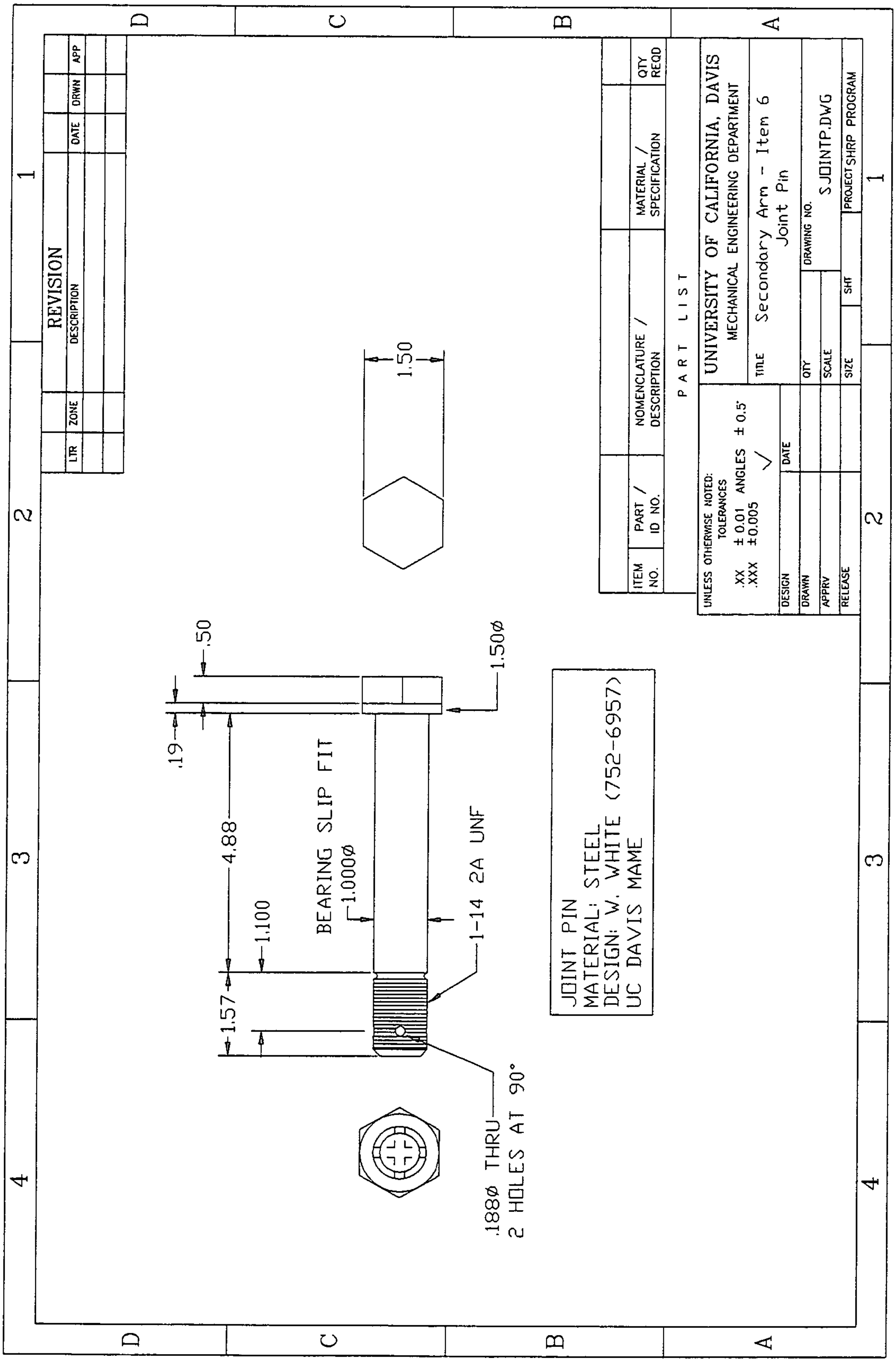


NOTE:
1. BEARING BORES TO BE CONCENTRIC ALONG COMMON AXIS. AXIS SHALL BE PARALLEL TO JOINT AXIS WHEN ASSEMBLED. TOLERANCES TO BE MINIMIZED WITHIN LIMITS OF STANDARD INDUSTRIAL PRACTICE.
ARM 2
MATERIAL: 1018 STRUCTURAL STEEL
DESIGN: W. WHITE (752-6957)
UC DAVIS MAME
5 X 5 X .188 WALL
1018 SQ TUBE
.250-20 2B UNC THRU
2 PL
1.25 R
31°
.25
2.00
.75
32.08
2.000ø bearing surface
CB TO DEPTH SHOWN
2 PL SEE NOTE
.375-16 2B UNC THRU
2 PL
.500
2.350
3.350
1.750ø THRU
.75 R
.6250ø THRU
2 PL
4.250
.750
.75ø X 1.00 BOSS
.375-16 UNC 2B .50 MIN. DEPTH
.63
2PL
.50
3.960
5.00
.25
.5 R MAX
FILLET
BOTH SIDES
1.38
.25
REVISION
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Secondary Arm - Item 5, Arm 2
SARM2.DWG
PART LIST

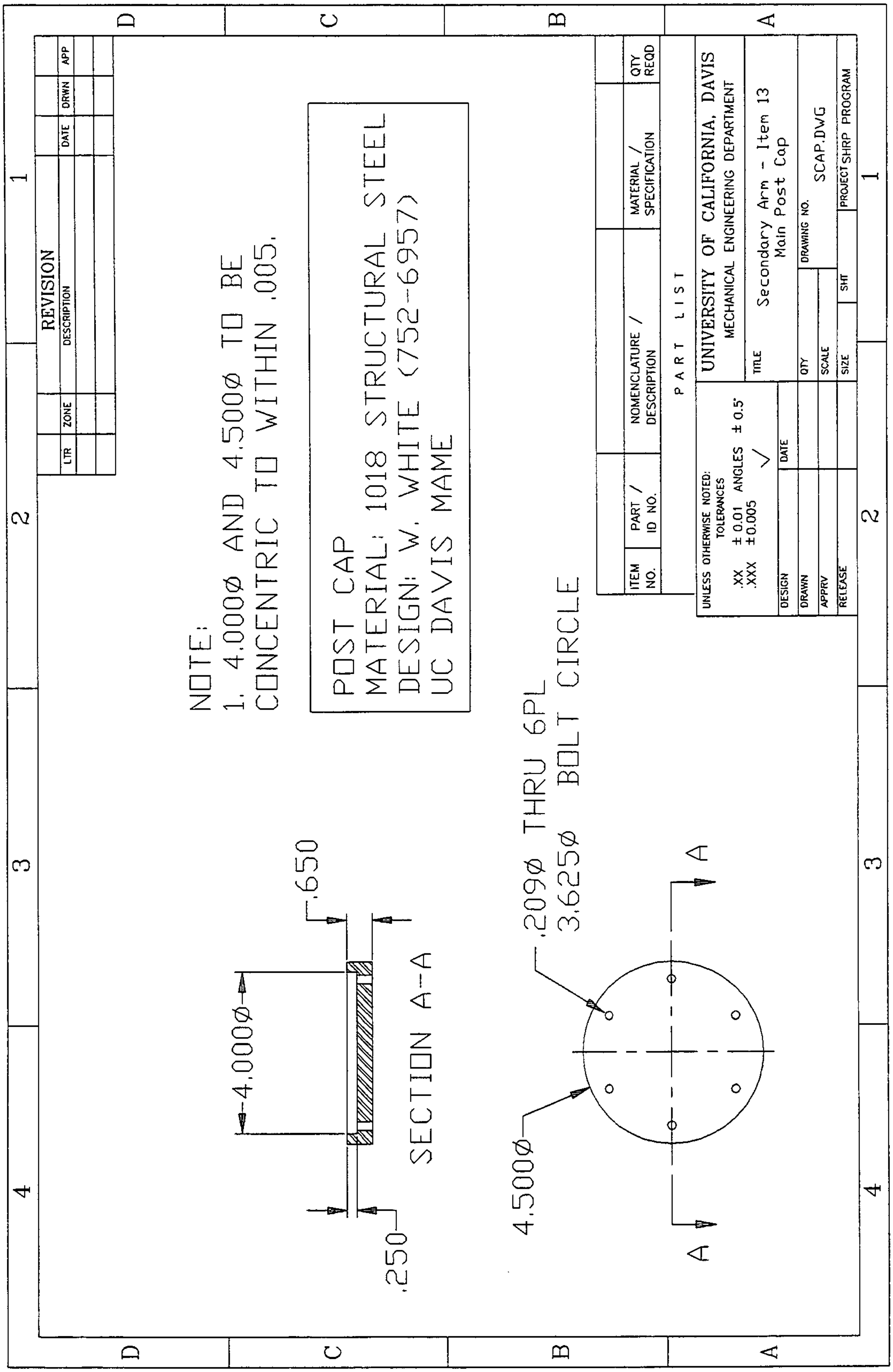
Drawing 5.1.7


NOTE:
1. AXIS TO BE PARALLEL TO AXIS ON ARM2 WHEN ASSEMBLED WITHIN MINIMUM TOLERANCES ACHIEVABLE WITH STANDARD MACHINING PRACTICE.
JOINT
MATERIAL: 1018 STRUCTURAL STEEL
DESIGN: W. WHITE (752-6957)
UC DAVIS MAME
UNIVERSITY OF CALIFORNIA, DAVIS
Secondary Arm - Item 4
Joint

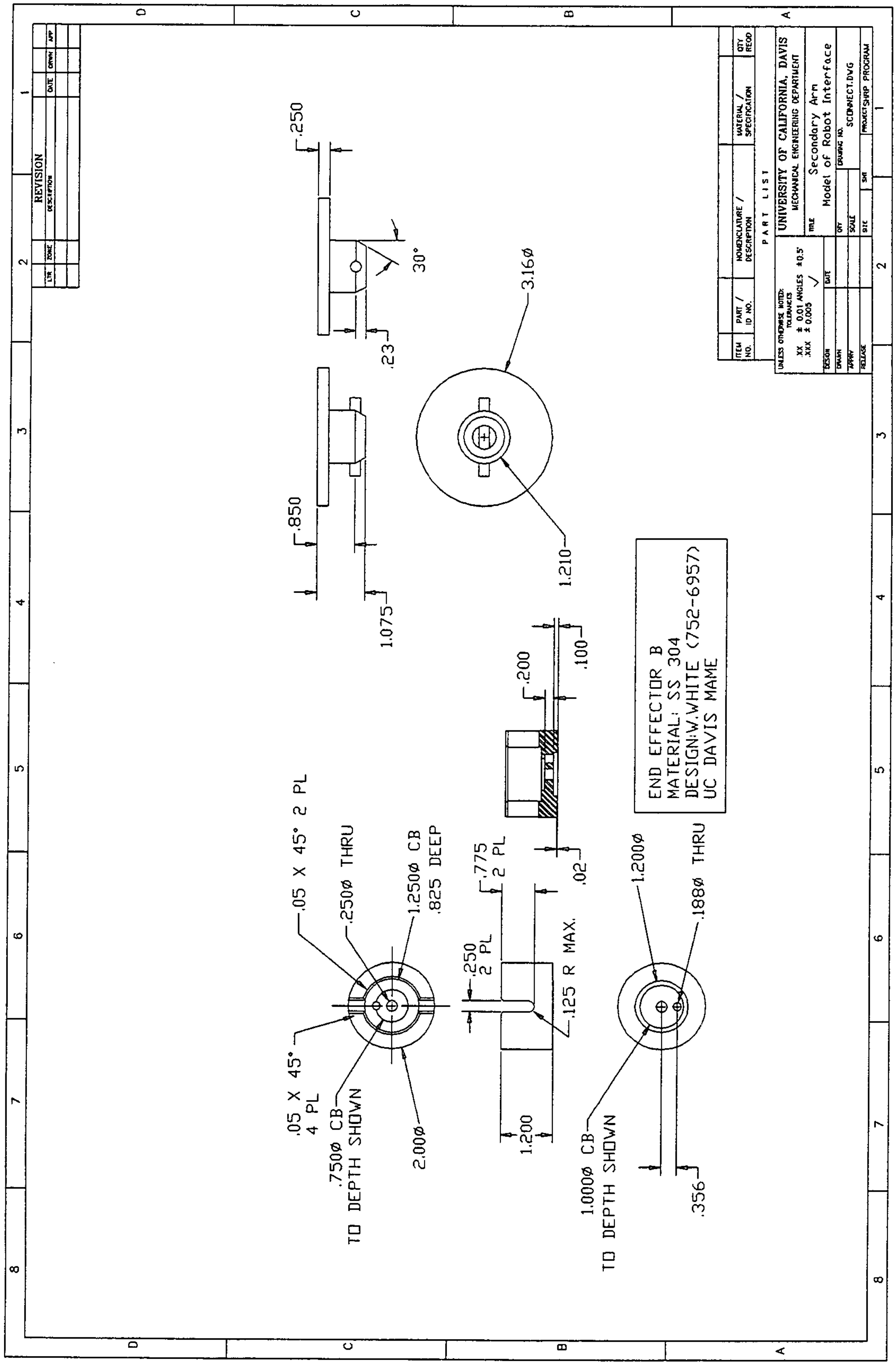
Drawing 5.1.8


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
JOINT PIN
MATERIAL: STEEL
DESIGN: W. WHITE (752-6957)
UC DAVIS MAME
BEARING SLIP FIT
1.000ø
1-14 2A UNF
.188ø THRU
2 HOLES AT 90°
1.50ø
1.50
.50
.19
4.88
1.100
1.57
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY REQD
PART LIST
UNLESS OTHERWISE NOTED:
TOLERANCES
.XX ± 0.01 ANGLES ± 0.5°
.XXX ±0.005
DESIGN
DRAWN
APPRV
RELEASE
DATE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE
Secondary Arm - Item 6
Joint Pin
QTY
SCALE
SIZE
SHT
DRAWING NO.
SJOINTP.DWG
PROJECT SHRP PROGRAM

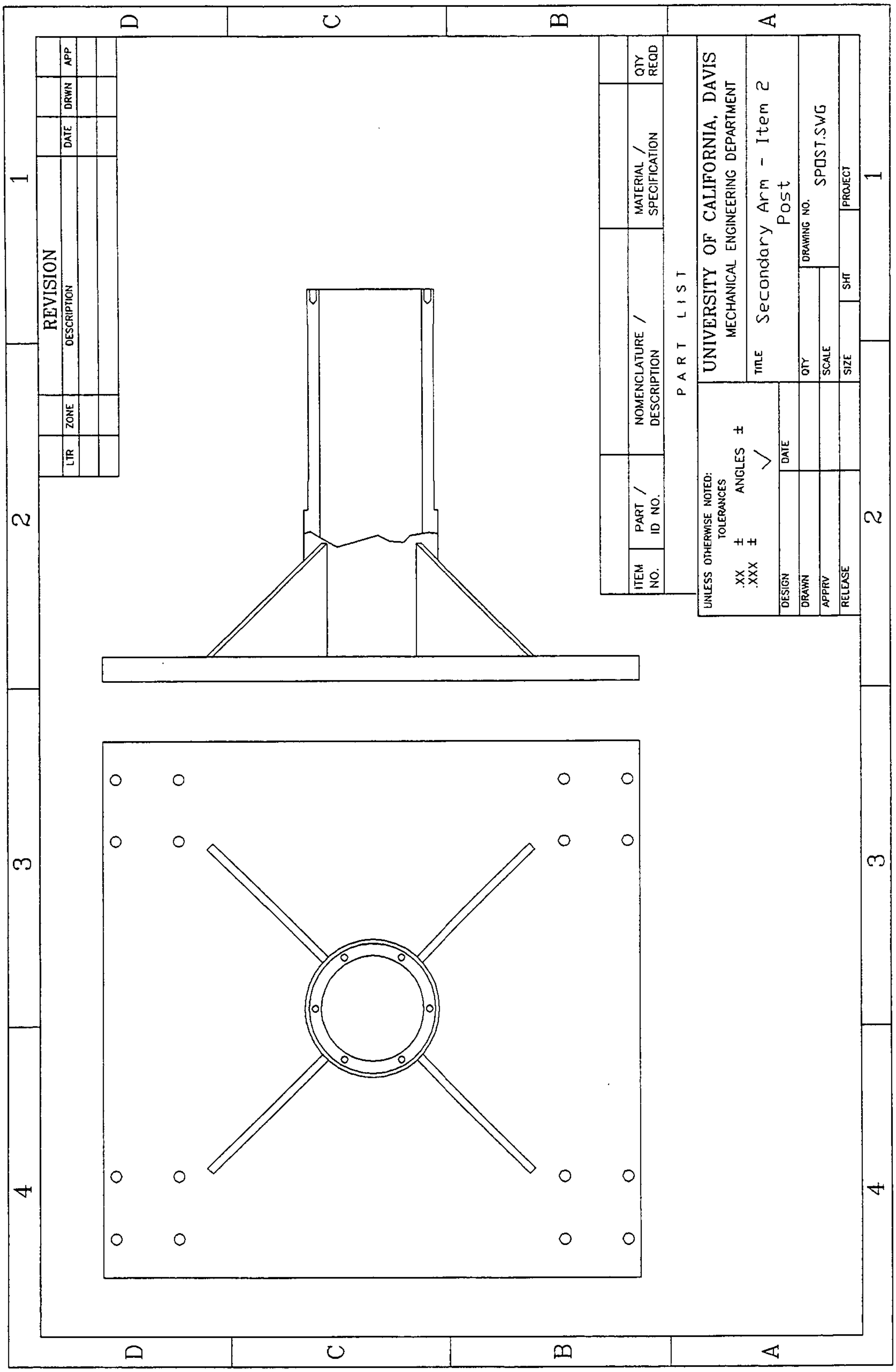
Drawing 5.1.9



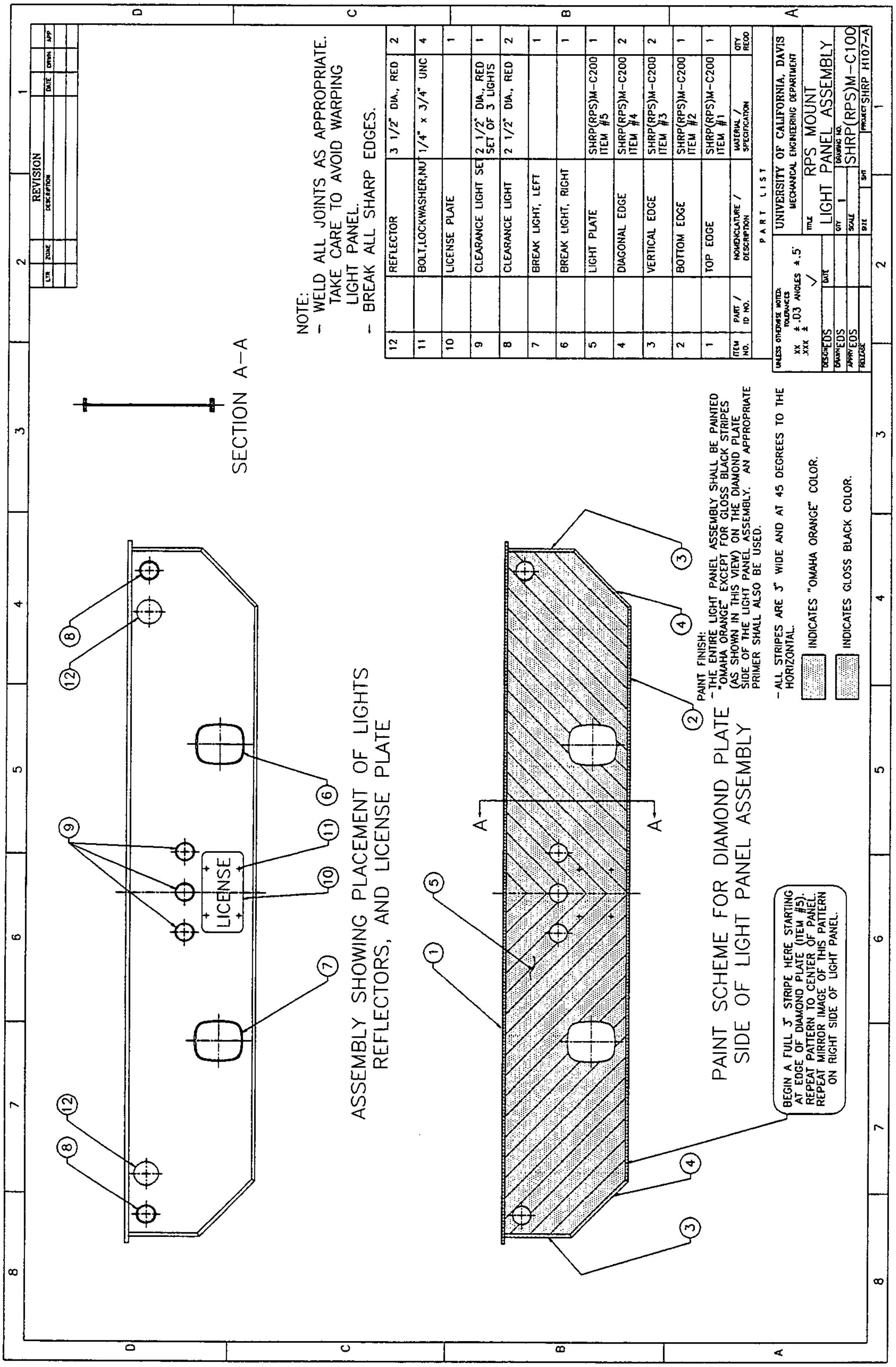
Drawing 5.1.10



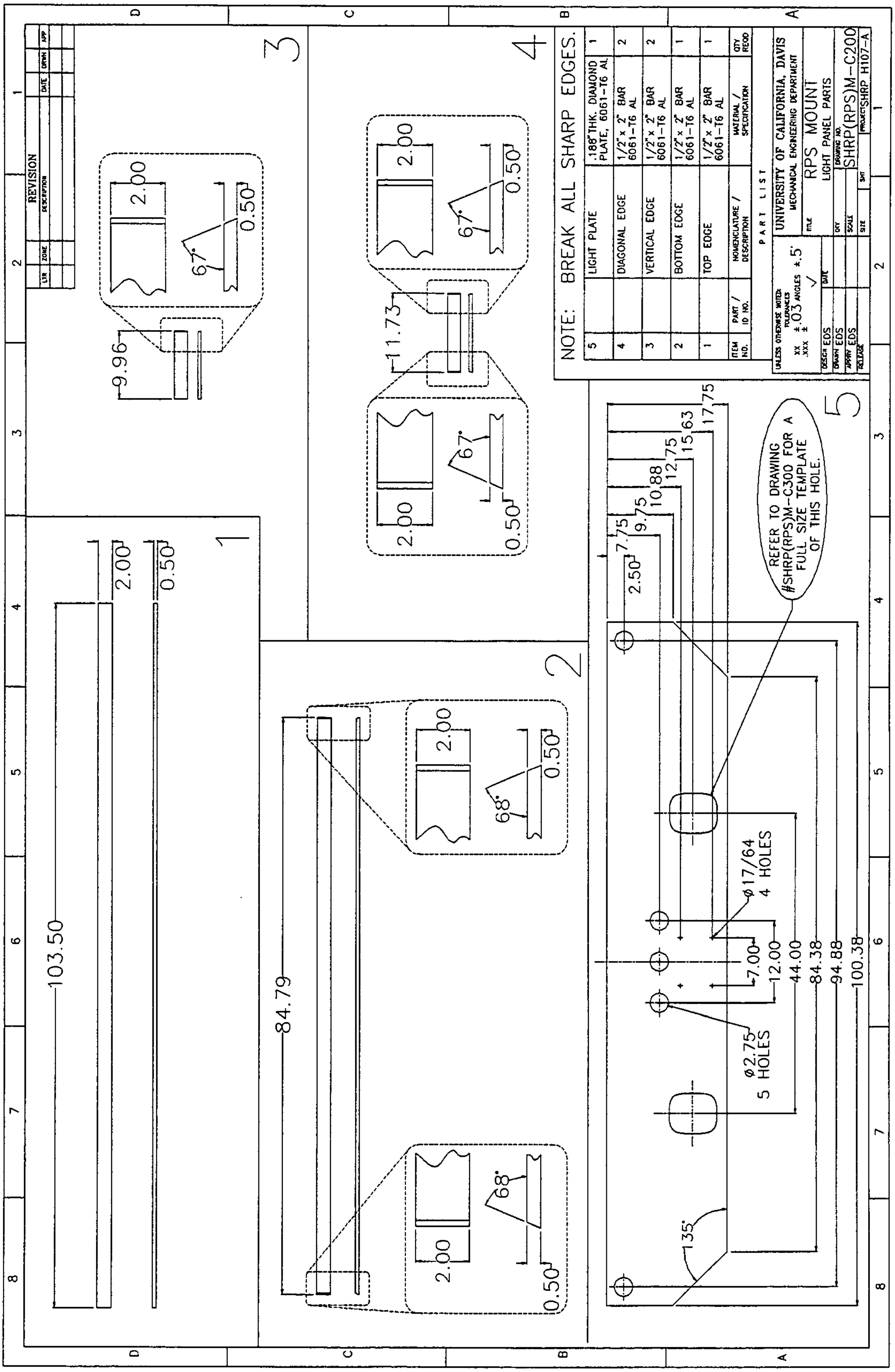
Drawing 5.1.11



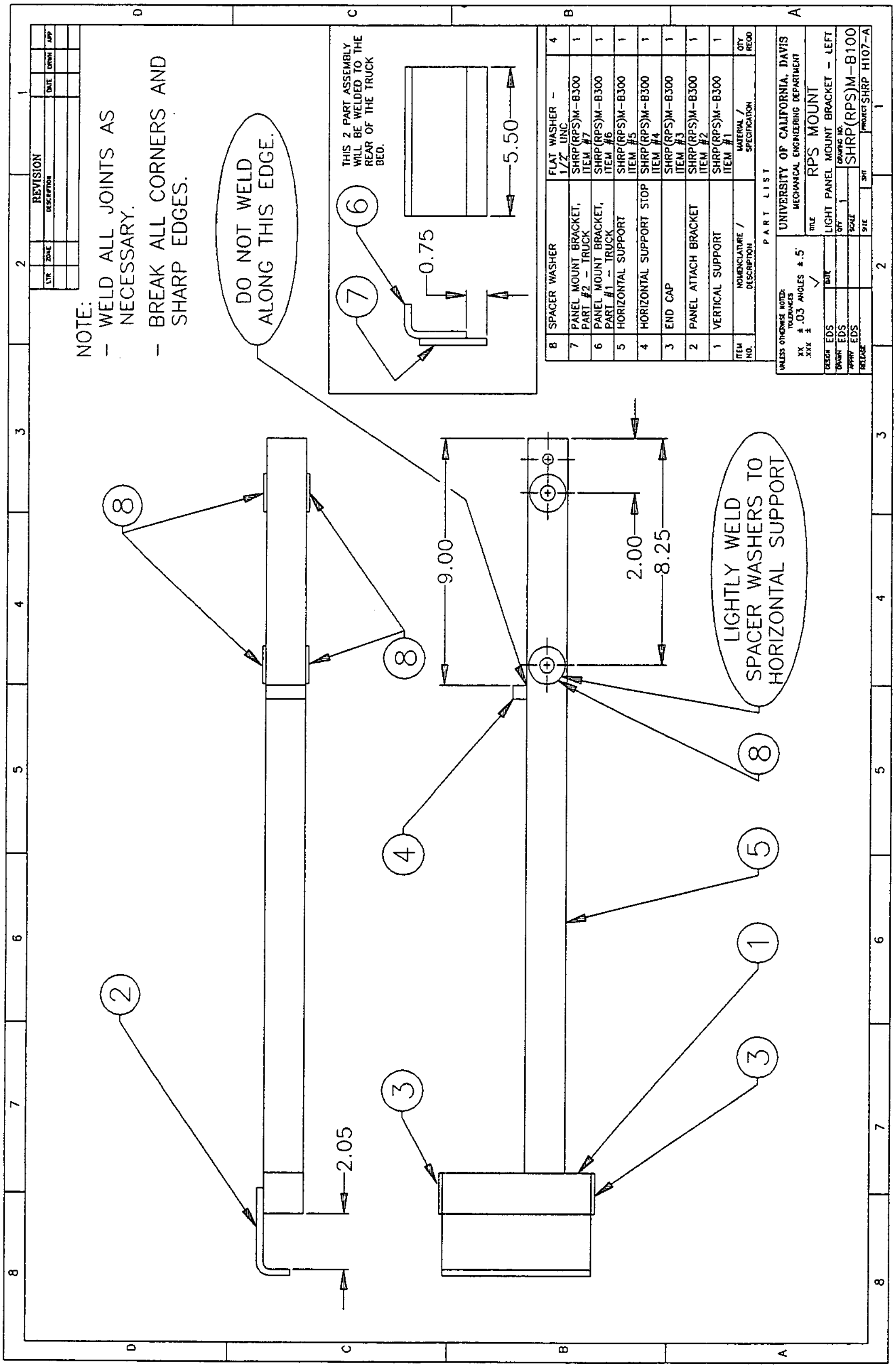
Drawing 5.1.12


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
NOTE:
- WELD ALL JOINTS AS APPROPRIATE. TAKE CARE TO AVOID WARPING LIGHT PANEL.
- BREAK ALL SHARP EDGES.
SECTION A-A
ASSEMBLY SHOWING PLACEMENT OF LIGHTS REFLECTORS, AND LICENSE PLATE
LICENSE
PAINT SCHEME FOR DIAMOND PLATE SIDE OF LIGHT PANEL ASSEMBLY
PAINT FINISH:
- THE ENTIRE LIGHT PANEL ASSEMBLY SHALL BE PAINTED "OMAHA ORANGE" EXCEPT FOR GLOSS BLACK STRIPES (AS SHOWN IN THIS VIEW) ON THE DIAMOND PLATE SIDE OF THE LIGHT PANEL ASSEMBLY. AN APPROPRIATE PRIMER SHALL ALSO BE USED.
- ALL STRIPES ARE 3" WIDE AND AT 45 DEGREES TO THE HORIZONTAL.
INDICATES "OMAHA ORANGE" COLOR.
INDICATES GLOSS BLACK COLOR.
BEGIN A FULL 3" STRIPE HERE STARTING AT EDGE OF DIAMOND PLATE (ITEM #5). REPEAT PATTERN TO CENTER OF PANEL. REPEAT MIRROR IMAGE OF THIS PANEL PATTERN ON RIGHT SIDE OF LIGHT PANEL.
12 REFLECTOR 3 1/2" DIA., RED 2
11 BOLT,LOCKWASHER,NUT 1/4" x 3/4" UNC 4
10 LICENSE PLATE 1
9 CLEARANCE LIGHT SET 2 1/2" DIA., RED SET OF 3 LIGHTS 1
8 CLEARANCE LIGHT 2 1/2" DIA., RED 2
7 BREAK LIGHT, LEFT 1
6 BREAK LIGHT, RIGHT 1
5 LIGHT PLATE SHRP(RPS)M-C200 ITEM #5 1
4 DIAGONAL EDGE SHRP(RPS)M-C200 ITEM #4 2
3 VERTICAL EDGE SHRP(RPS)M-C200 ITEM #3 2
2 BOTTOM EDGE SHRP(RPS)M-C200 ITEM #2 1
1 TOP EDGE SHRP(RPS)M-C200 ITEM #1 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY. REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES XX ± .03 ANGLES ±.5°
DESIGN EDS
DRAWN EDS
APPRV EDS
RELEASE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
LIGHT PANEL ASSEMBLY
SHRP(RPS)M-C100
PROJECT SHRP H107-A

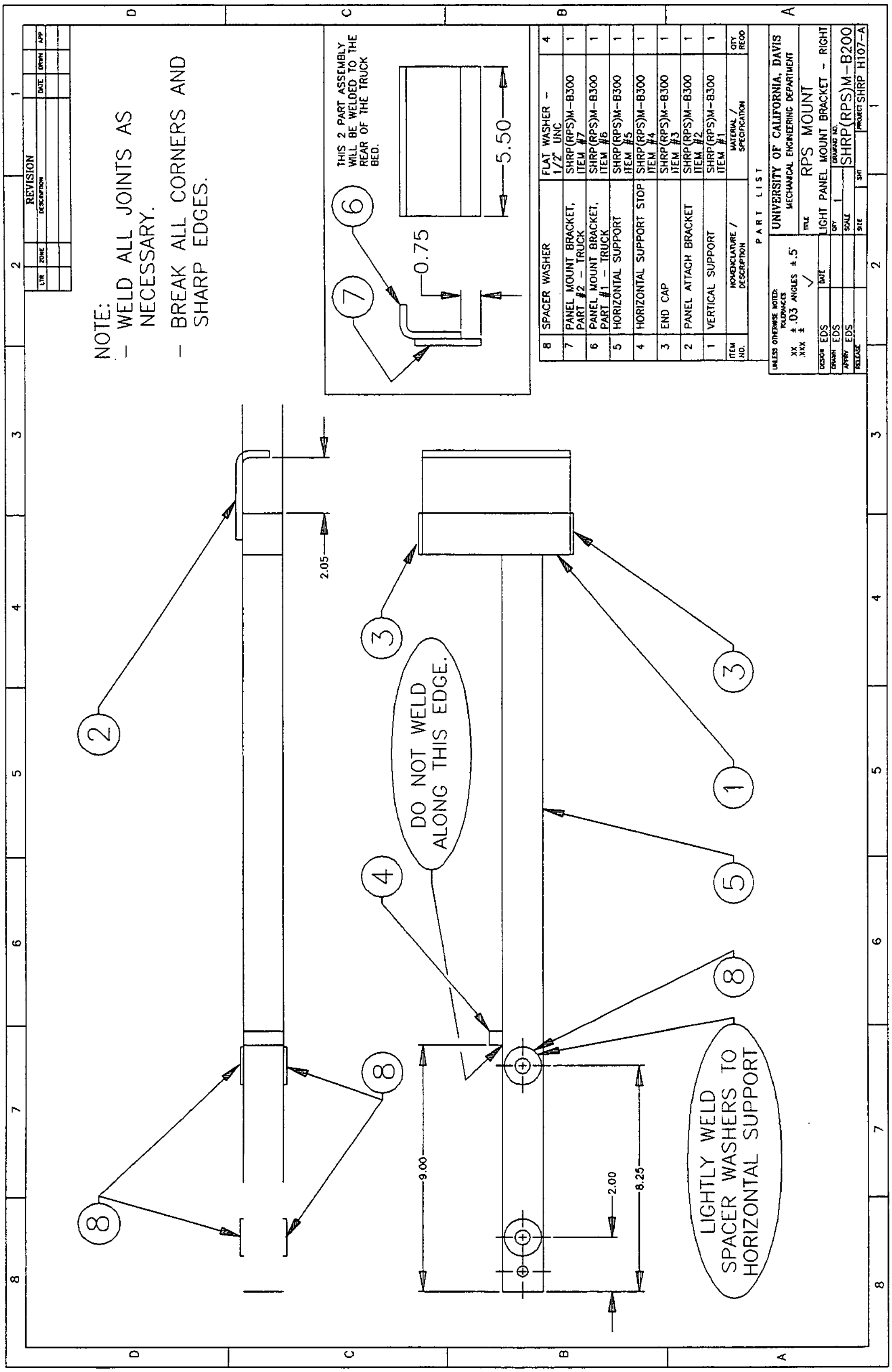
Drawing 5.2.1


NOTE: BREAK ALL SHARP EDGES.
LIGHT PLATE
.188"THK. DIAMOND PLATE, 6061-T6 AL
DIAGONAL EDGE
VERTICAL EDGE
BOTTOM EDGE
TOP EDGE
1/2"x 2" BAR 6061-T6 AL
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
LIGHT PANEL PARTS
SHRP(RPS)M-C200
SHRP H107-A
REFER TO DRAWING #SHRP(RPS)M-C300 FOR A FULL SIZE TEMPLATE OF THIS HOLE.
ϕ17/64 4 HOLES
ϕ2.75 5 HOLES
REVISION

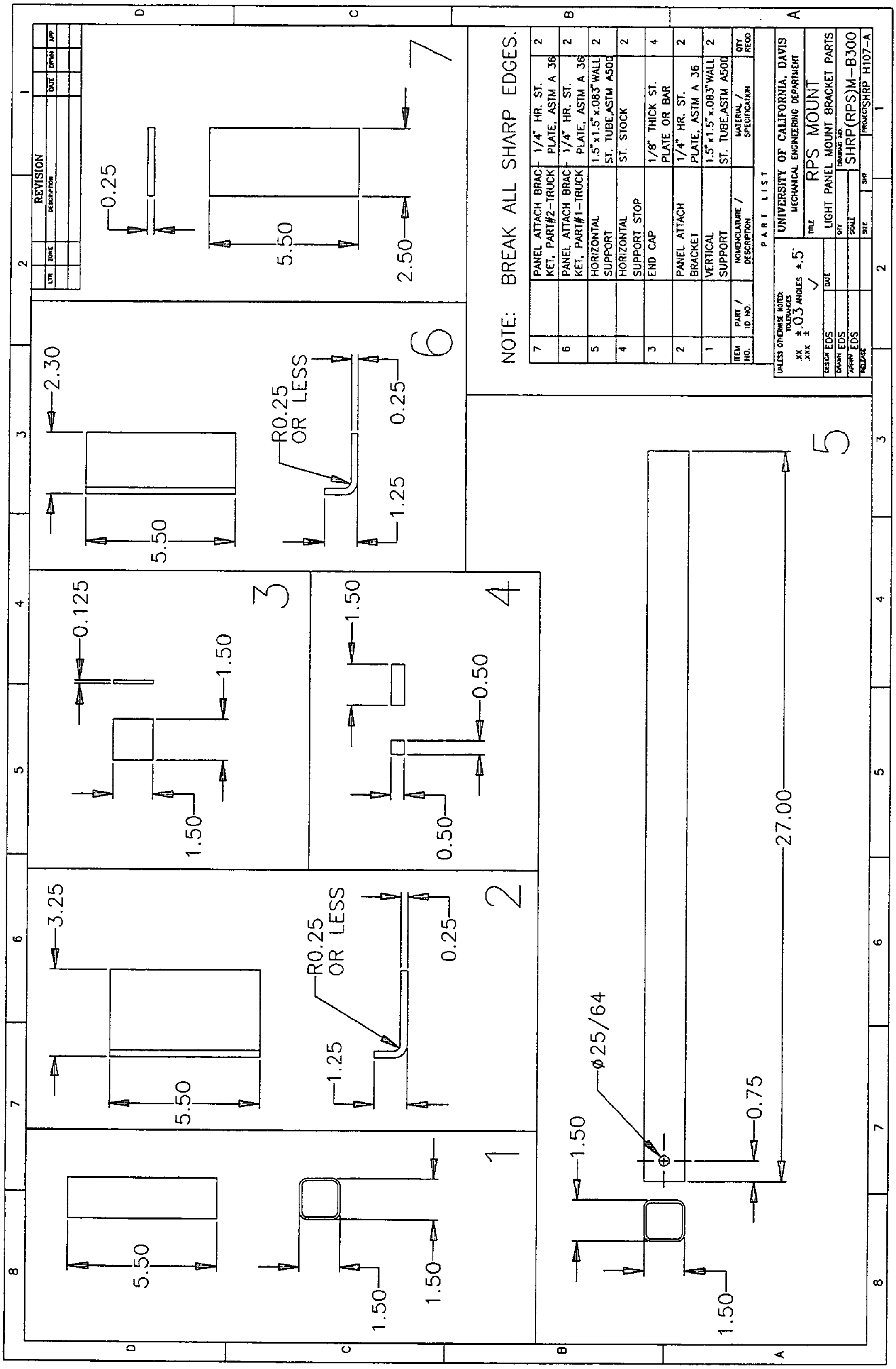
Drawing 5.2.2


NOTE:
- WELD ALL JOINTS AS NECESSARY.
- BREAK ALL CORNERS AND SHARP EDGES.
DO NOT WELD ALONG THIS EDGE.
THIS 2 PART ASSEMBLY WILL BE WELDED TO THE REAR OF THE TRUCK BED.
LIGHTLY WELD SPACER WASHERS TO HORIZONTAL SUPPORT
0.75
5.50
9.00
2.00
8.25
2.05
REVISION
8 SPACER WASHER FLAT WASHER - 1/2" UNC 4
7 PANEL MOUNT BRACKET, PART #2 - TRUCK SHRP(RPS)M-B300 ITEM #7 1
6 PANEL MOUNT BRACKET, PART #1 - TRUCK SHRP(RPS)M-B300 ITEM #6 1
5 HORIZONTAL SUPPORT SHRP(RPS)M-B300 ITEM #5 1
4 HORIZONTAL SUPPORT STOP SHRP(RPS)M-B300 ITEM #4 1
3 END CAP SHRP(RPS)M-B300 ITEM #3 1
2 PANEL ATTACH BRACKET SHRP(RPS)M-B300 ITEM #2 1
1 VERTICAL SUPPORT SHRP(RPS)M-B300 ITEM #1 1
ITEM NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY. REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
LIGHT PANEL MOUNT BRACKET - LEFT
SHRP(RPS)M-B100
SHRP H107-A
EDS

Drawing 5.2.3

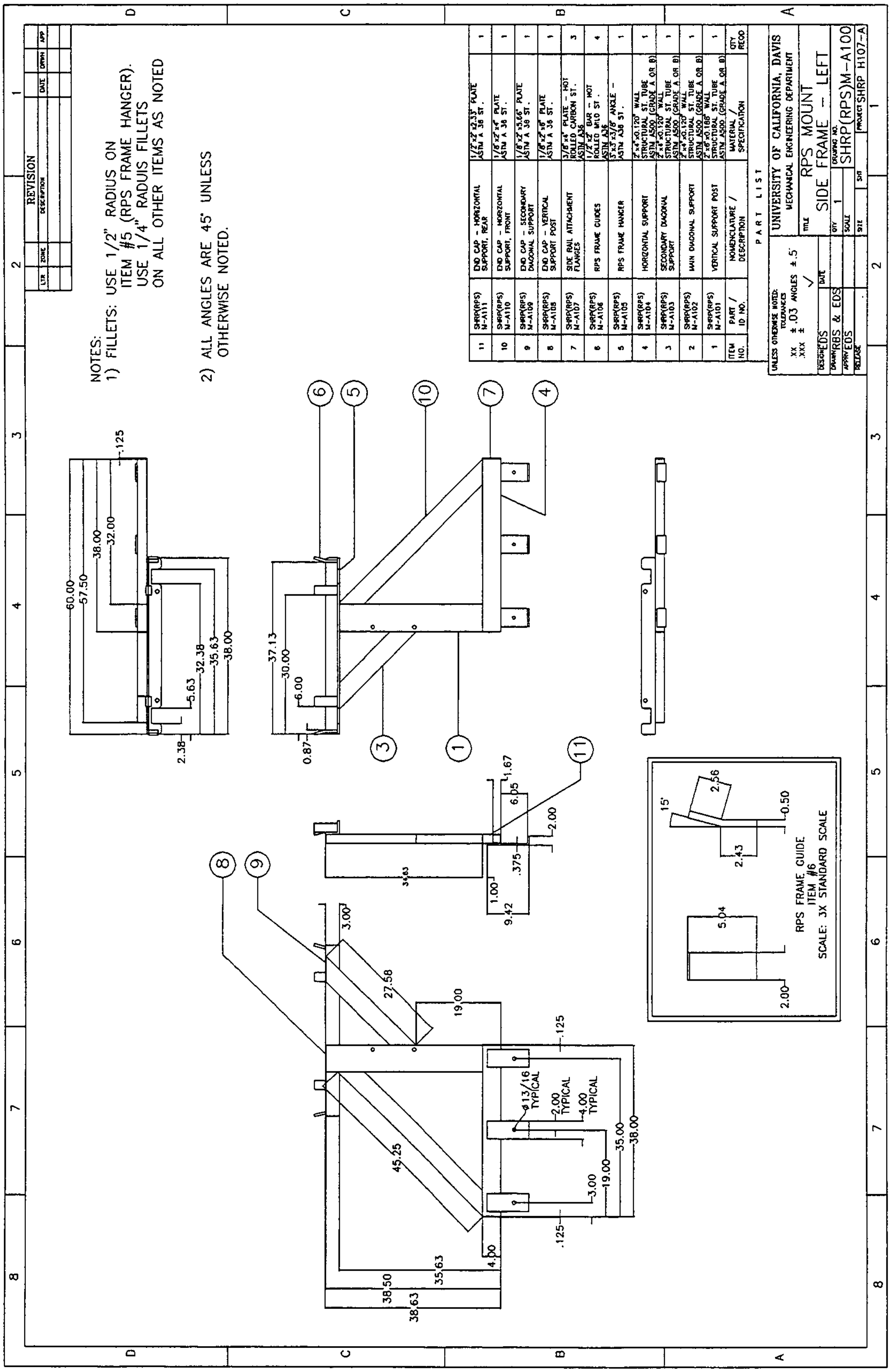

NOTE:
- WELD ALL JOINTS AS NECESSARY.
- BREAK ALL CORNERS AND SHARP EDGES.
THIS 2 PART ASSEMBLY WILL BE WELDED TO THE REAR OF THE TRUCK BED.
0.75
5.50
2.05
9.00
8.25
2.00
DO NOT WELD ALONG THIS EDGE.
LIGHTLY WELD SPACER WASHERS TO HORIZONTAL SUPPORT
8 SPACER WASHER FLAT WASHER - 1/2" UNC 4
7 PANEL MOUNT BRACKET, PART #2 - TRUCK SHRP(RPS)M-B300 ITEM #7 1
6 PANEL MOUNT BRACKET, PART #1 - TRUCK SHRP(RPS)M-B300 ITEM #6 1
5 HORIZONTAL SUPPORT SHRP(RPS)M-B300 ITEM #5 1
4 HORIZONTAL SUPPORT STOP SHRP(RPS)M-B300 ITEM #4 1
3 END CAP SHRP(RPS)M-B300 ITEM #3 1
2 PANEL ATTACH BRACKET SHRP(RPS)M-B300 ITEM #2 1
1 VERTICAL SUPPORT SHRP(RPS)M-B300 ITEM #1 1
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
LIGHT PANEL MOUNT BRACKET - RIGHT
SHRP(RPS)M-B200
SHRP H107-A

Drawing 5.2.4

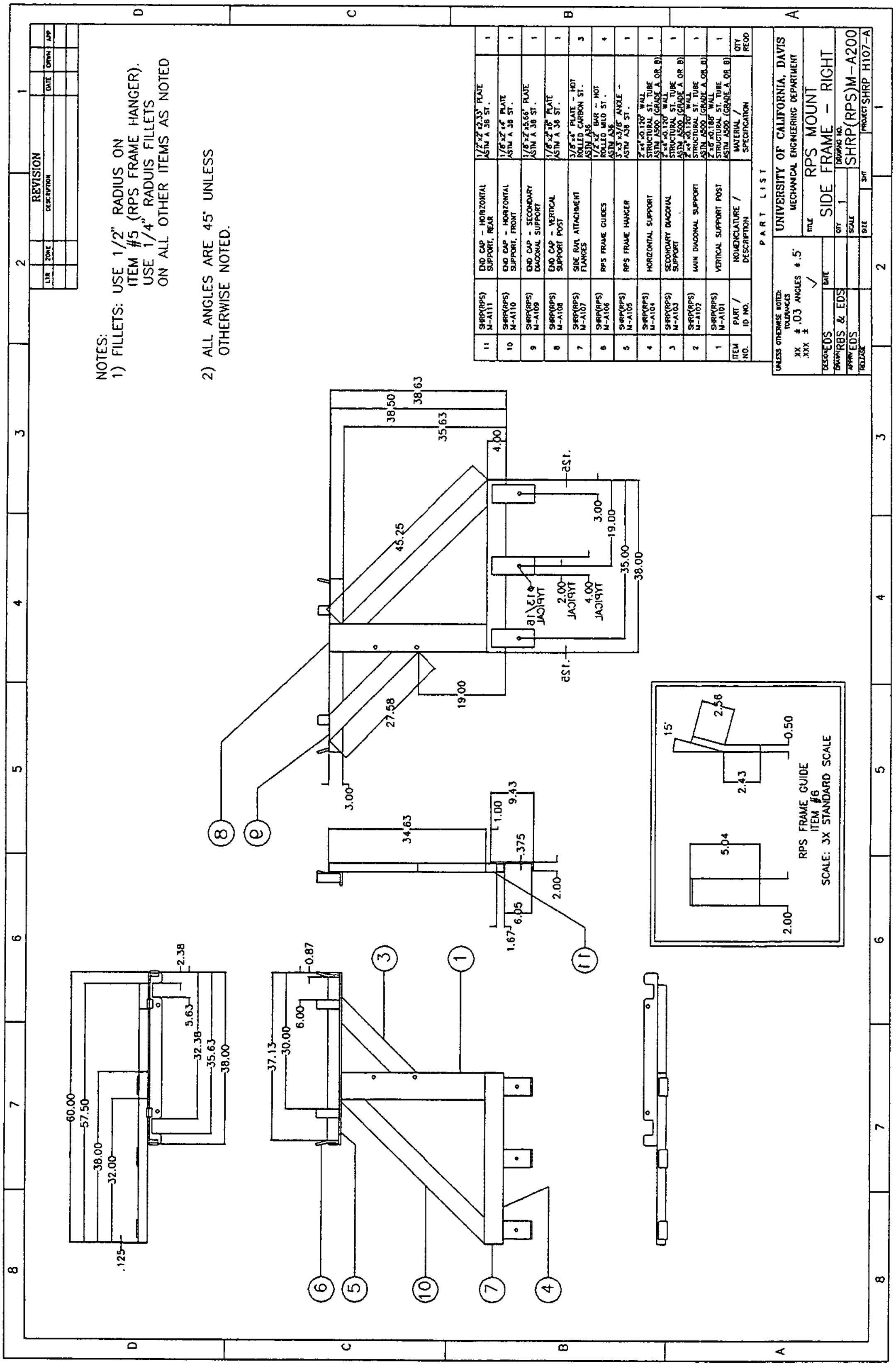


NOTE: BREAK ALL SHARP EDGES.
7 PANEL ATTACH BRACKET, PART#2-TRUCK 1/4" HR. ST. PLATE, ASTM A 36 2
6 PANEL ATTACH BRACKET, PART#1-TRUCK 1/4" HR. ST. PLATE, ASTM A 36 2
5 HORIZONTAL SUPPORT 1.5"x1.5"x.083" WALL ST. TUBE, ASTM A500 2
4 HORIZONTAL SUPPORT STOP ST. STOCK 2
3 END CAP 1/8" THICK ST. PLATE OR BAR 4
2 PANEL ATTACH BRACKET 1/4" HR. ST. PLATE, ASTM A 36 2
1 VERTICAL SUPPORT 1.5"x1.5"x.083" WALL ST. TUBE, ASTM A500 2
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
LIGHT PANEL MOUNT BRACKET PARTS
SHRP(RPS)M-B300
SHRP H107-A
REVISION
R0.25 OR LESS
ø25/64
27.00

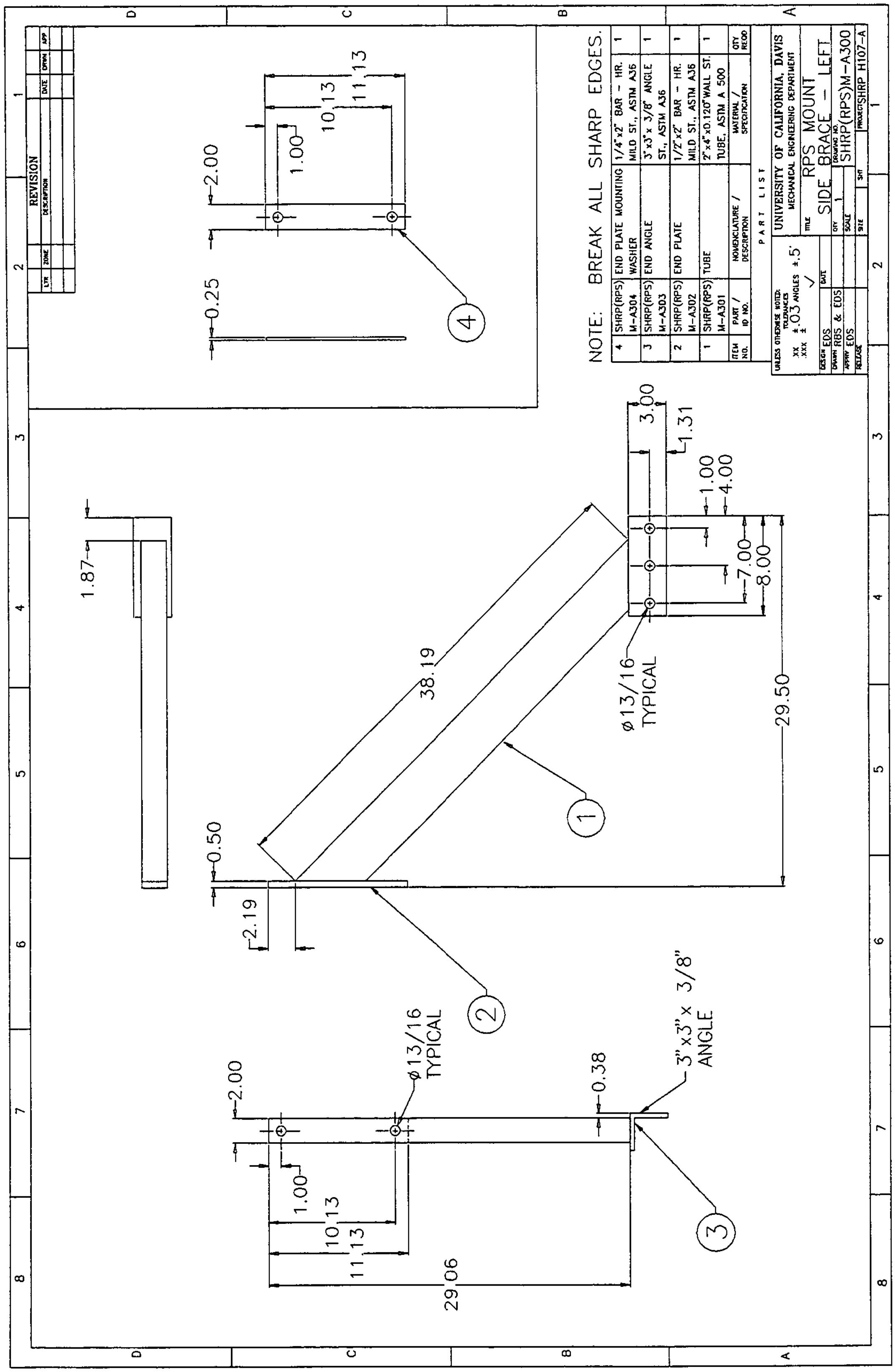
Drawing 5.2.5


NOTES:
1) FILLETS: USE 1/2" RADIUS ON ITEM #5 (RPS FRAME HANGER). USE 1/4" RADUIS FILLETS ON ALL OTHER ITEMS AS NOTED
2) ALL ANGLES ARE 45° UNLESS OTHERWISE NOTED.
RPS FRAME GUIDE
ITEM #6
SCALE: 3X STANDARD SCALE
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
SIDE FRAME — LEFT
SHRP(RPS)M-A100
SHRP H107-A

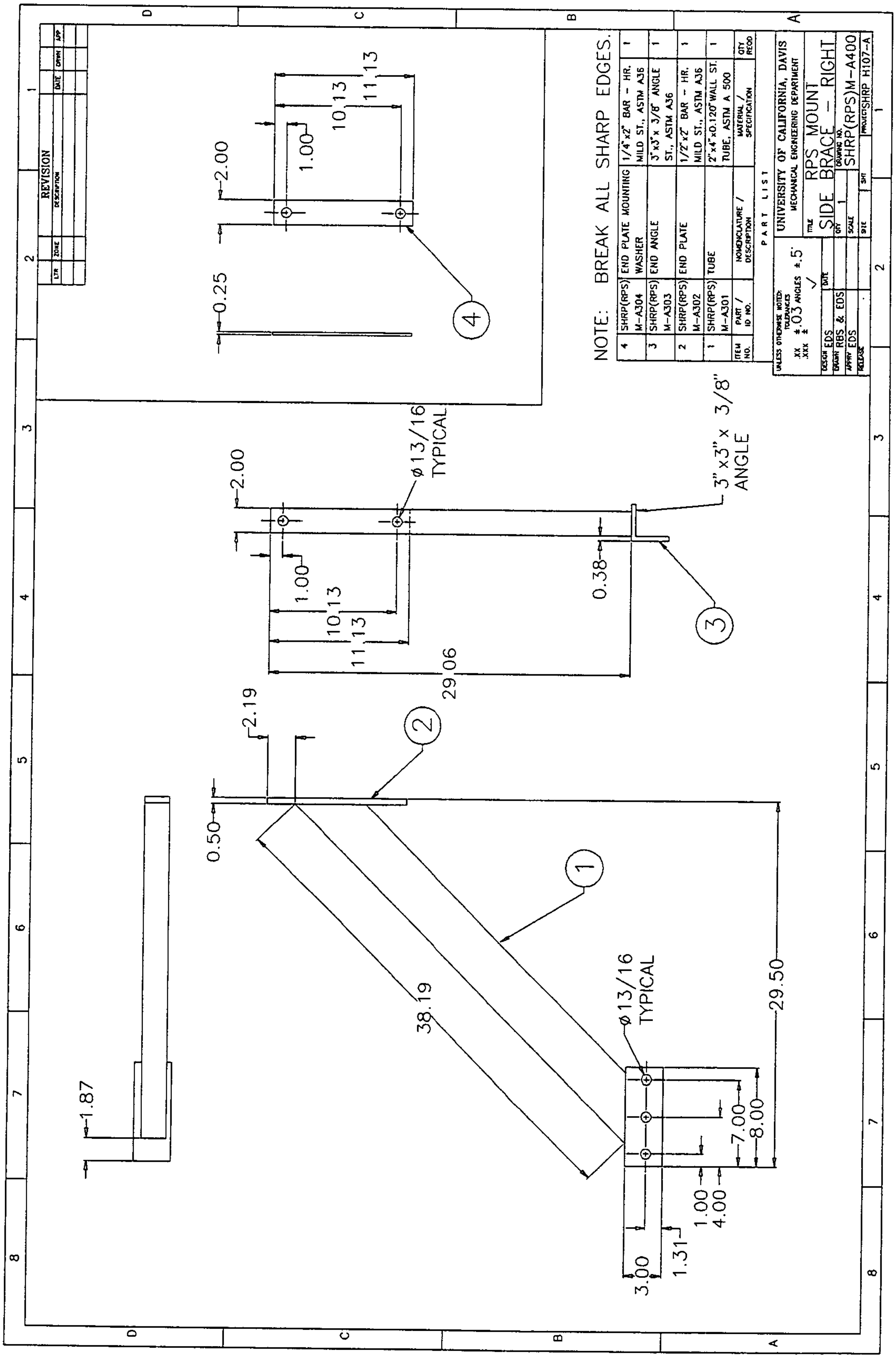
Drawing 5.2.6


NOTES:
1) FILLETS: USE 1/2" RADIUS ON ITEM #5 (RPS FRAME HANGER). USE 1/4" RADUIS FILLETS ON ALL OTHER ITEMS AS NOTED
2) ALL ANGLES ARE 45° UNLESS OTHERWISE NOTED.
REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
SIDE FRAME - RIGHT
SHRP(RPS)M-A200
SHRP H107-A
RPS FRAME GUIDE
ITEM #6
SCALE: 3X STANDARD SCALE

Drawing 5.2.7

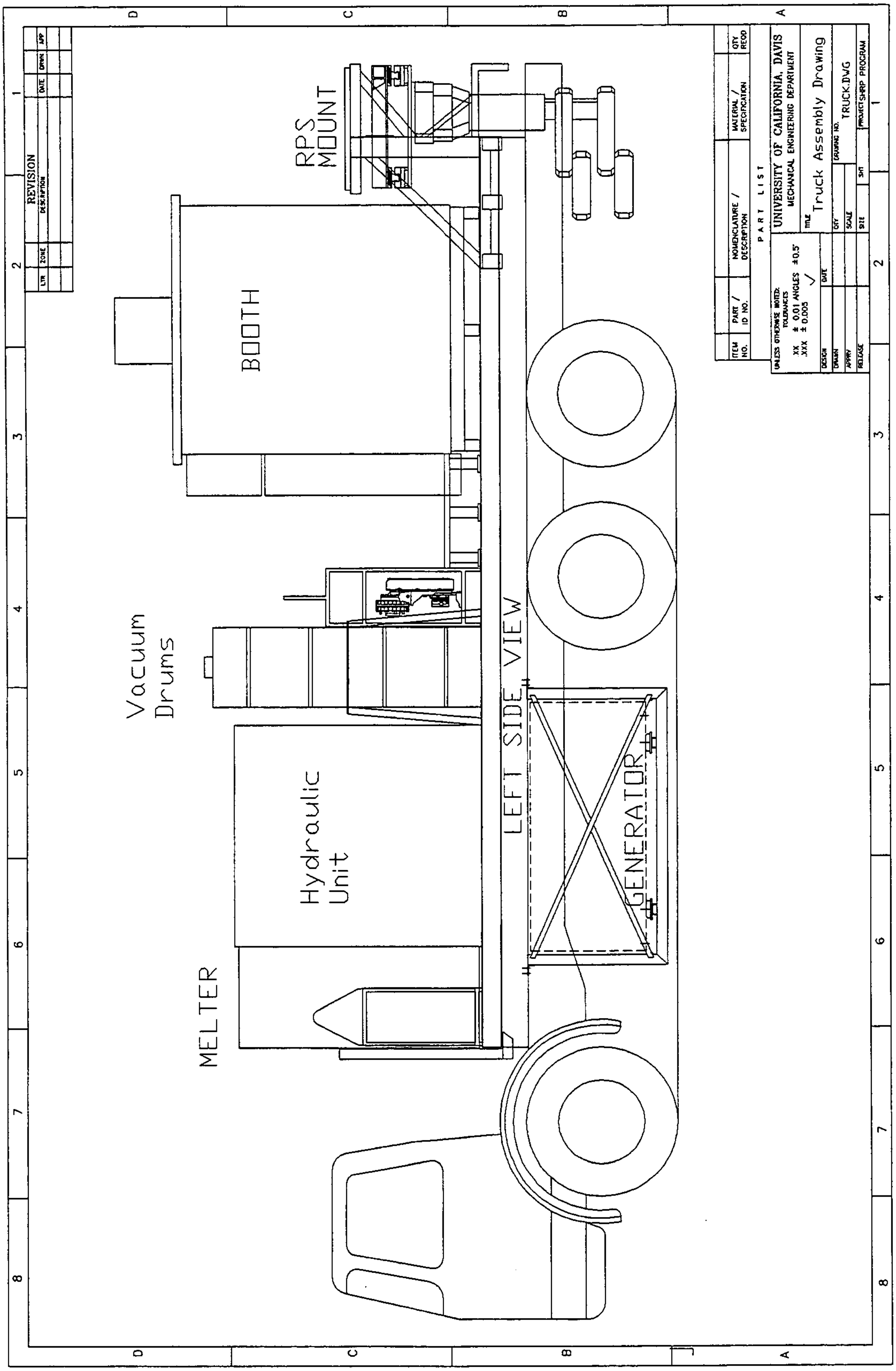

NOTE: BREAK ALL SHARP EDGES.
REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
4 SHRP(RPS) M-A304 END PLATE MOUNTING WASHER 1/4"x2" BAR - HR. MILD ST., ASTM A36 1
3 SHRP(RPS) M-A303 END ANGLE 3"x3" x 3/8" ANGLE ST., ASTM A36 1
2 SHRP(RPS) M-A302 END PLATE 1/2"x2" BAR - HR. MILD ST., ASTM A36 1
1 SHRP(RPS) M-A301 TUBE 2"x4"x0.120"WALL ST. TUBE, ASTM A 500 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
SIDE BRACE - LEFT
SHRP(RPS)M-A300
SHRP H107-A
EDS
RBS & EDS
EDS
3"x3" x 3/8" ANGLE
ø13/16 TYPICAL
38.19
29.50
29.06
1.87
0.50
2.19
0.38
0.25
2.00
1.00
10.13
11.13
3.00
1.31
4.00
7.00
8.00

Drawing 5.2.8

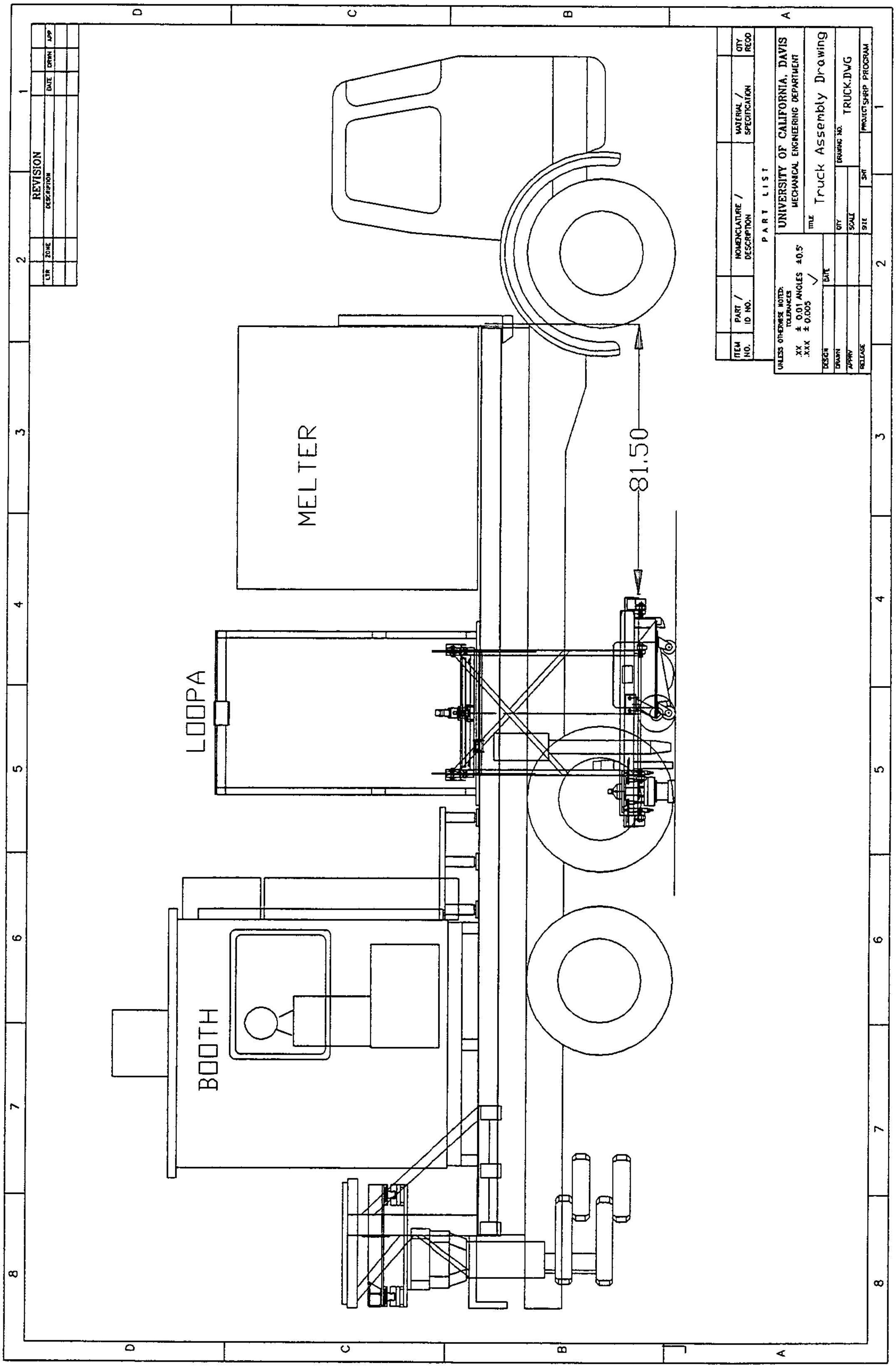


NOTE: BREAK ALL SHARP EDGES.
REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
4 SHRP(RPS) M-A304 END PLATE MOUNTING WASHER 1/4"x2" BAR - HR. MILD ST., ASTM A36 1
3 SHRP(RPS) M-A303 END ANGLE 3"x3"x 3/8" ANGLE ST., ASTM A36 1
2 SHRP(RPS) M-A302 END PLATE 1/2"x2" BAR - HR. MILD ST., ASTM A36 1
1 SHRP(RPS) M-A301 TUBE 2"x4"x0.120"WALL ST. TUBE, ASTM A 500 1
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY RECD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
RPS MOUNT
SIDE BRACE - RIGHT
SHRP(RPS)M-A400
SHRP H107-A
DESIGN EDS
DRAWN RBS & EDS
APPRV EDS
RELEASE
3"x3" x 3/8" ANGLE
ø13/16 TYPICAL
29.06
38.19
29.50

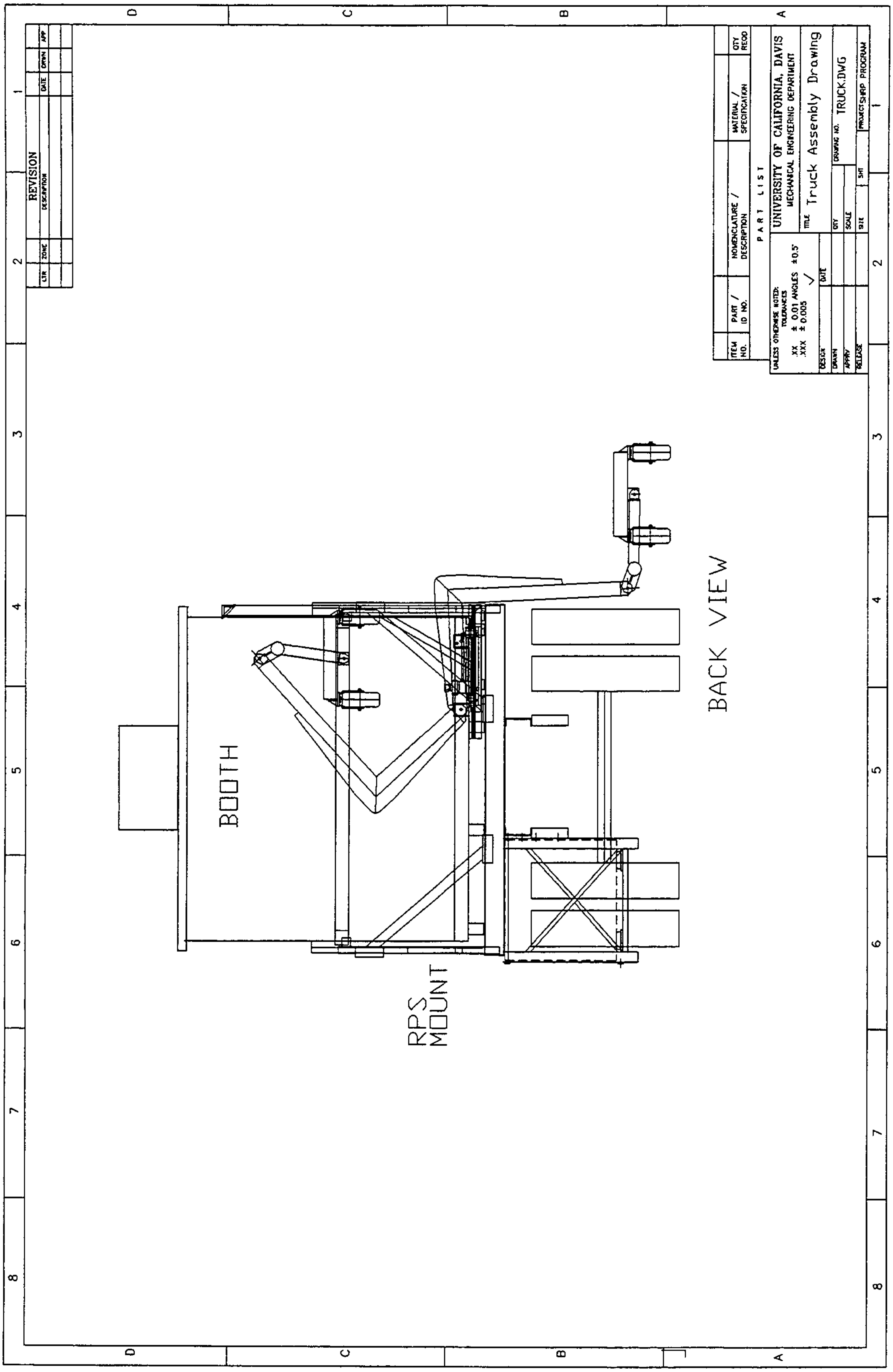
Drawing 5.2.9


RPS MOUNT
BOOTH
Vacuum Drums
Hydraulic Unit
MELTER
LEFT SIDE VIEW
GENERATOR
REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Truck Assembly Drawing
TRUCK.DWG
PROJECT SHRP PROGRAM

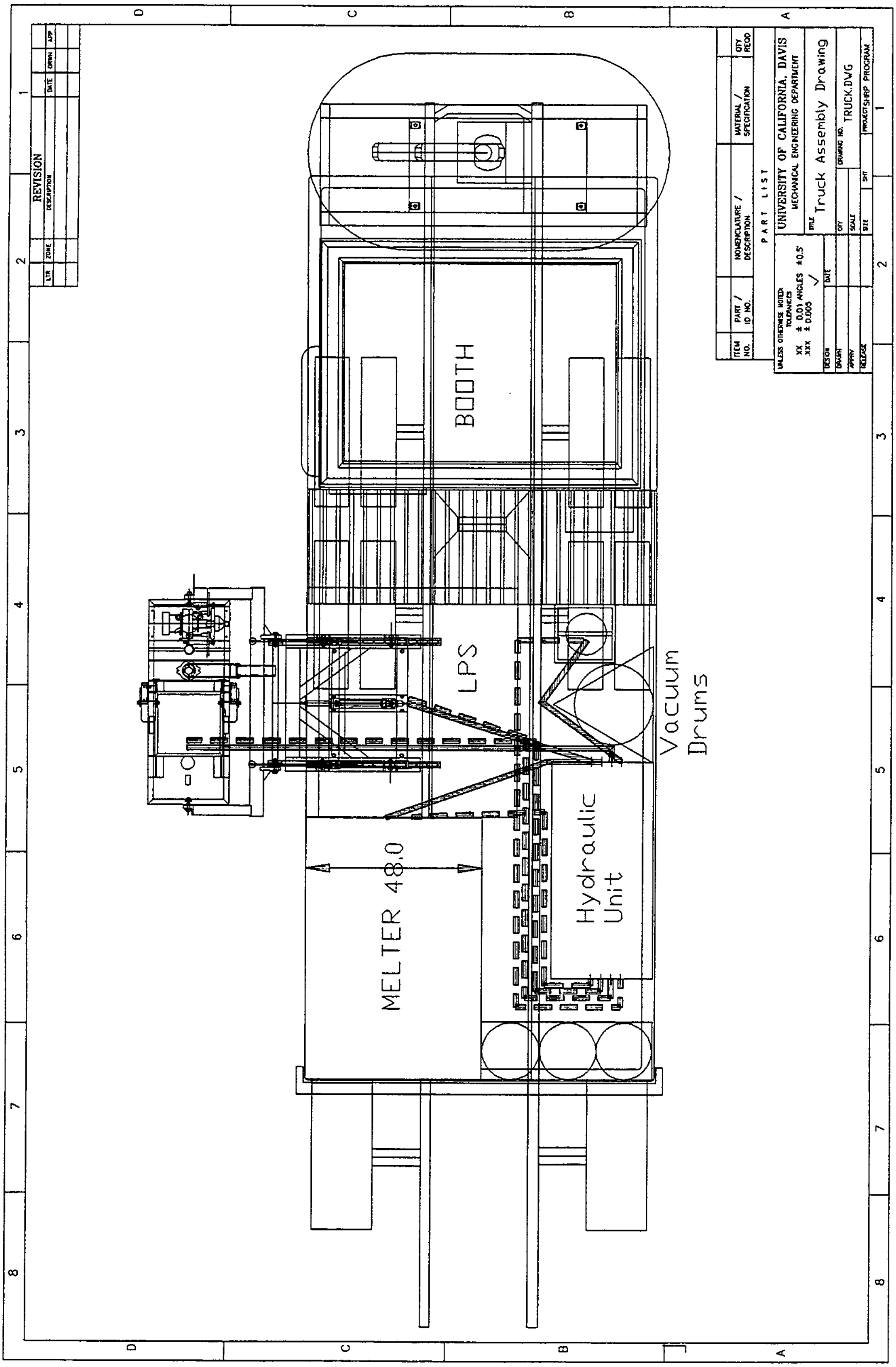
Drawing 6.1


REVISION
MELTER
81.50
LOOPA
BOOTH
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Truck Assembly Drawing
TRUCK.DWG

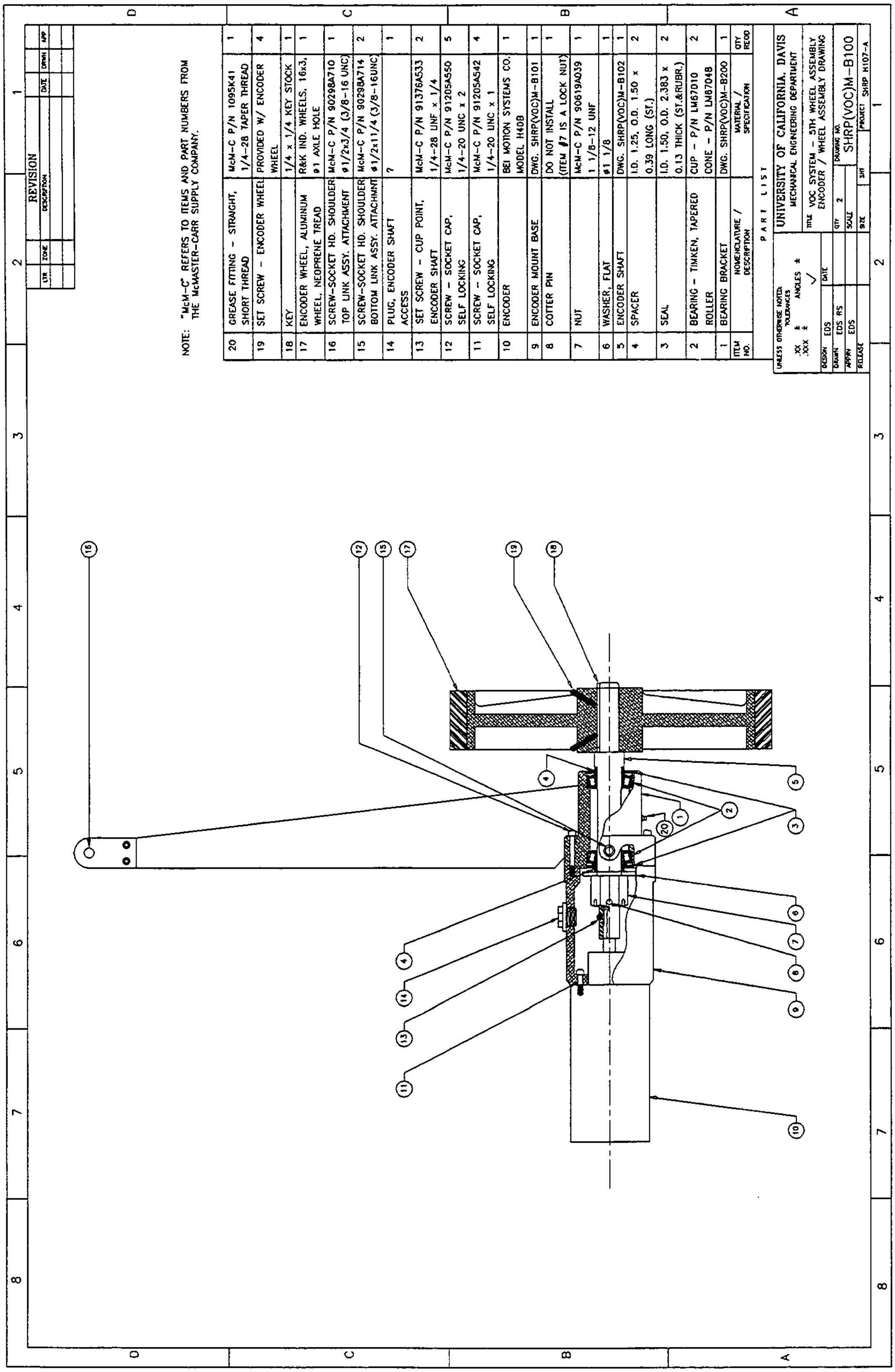
Drawing 6.2


BOOTH
RPS MOUNT
BACK VIEW
REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Truck Assembly Drawing
TRUCK.DWG

Drawing 6.3

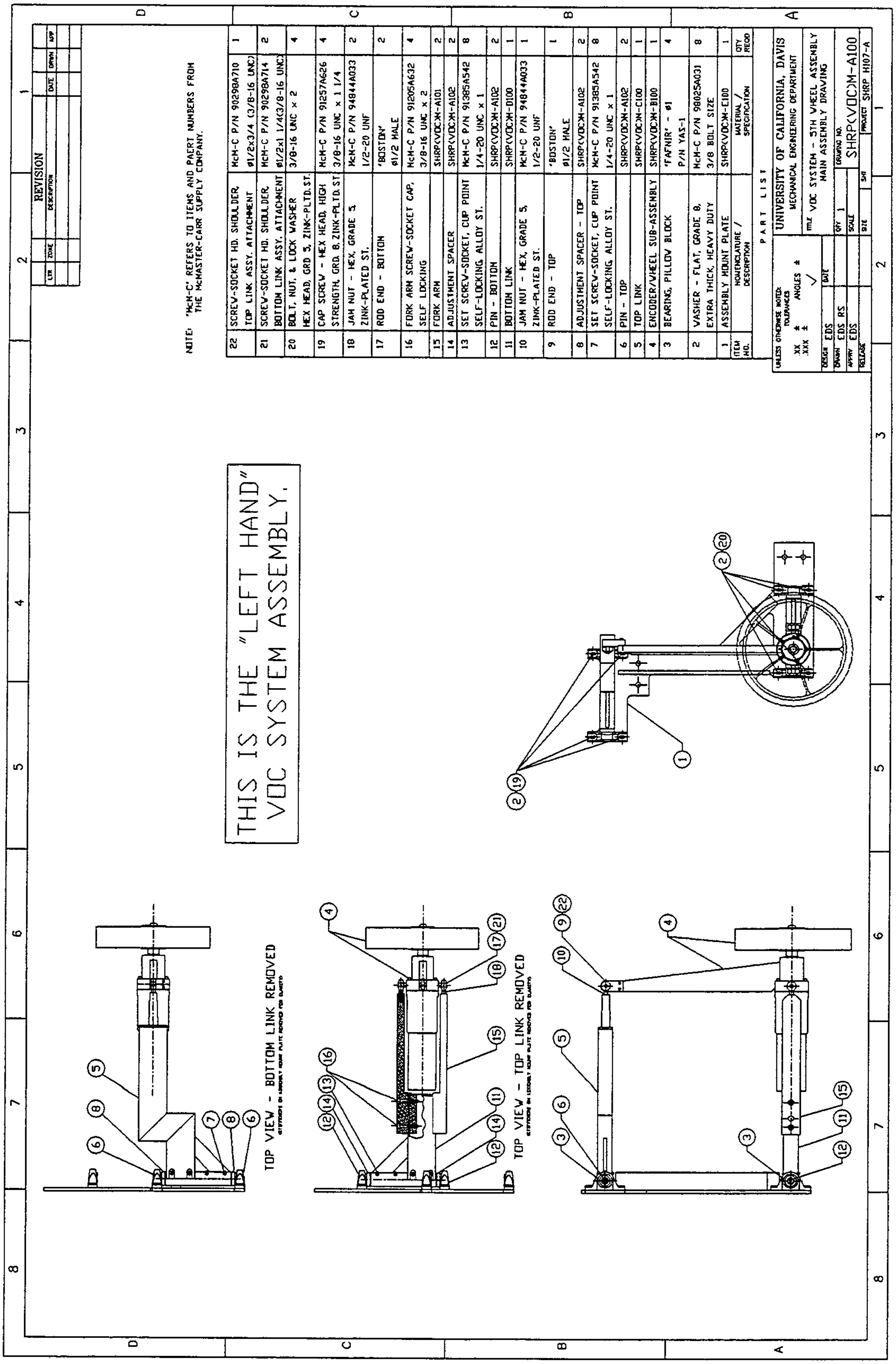

BOOTH
LPS
Vacuum Drums
Hydraulic Unit
MELTER 48.0
REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Truck Assembly Drawing
TRUCK.DWG

Drawing 6.4

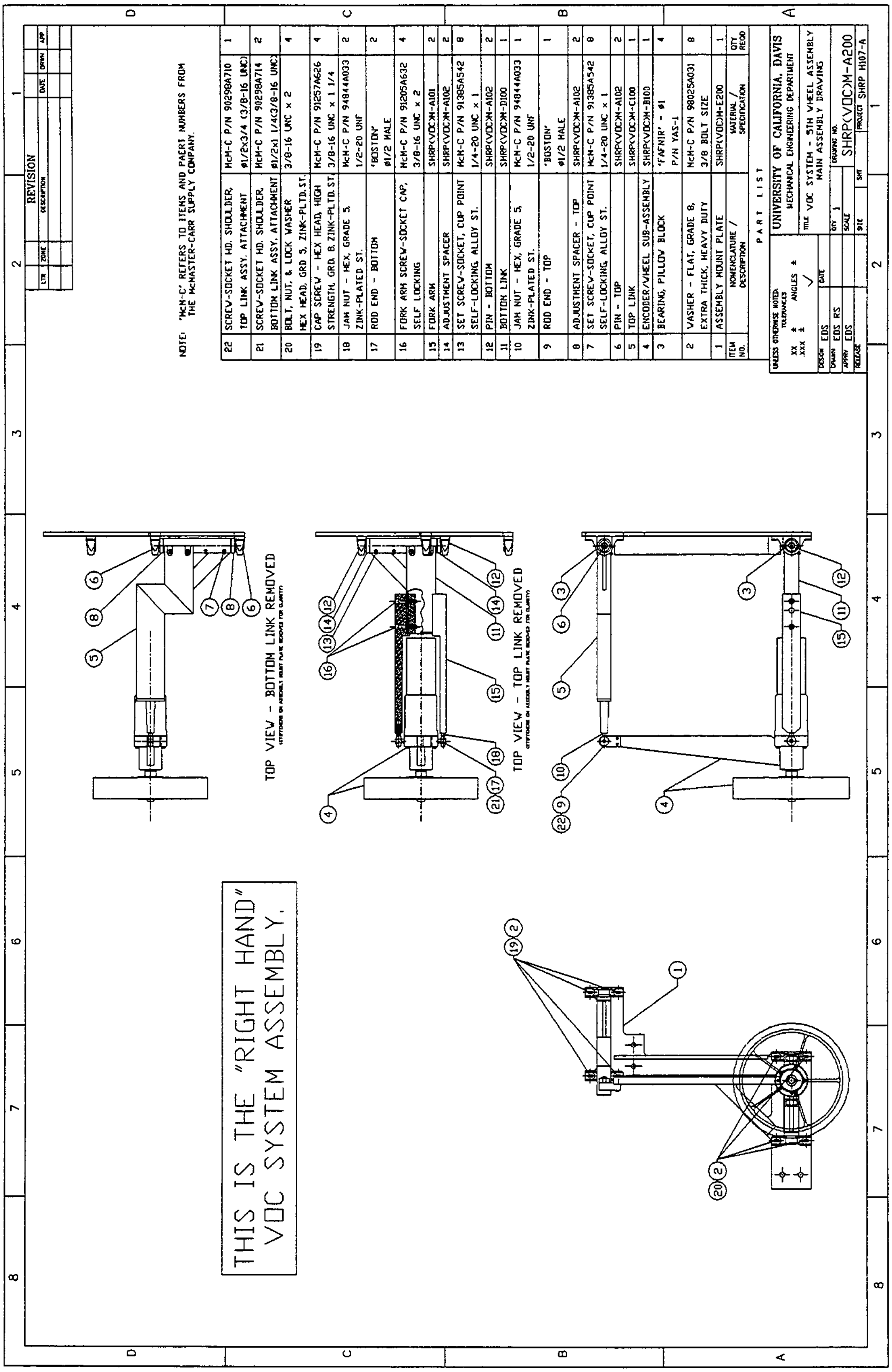


ITEM NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
20	GREASE FITTING – STRAIGHT, SHORT THREAD	McM-C P/N 1095K41 1/4-28 TAPER THREAD	1
19	SET SCREW – ENCODER WHEEL	PROVIDED W/ ENCODER WHEEL	4
18	KEY	1/4 x 1/4 KEY STOCK	1
17	ENCODER WHEEL, ALUMINUM WHEEL, NEOPRENE TREAD	R&K IND. WHEELS, 16x3, ø1 AXLE HOLE	1
16	SCREW-SOCKET HD. SHOULDER TOP LINK ASSY. ATTACHMENT	McM-C P/N 90298A710 ø1/2x3/4 (3/8-16 UNC)	1
15	SCREW-SOCKET HD. SHOULDER BOTTOM LINK ASSY. ATTACHMNT	McM-C P/N 90298A714 ø1/2x11/4 (3/8-16UNC)	2
14	PLUG, ENCODER SHAFT ACCESS	?	1
13	SET SCREW – CUP POINT, ENCODER SHAFT	McM-C P/N 91376A533 1/4-28 UNF x 1/4	2
12	SCREW – SOCKET CAP, SELF LOCKING	McM-C P/N 91205A550 1/4-20 UNC x 2	5
11	SCREW – SOCKET CAP, SELF LOCKING	McM-C P/N 91205A542 1/4-20 UNC x 1	4
10	ENCODER	BEI MOTION SYSTEMS CO. MODEL H40B	1
9	ENCODER MOUNT BASE	DWG. SHRP(VOC)M-B101	1
8	COTTER PIN	DO NOT INSTALL (ITEM #7 IS A LOCK NUT)	1
7	NUT	McM-C P/N 90619A039 1 1/8-12 UNF	1
6	WASHER, FLAT	ø1 1/8	1
5	ENCODER SHAFT	DWG. SHRP(VOC)M-B102	1
4	SPACER	I.D. 1.25, O.D. 1.50 x 0.39 LONG (ST.)	2
3	SEAL	I.D. 1.50, O.D. 2.383 x 0.13 THICK (ST.&RUBR.)	2
2	BEARING – TIMKEN, TAPERED ROLLER	CUP – P/N LM67010 CONE – P/N LM67048	2
1	BEARING BRACKET	DWG. SHRP(VOC)M-B200	1

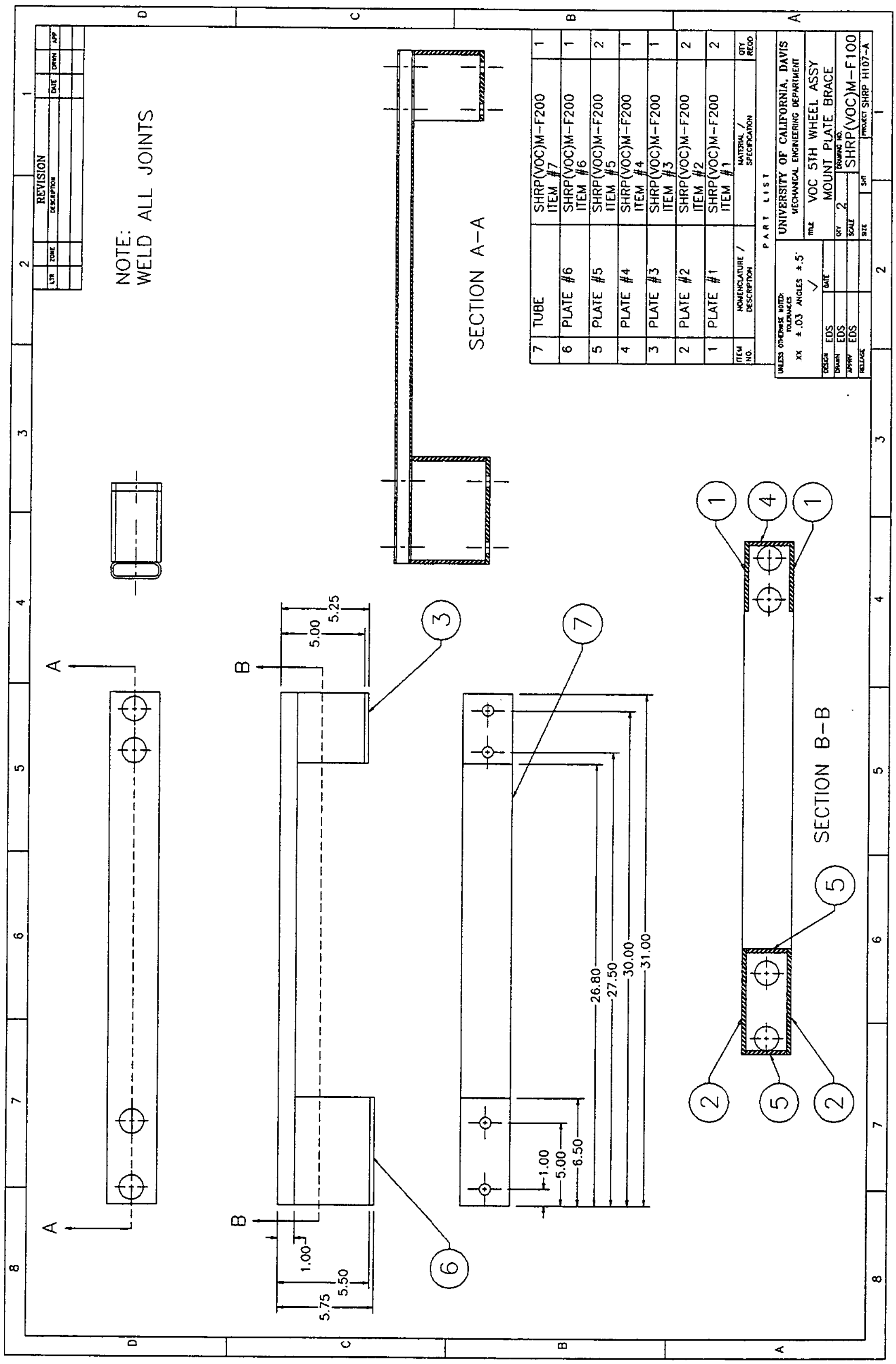
Drawing 7.1


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
NOTE: "McM-C" REFERS TO ITEMS AND PAERT NUMBERS FROM THE McMASTER-CARR SUPPLY COMPANY.
THIS IS THE "LEFT HAND" VDC SYSTEM ASSEMBLY.
TOP VIEW - BOTTOM LINK REMOVED
TOP VIEW - TOP LINK REMOVED
22 SCREW-SOCKET HD. SHOULDER, TOP LINK ASSY. ATTACHMENT McM-C P/N 90298A710 ø1/2x3/4 (3/8-16 UNC) 1
21 SCREW-SOCKET HD. SHOULDER, BOTTOM LINK ASSY. ATTACHMENT McM-C P/N 90298A714 ø1/2x1 1/4(3/8-16 UNC) 2
20 BOLT, NUT, & LOCK WASHER HEX HEAD, GRD 5, ZINK-PLTD.ST. 3/8-16 UNC x 2 4
19 CAP SCREW - HEX HEAD, HIGH STRENGTH, GRD. 8, ZINK-PLTD.ST. McM-C P/N 91257A626 3/8-16 UNC x 1 1/4 4
18 JAM NUT - HEX, GRADE 5, ZINK-PLATED ST. McM-C P/N 94844A033 1/2-20 UNF 2
17 ROD END - BOTTOM 'BOSTON' ø1/2 MALE 2
16 FORK ARM SCREW-SOCKET CAP, SELF LOCKING McM-C P/N 91205A632 3/8-16 UNC x 2 4
15 FORK ARM SHRP(VDC)M-A101 2
14 ADJUSTMENT SPACER SHRP(VDC)M-A102 2
13 SET SCREW-SOCKET, CUP POINT SELF-LOCKING ALLOY ST. McM-C P/N 91385A542 1/4-20 UNC x 1 8
12 PIN - BOTTOM SHRP(VDC)M-A102 2
11 BOTTOM LINK SHRP(VDC)M-D100 1
10 JAM NUT - HEX, GRADE 5, ZINK-PLATED ST. McM-C P/N 94844A033 1/2-20 UNF 1
9 ROD END - TOP 'BOSTON' ø1/2 MALE 1
8 ADJUSTMENT SPACER - TOP SHRP(VDC)M-A102 2
7 SET SCREW-SOCKET, CUP POINT SELF-LOCKING ALLOY ST. McM-C P/N 91385A542 1/4-20 UNC x 1 8
6 PIN - TOP SHRP(VDC)M-A102 2
5 TOP LINK SHRP(VDC)M-C100 1
4 ENCODER/WHEEL SUB-ASSEMBLY SHRP(VDC)M-B100 1
3 BEARING, PILLOW BLOCK 'FAFNIR' - ø1 P/N YAS-1 4
2 WASHER - FLAT, GRADE 8, EXTRA THICK, HEAVY DUTY McM-C P/N 98025A031 3/8 BOLT SIZE 8
1 ASSEMBLY MOUNT PLATE SHRP(VDC)M-E100 1
ITEM NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES .XX ± .XXX ± ANGLES ±
DESIGN EDS
DRAWN EDS RS
APPRV EDS
RELEASE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE VDC SYSTEM - 5TH WHEEL ASSEMBLY MAIN ASSEMBLY DRAWING
QTY 1
DRAWING NO. SHRP(VDC)M-A100
PROJECT SHRP H107-A

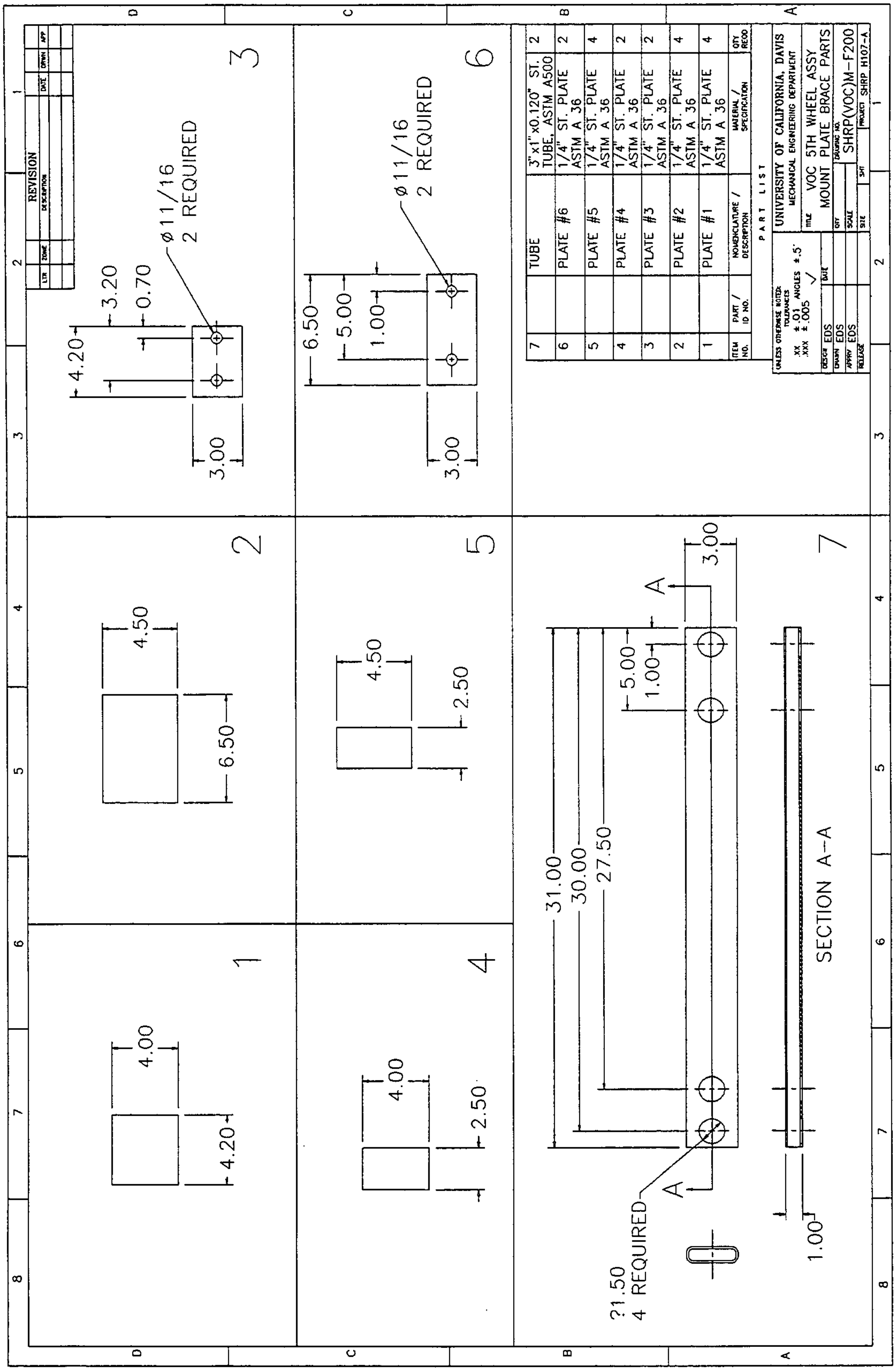
Drawing 7.2


REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
NOTE: 'McM-C' REFERS TO ITEMS AND PAERT NUMBERS FROM THE McMASTER-CARR SUPPLY COMPANY.
THIS IS THE "RIGHT HAND" VOC SYSTEM ASSEMBLY.
TOP VIEW - BOTTOM LINK REMOVED
TOP VIEW - TOP LINK REMOVED
22 SCREW-SOCKET HD. SHOULDER, TOP LINK ASSY. ATTACHMENT | McM-C P/N 90298A710 ø1/2x3/4 (3/8-16 UNC) | 1
21 SCREW-SOCKET HD. SHOULDER, BOTTOM LINK ASSY. ATTACHMENT | McM-C P/N 90298A714 ø1/2x1 1/4(3/8-16 UNC) | 2
20 BOLT, NUT, & LOCK WASHER HEX HEAD, GRD 5, ZINK-PLTD.ST. | 3/8-16 UNC x 2 | 4
19 CAP SCREW - HEX HEAD, HIGH STRENGTH, GRD. 8, ZINK-PLTD.ST. | McM-C P/N 91257A626 3/8-16 UNC x 1 1/4 | 4
18 JAM NUT - HEX, GRADE 5, ZINK-PLATED ST. | McM-C P/N 94844A033 1/2-20 UNF | 2
17 ROD END - BOTTOM | 'BOSTON' ø1/2 MALE | 2
16 FORK ARM SCREW-SOCKET CAP, SELF LOCKING | McM-C P/N 91205A632 3/8-16 UNC x 2 | 4
15 FORK ARM | SHRP(VOC)M-A101 | 2
14 ADJUSTMENT SPACER | SHRP(VOC)M-A102 | 2
13 SET SCREW-SOCKET, CUP POINT SELF-LOCKING ALLOY ST. | McM-C P/N 91385A542 1/4-20 UNC x 1 | 8
12 PIN - BOTTOM | SHRP(VOC)M-A102 | 2
11 BOTTOM LINK | SHRP(VOC)M-D100 | 1
10 JAM NUT - HEX, GRADE 5, ZINK-PLATED ST. | McM-C P/N 94844A033 1/2-20 UNF | 1
9 ROD END - TOP | 'BOSTON' ø1/2 MALE | 1
8 ADJUSTMENT SPACER - TOP | SHRP(VOC)M-A102 | 2
7 SET SCREW-SOCKET, CUP POINT SELF-LOCKING ALLOY ST. | McM-C P/N 91385A542 1/4-20 UNC x 1 | 8
6 PIN - TOP | SHRP(VOC)M-A102 | 2
5 TOP LINK | SHRP(VOC)M-C100 | 1
4 ENCODER/WHEEL SUB-ASSEMBLY | SHRP(VOC)M-B100 | 1
3 BEARING, PILLOW BLOCK | 'FAFNIR' - ø1 P/N YAS-1 | 4
2 WASHER - FLAT, GRADE 8, EXTRA THICK, HEAVY DUTY | McM-C P/N 98025A031 3/8 BOLT SIZE | 8
1 ASSEMBLY MOUNT PLATE | SHRP(VOC)M-E200 | 1
ITEM NO. | NOMENCLATURE / DESCRIPTION | MATERIAL / SPECIFICATION | QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES .XX ± .XXX ± ANGLES ±
DESIGN EDS
DRAWN EDS RS
APPRV EDS
RELEASE
DATE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE VOC SYSTEM - 5TH WHEEL ASSEMBLY MAIN ASSEMBLY DRAWING
QTY 1
SCALE
SIZE
SHT
DRAWING NO. SHRP(VOC)M-A200
PROJECT SHRP H107-A

Drawing 7.3

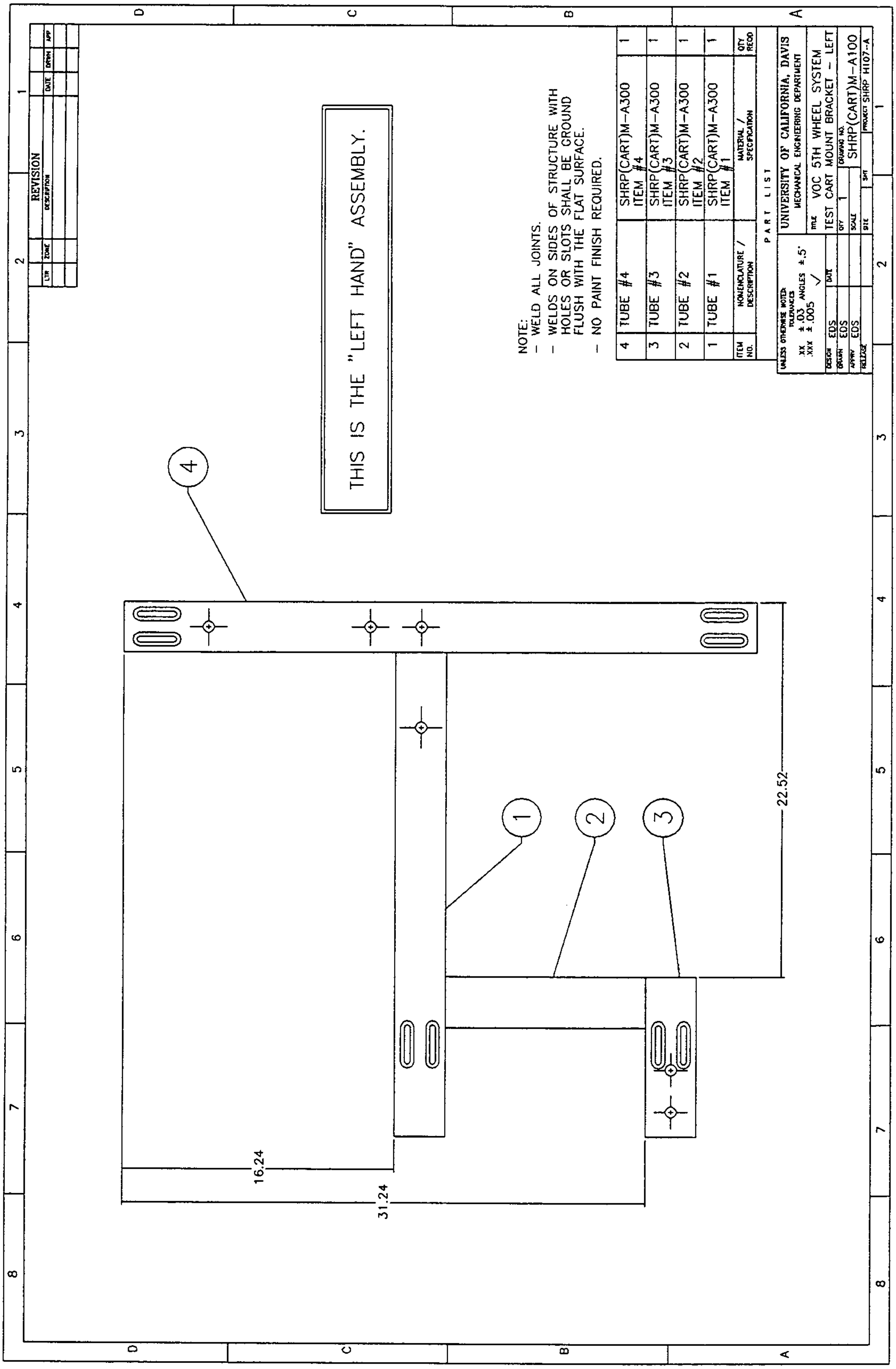

NOTE:
WELD ALL JOINTS
REVISION
SECTION A-A
SECTION B-B
A
B
5.00
5.25
1.00
5.50
5.75
26.80
27.50
30.00
31.00
6.50
5.00
1.00
7 TUBE SHRP(VOC)M-F200 ITEM #7 1
6 PLATE #6 SHRP(VOC)M-F200 ITEM #6 1
5 PLATE #5 SHRP(VOC)M-F200 ITEM #5 2
4 PLATE #4 SHRP(VOC)M-F200 ITEM #4 1
3 PLATE #3 SHRP(VOC)M-F200 ITEM #3 1
2 PLATE #2 SHRP(VOC)M-F200 ITEM #2 2
1 PLATE #1 SHRP(VOC)M-F200 ITEM #1 2
ITEM NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL ASSY
MOUNT PLATE BRACE
SHRP(VOC)M-F100
PROJECT SHRP H107-A
EDS
EDS
EDS

Drawing 7.4

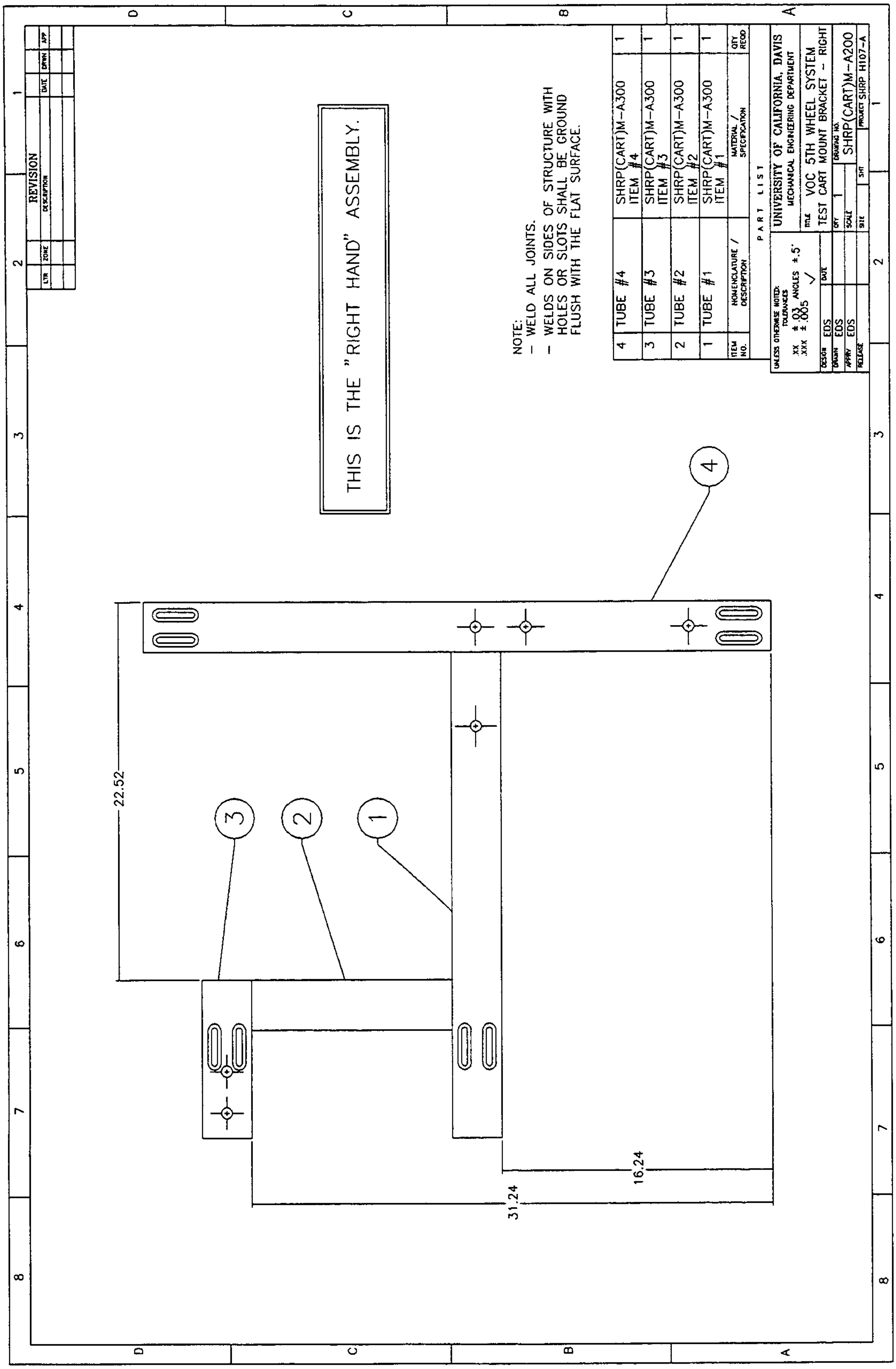


UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL ASSY
MOUNT PLATE BRACE PARTS
SHRP(VOC)M-F200
PART LIST
TUBE
3"x1"x0.120" ST. TUBE, ASTM A500
PLATE #6
PLATE #5
PLATE #4
PLATE #3
PLATE #2
PLATE #1
1/4" ST. PLATE ASTM A 36
SECTION A-A
2 REQUIRED
4 REQUIRED

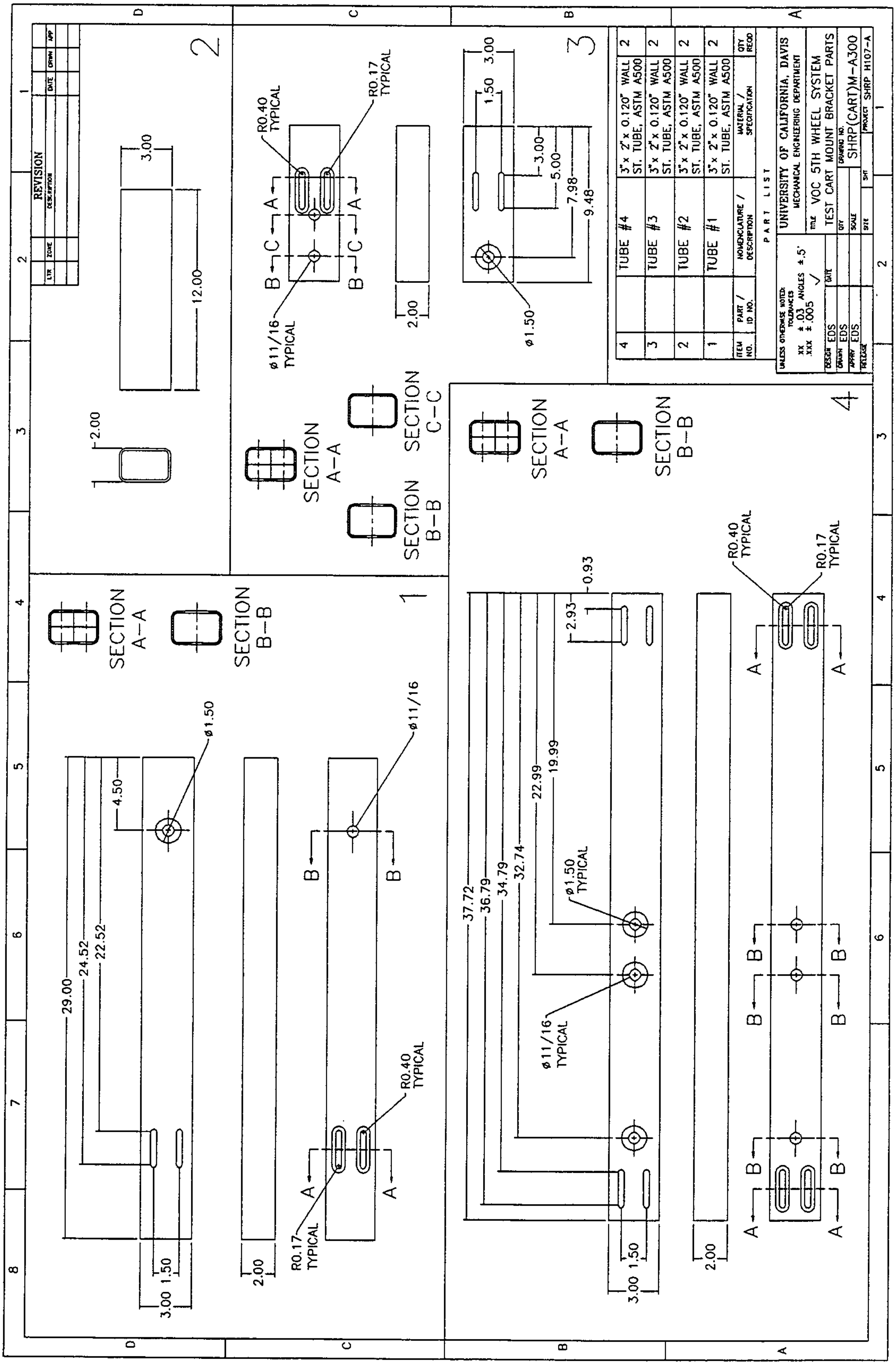
Drawing 7.5


THIS IS THE "LEFT HAND" ASSEMBLY.
NOTE:
- WELD ALL JOINTS.
- WELDS ON SIDES OF STRUCTURE WITH HOLES OR SLOTS SHALL BE GROUND FLUSH WITH THE FLAT SURFACE.
- NO PAINT FINISH REQUIRED.
4 TUBE #4 SHRP(CART)M-A300 ITEM #4 1
3 TUBE #3 SHRP(CART)M-A300 ITEM #3 1
2 TUBE #2 SHRP(CART)M-A300 ITEM #2 1
1 TUBE #1 SHRP(CART)M-A300 ITEM #1 1
ITEM NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL SYSTEM
TEST CART MOUNT BRACKET - LEFT
SHRP(CART)M-A100
PROJECT SHRP H107-A
EDS
EDS
EDS
REVISION
22.52
16.24
31.24
1
2
3
4

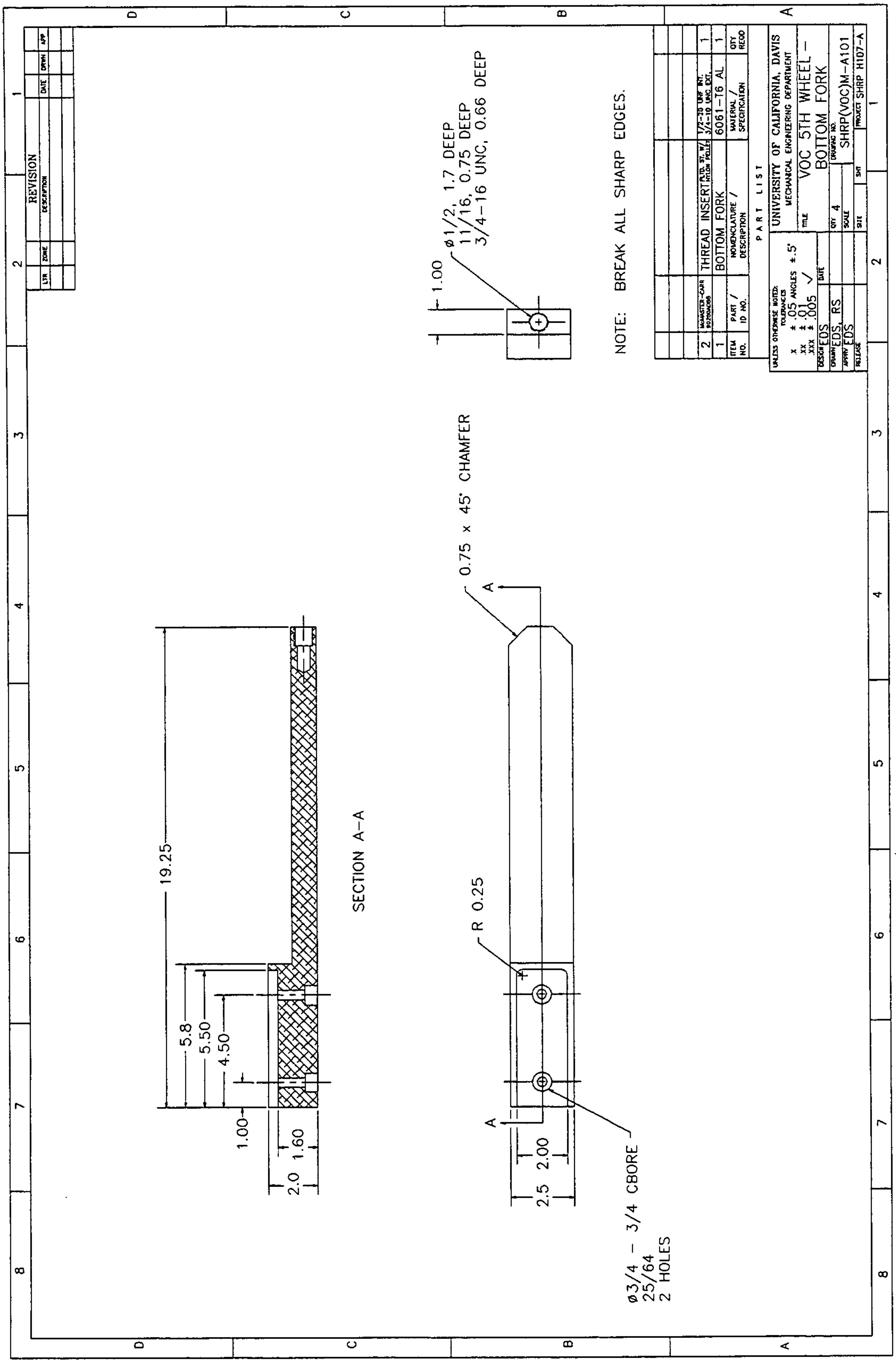
Drawing 7.6


THIS IS THE "RIGHT HAND" ASSEMBLY.
NOTE:
- WELD ALL JOINTS.
- WELDS ON SIDES OF STRUCTURE WITH HOLES OR SLOTS SHALL BE GROUND FLUSH WITH THE FLAT SURFACE.
REVISION
4 TUBE #4 SHRP(CART)M-A300 ITEM #4 1
3 TUBE #3 SHRP(CART)M-A300 ITEM #3 1
2 TUBE #2 SHRP(CART)M-A300 ITEM #2 1
1 TUBE #1 SHRP(CART)M-A300 ITEM #1 1
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL SYSTEM
TEST CART MOUNT BRACKET - RIGHT
SHRP(CART)M-A200
PROJECT SHRP H107-A
EDS
22.52
16.24
31.24

Drawing 7.7

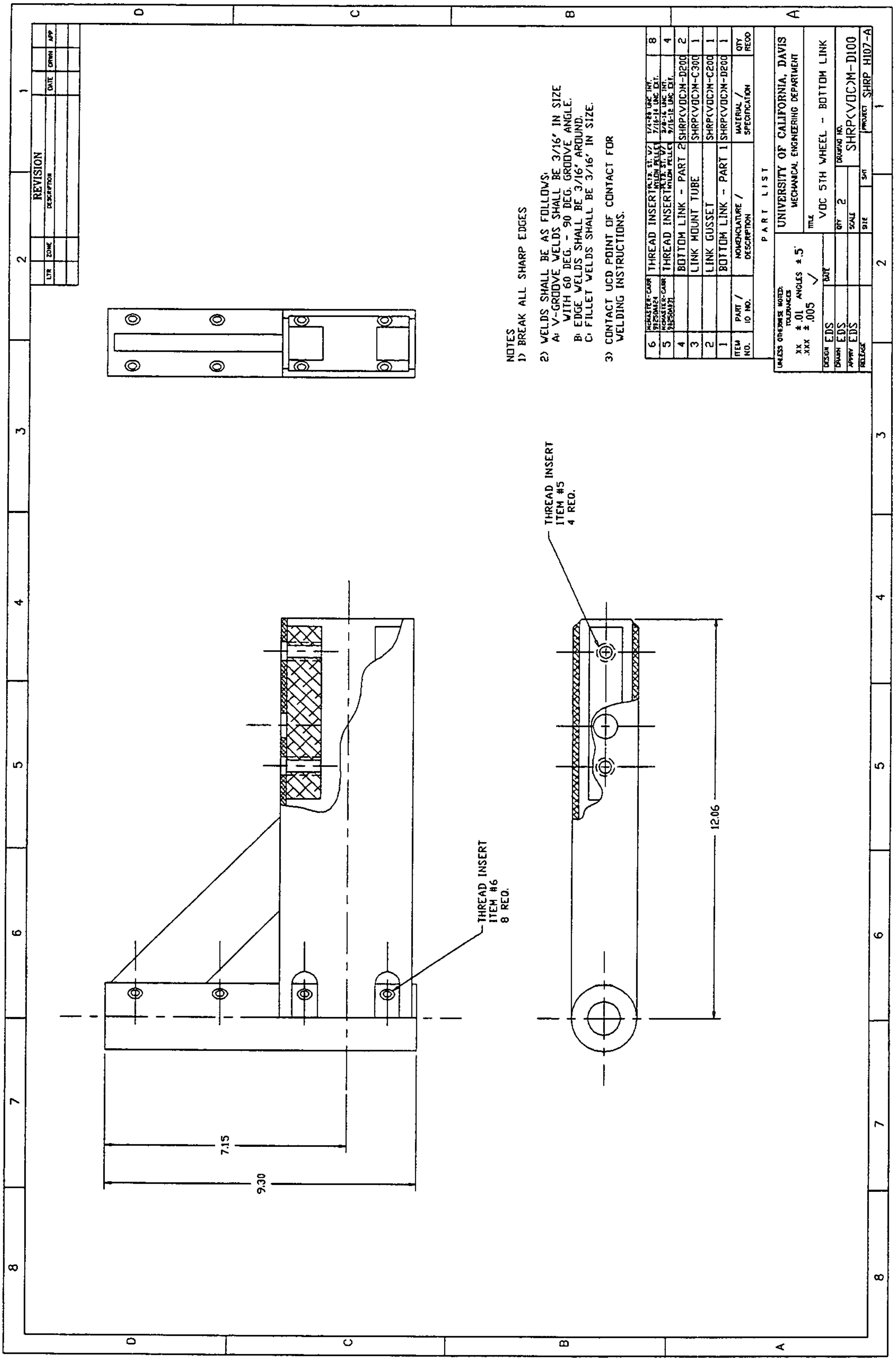

REVISION
SECTION A-A
SECTION B-B
SECTION C-C
TUBE #4 | 3"x 2"x 0.120" WALL ST. TUBE, ASTM A500 | 2
TUBE #3 | 3"x 2"x 0.120" WALL ST. TUBE, ASTM A500 | 2
TUBE #2 | 3"x 2"x 0.120" WALL ST. TUBE, ASTM A500 | 2
TUBE #1 | 3"x 2"x 0.120" WALL ST. TUBE, ASTM A500 | 2
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES XX ±.03 XXX ±.005 ANGLES ±.5°
DESIGN EDS
DRAWN EDS
APPRV EDS
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL SYSTEM
TEST CART MOUNT BRACKET PARTS
SHRP(CART)M-A300
SHRP H107-A

Drawing 7.8

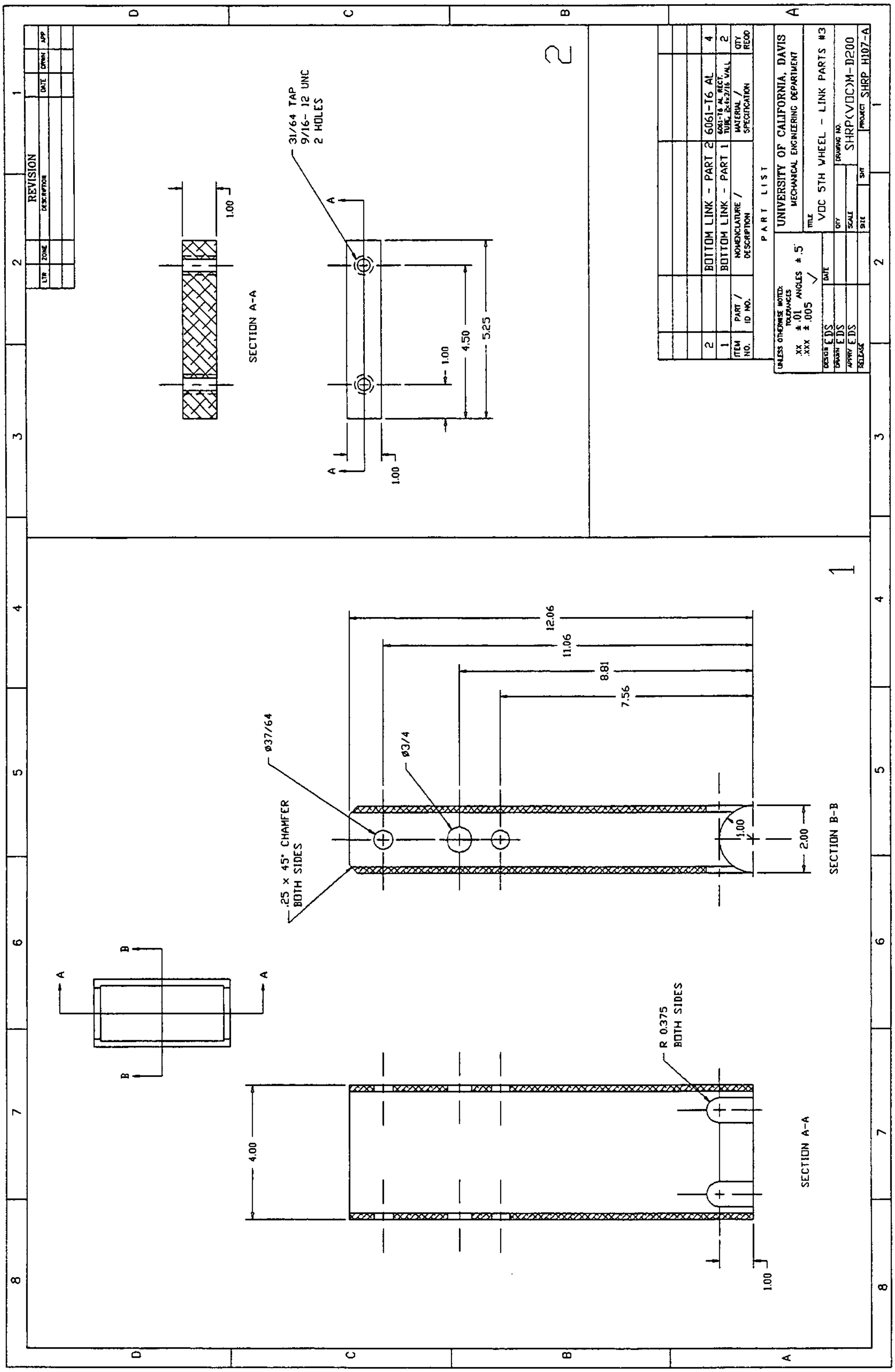


SECTION A–A
19.25
5.8
5.50
4.50
1.00
2.0
1.60
0.75 x 45° CHAMFER
R 0.25
2.5
2.00
ø3/4 – 3/4 CBORE
25/64
2 HOLES
1.00
ø1/2, 1.7 DEEP
11/16, 0.75 DEEP
3/4–16 UNC, 0.66 DEEP
NOTE: BREAK ALL SHARP EDGES.
REVISION
THREAD INSERT
BOTTOM FORK
6061-T6 AL
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL – BOTTOM FORK
SHRP(VOC)M–A101
PROJECT SHRP H107–A
EDS
RS

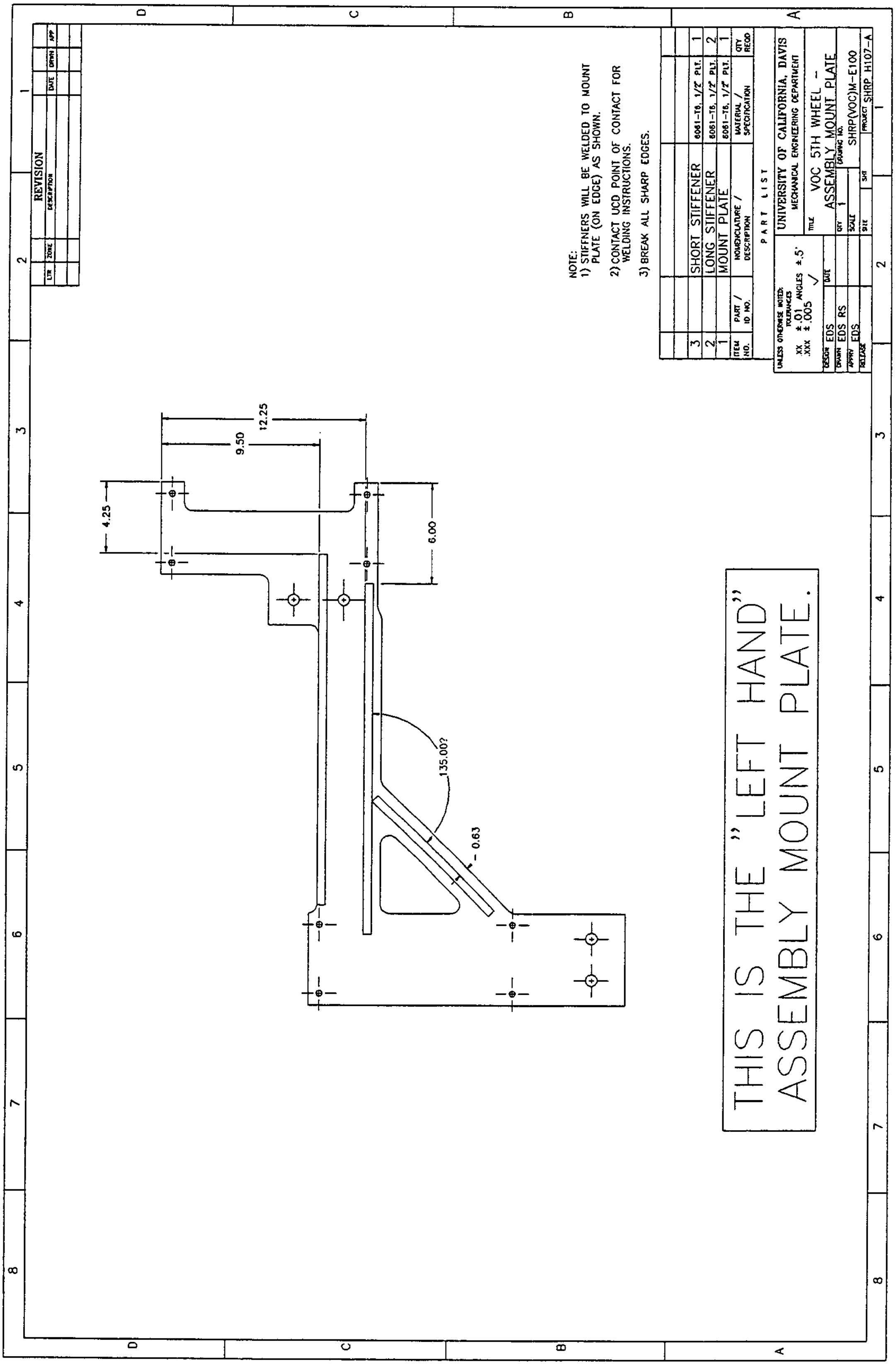
Drawing 7.9


NOTES
1) BREAK ALL SHARP EDGES
2) WELDS SHALL BE AS FOLLOWS:
A: V-GROOVE WELDS SHALL BE 3/16' IN SIZE WITH 60 DEG. - 90 DEG. GROOVE ANGLE.
B: EDGE WELDS SHALL BE 3/16' AROUND.
C: FILLET WELDS SHALL BE 3/16' IN SIZE.
3) CONTACT UCD POINT OF CONTACT FOR WELDING INSTRUCTIONS.
THREAD INSERT ITEM #5 4 REQ.
THREAD INSERT ITEM #6 8 REQ.
12.06
7.15
9.30
PART LIST
BOTTOM LINK - PART 2
LINK MOUNT TUBE
LINK GUSSET
BOTTOM LINK - PART 1
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL - BOTTOM LINK
SHRP(VOC)M-D100
SHRP H107-A
REVISION

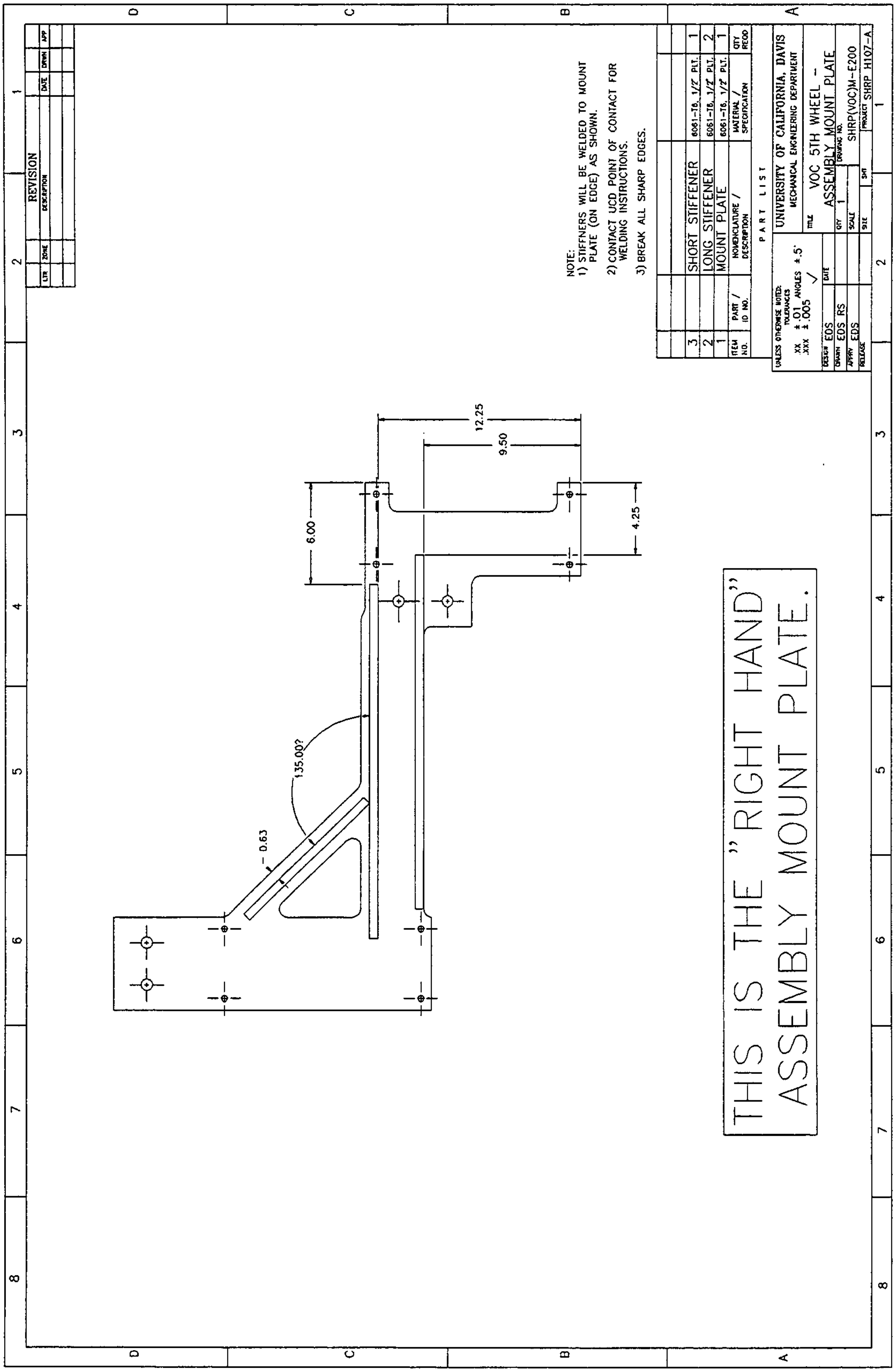
Drawing 7.10


UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VDC 5TH WHEEL - LINK PARTS #3
SHRP(VDC)M-D200
BOTTOM LINK - PART 2
BOTTOM LINK - PART 1
6061-T6 AL
PART LIST
REVISION
31/64 TAP
9/16- 12 UNC
2 HOLES
SECTION A-A
SECTION B-B
.25 x 45° CHAMFER
BOTH SIDES
R 0.375
BOTH SIDES
ø37/64
ø3/4
12.06
11.06
8.81
7.56
5.25
4.50
4.00
2.00
1.00

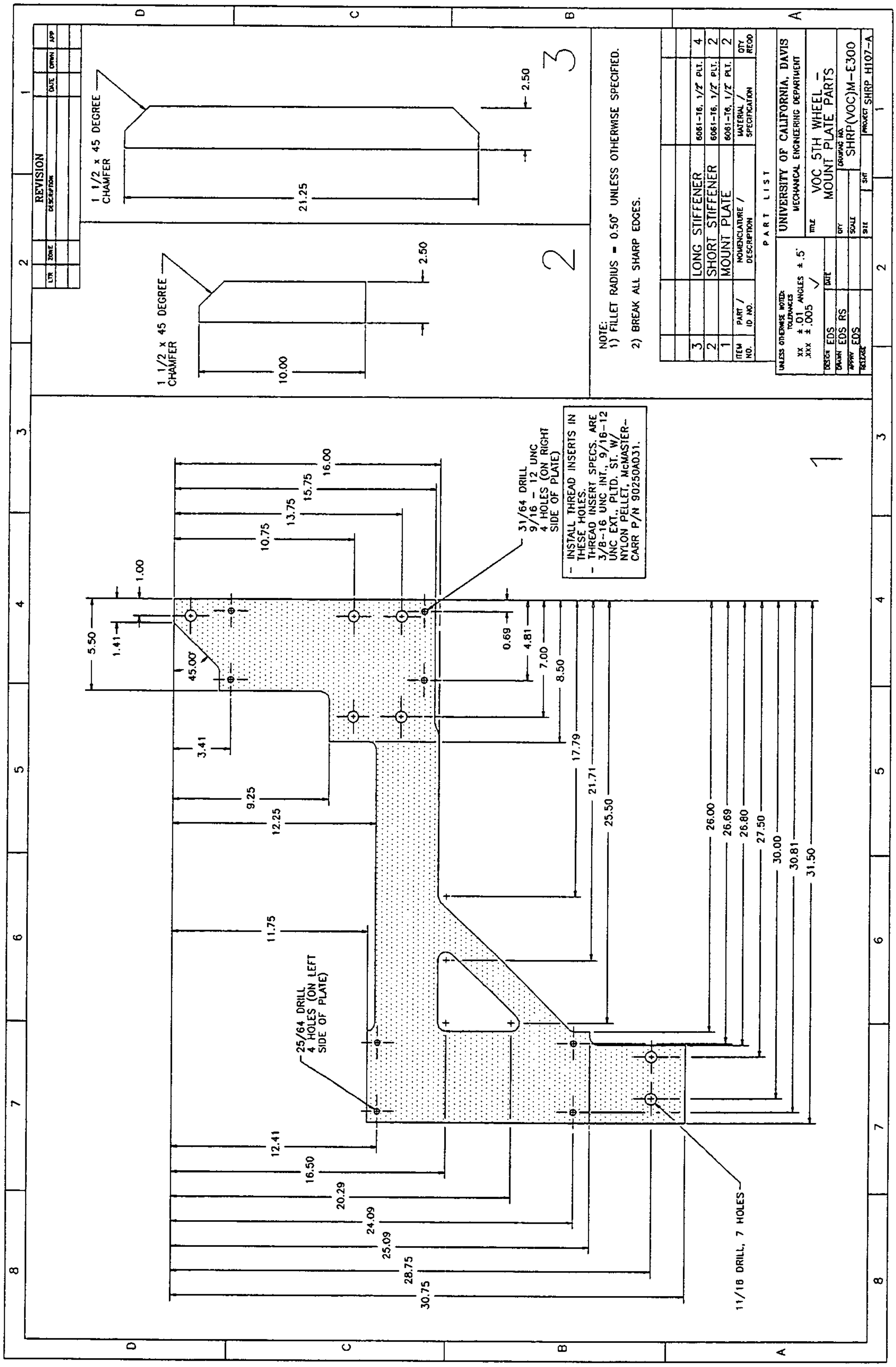
Drawing 7.11


REVISION
NOTE:
1) STIFFNERS WILL BE WELDED TO MOUNT PLATE (ON EDGE) AS SHOWN.
2) CONTACT UCD POINT OF CONTACT FOR WELDING INSTRUCTIONS.
3) BREAK ALL SHARP EDGES.
3 SHORT STIFFENER 6061-T6, 1/2" PLT. 1
2 LONG STIFFENER 6061-T6, 1/2" PLT. 2
1 MOUNT PLATE 6061-T6, 1/2" PLT. 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY. REQD
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL - ASSEMBLY MOUNT PLATE
SHRP(VOC)M-E100
SHRP H107-A
DESIGN EDS
DRAWN EDS RS
APPRV EDS
12.25
9.50
4.25
6.00
135.00?
0.63
THIS IS THE "LEFT HAND" ASSEMBLY MOUNT PLATE.

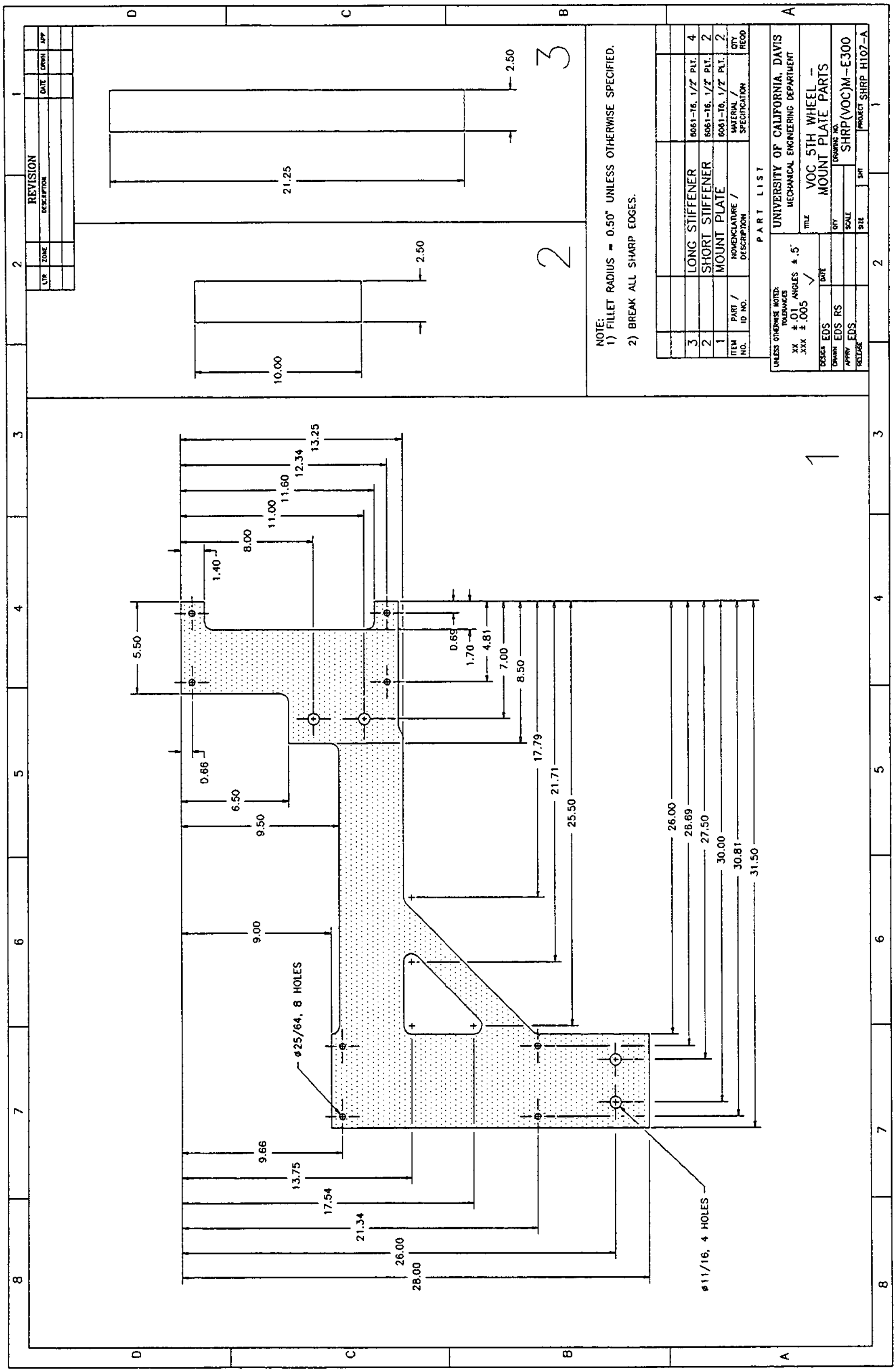
Drawing 7.12


THIS IS THE "RIGHT HAND" ASSEMBLY MOUNT PLATE.
NOTE:
1) STIFFNERS WILL BE WELDED TO MOUNT PLATE (ON EDGE) AS SHOWN.
2) CONTACT UCD POINT OF CONTACT FOR WELDING INSTRUCTIONS.
3) BREAK ALL SHARP EDGES.
3 SHORT STIFFENER 6061-T6, 1/2" PLT. 1
2 LONG STIFFENER 6061-T6, 1/2" PLT. 2
1 MOUNT PLATE 6061-T6, 1/2" PLT. 1
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL - ASSEMBLY MOUNT PLATE
SHRP(VOC)M-E200
SHRP H107-A
12.25
9.50
6.00
4.25
135.00?
0.63
REVISION

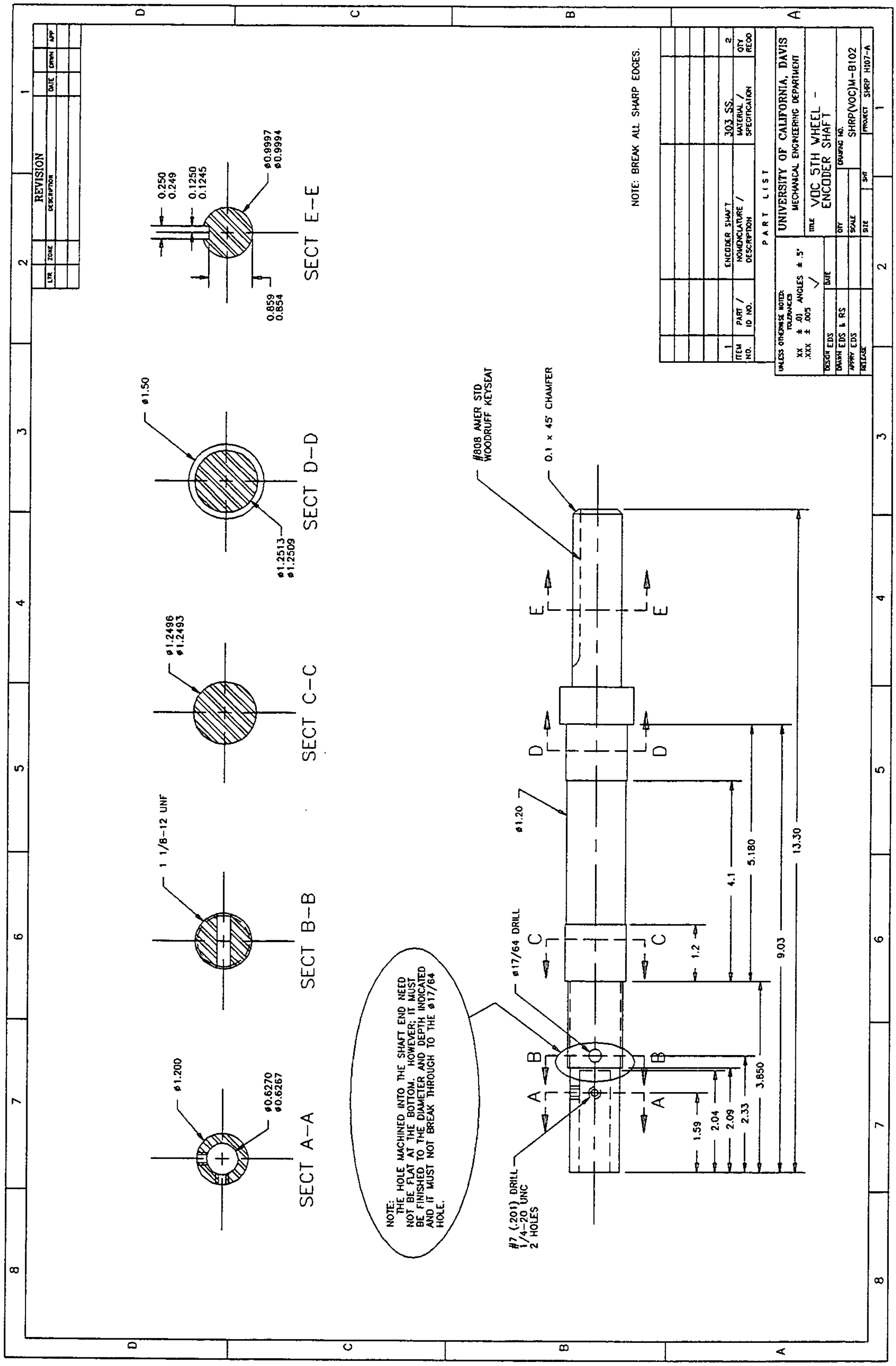
Drawing 7.13


REVISION
1 1/2 x 45 DEGREE CHAMFER
21.25
2.50
10.00
NOTE:
1) FILLET RADIUS = 0.50" UNLESS OTHERWISE SPECIFIED.
2) BREAK ALL SHARP EDGES.
LONG STIFFENER
SHORT STIFFENER
MOUNT PLATE
6061-T6, 1/2" PLT.
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL - MOUNT PLATE PARTS
SHRP(VOC)M-E300
SHRP H107-A
31/64 DRILL 9/16 - 12 UNC 4 HOLES (ON RIGHT SIDE OF PLATE)
- INSTALL THREAD INSERTS IN THESE HOLES.
- THREAD INSERT SPECS. ARE 3/8-16 UNC INT., 9/16-12 UNC EXT., PLTD. ST. W/ NYLON PELLET, McMASTER-CARR P/N 90250A031.
25/64 DRILL 4 HOLES (ON LEFT SIDE OF PLATE)
11/16 DRILL, 7 HOLES
45.00°

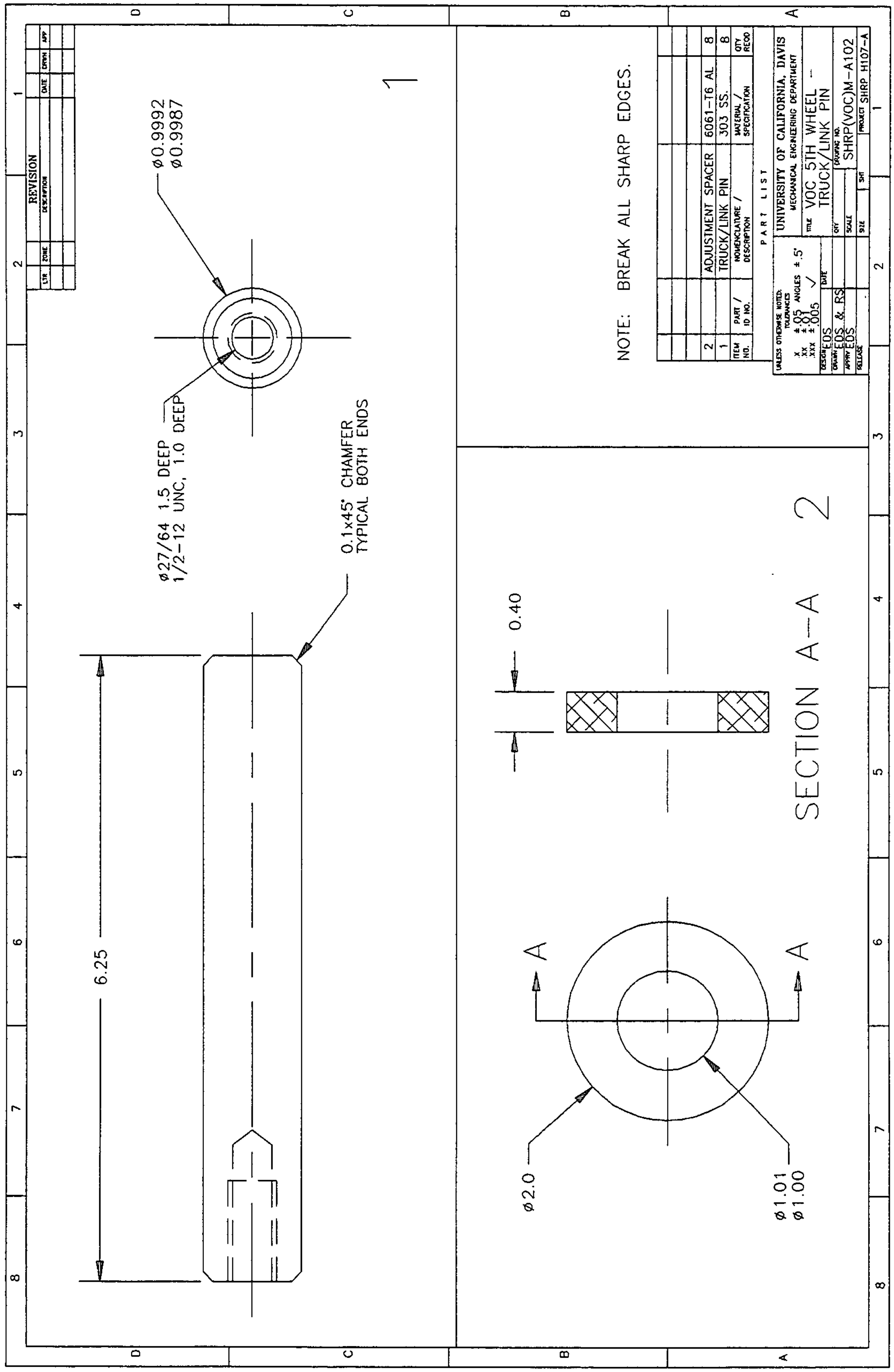
Drawing 7.14


REVISION
NOTE:
1) FILLET RADIUS = 0.50" UNLESS OTHERWISE SPECIFIED.
2) BREAK ALL SHARP EDGES.
3 LONG STIFFENER 6061-T6, 1/2" PLT. 4
2 SHORT STIFFENER 6061-T6, 1/2" PLT. 2
1 MOUNT PLATE 6061-T6, 1/2" PLT. 2
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY RECQ
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL - MOUNT PLATE PARTS
SHRP(VOC)M-E300
SHRP H107-A
ø25/64, 8 HOLES
ø11/16, 4 HOLES

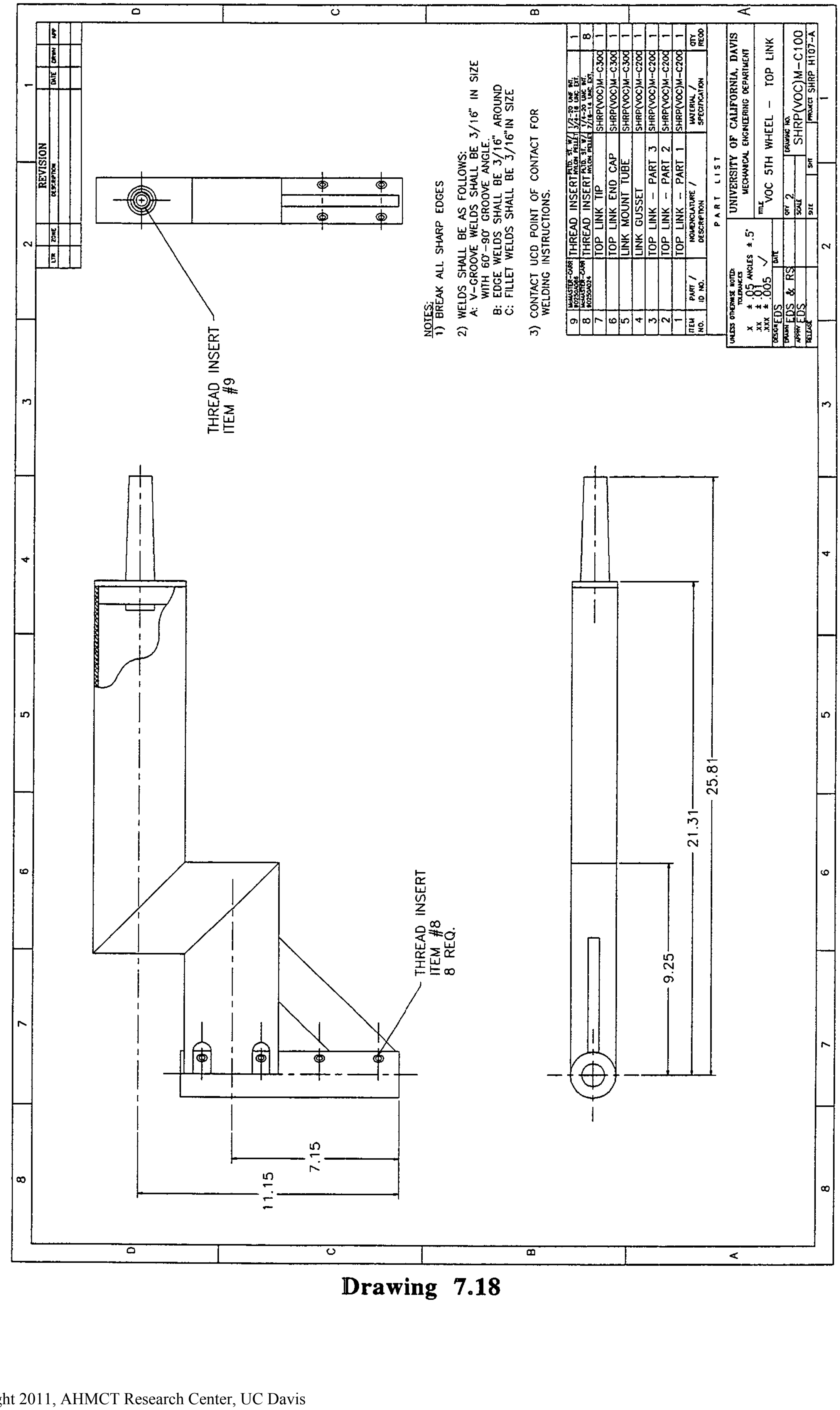
Drawing 7.15


REVISION
LTR
ZONE
DESCRIPTION
DATE
DRWN
APP
SECT A-A
SECT B-B
SECT C-C
SECT D-D
SECT E-E
ø1.200
ø0.6270
ø0.6267
1 1/8-12 UNF
ø1.2496
ø1.2493
ø1.50
ø1.2513
ø1.2509
0.250
0.249
0.1250
0.1245
ø0.9997
ø0.9994
0.859
0.854
NOTE: BREAK ALL SHARP EDGES.
#808 AMER STD WOODRUFF KEYSEAT
0.1 x 45° CHAMFER
ø1.20
ø17/64 DRILL
#7 (.201) DRILL
1/4-20 UNC
2 HOLES
NOTE: THE HOLE MACHINED INTO THE SHAFT END NEED NOT BE FLAT AT THE BOTTOM. HOWEVER; IT MUST BE FINISHED TO THE DIAMETER AND DEPTH INDICATED AND IT MUST NOT BREAK THROUGH TO THE ø17/64 HOLE.
1.59
2.04
2.09
2.33
3.850
1.2
4.1
5.180
9.03
13.30
ITEM NO.
PART / ID NO.
NOMENCLATURE / DESCRIPTION
MATERIAL / SPECIFICATION
QTY RECD
1
ENCODER SHAFT
303 SS
2
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE VOC 5TH WHEEL - ENCODER SHAFT
DRAWING NO. SHRP(VOC)M-B102
PROJECT SHRP H107-A
DESIGN EDS
DRAWN EDS & RS
APPRV EDS

Drawing 7.16

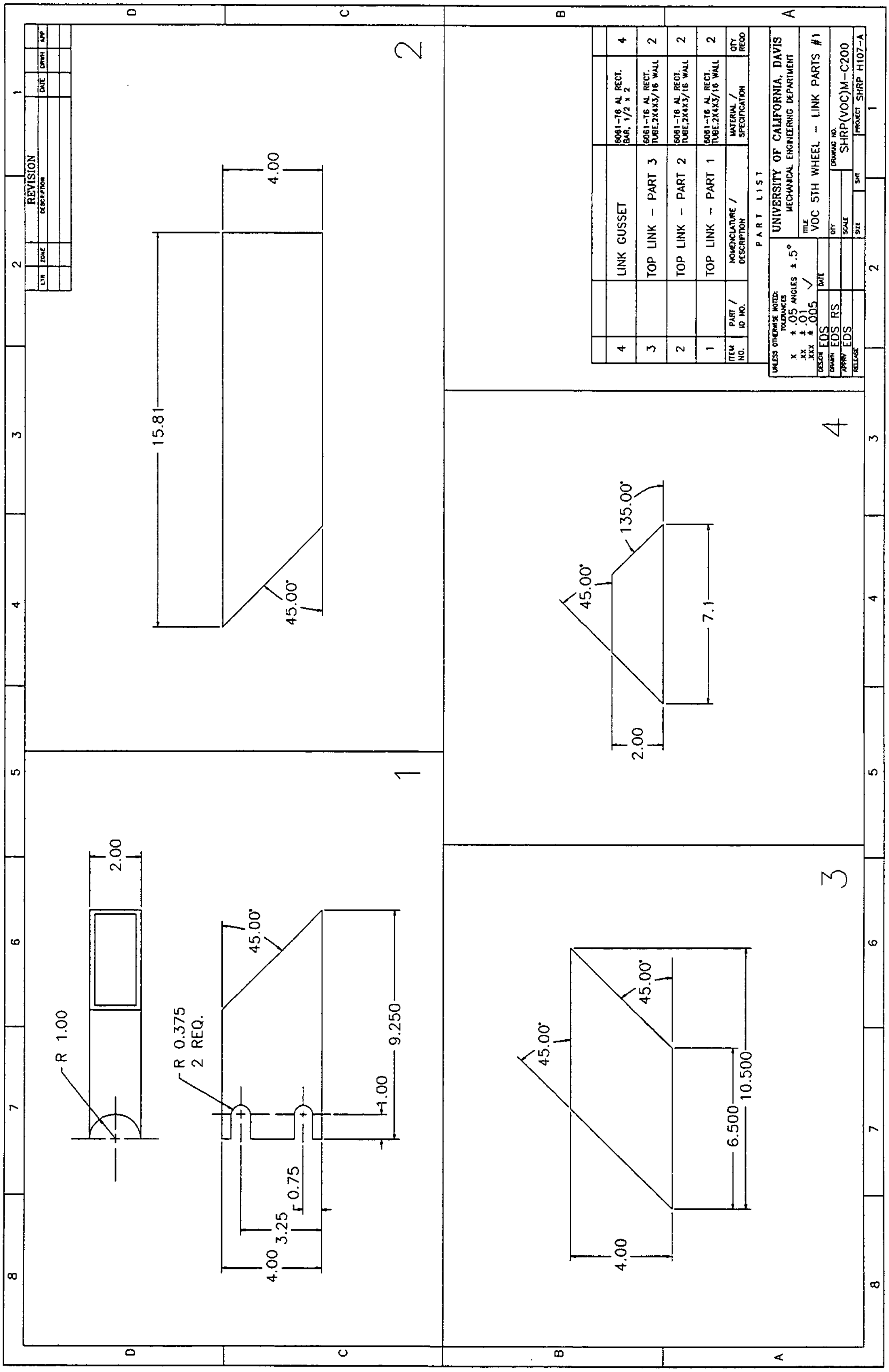

ø0.9992
ø0.9987
ø27/64 1.5 DEEP
1/2-12 UNC, 1.0 DEEP
0.1x45° CHAMFER
TYPICAL BOTH ENDS
6.25
0.40
ø2.0
ø1.01
ø1.00
SECTION A–A
NOTE: BREAK ALL SHARP EDGES.
REVISION
2 ADJUSTMENT SPACER 6061-T6 AL 8
1 TRUCK/LINK PIN 303 SS. 8
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL –
TRUCK/LINK PIN
SHRP(VOC)M-A102
SHRP H107-A

Drawing 7.17

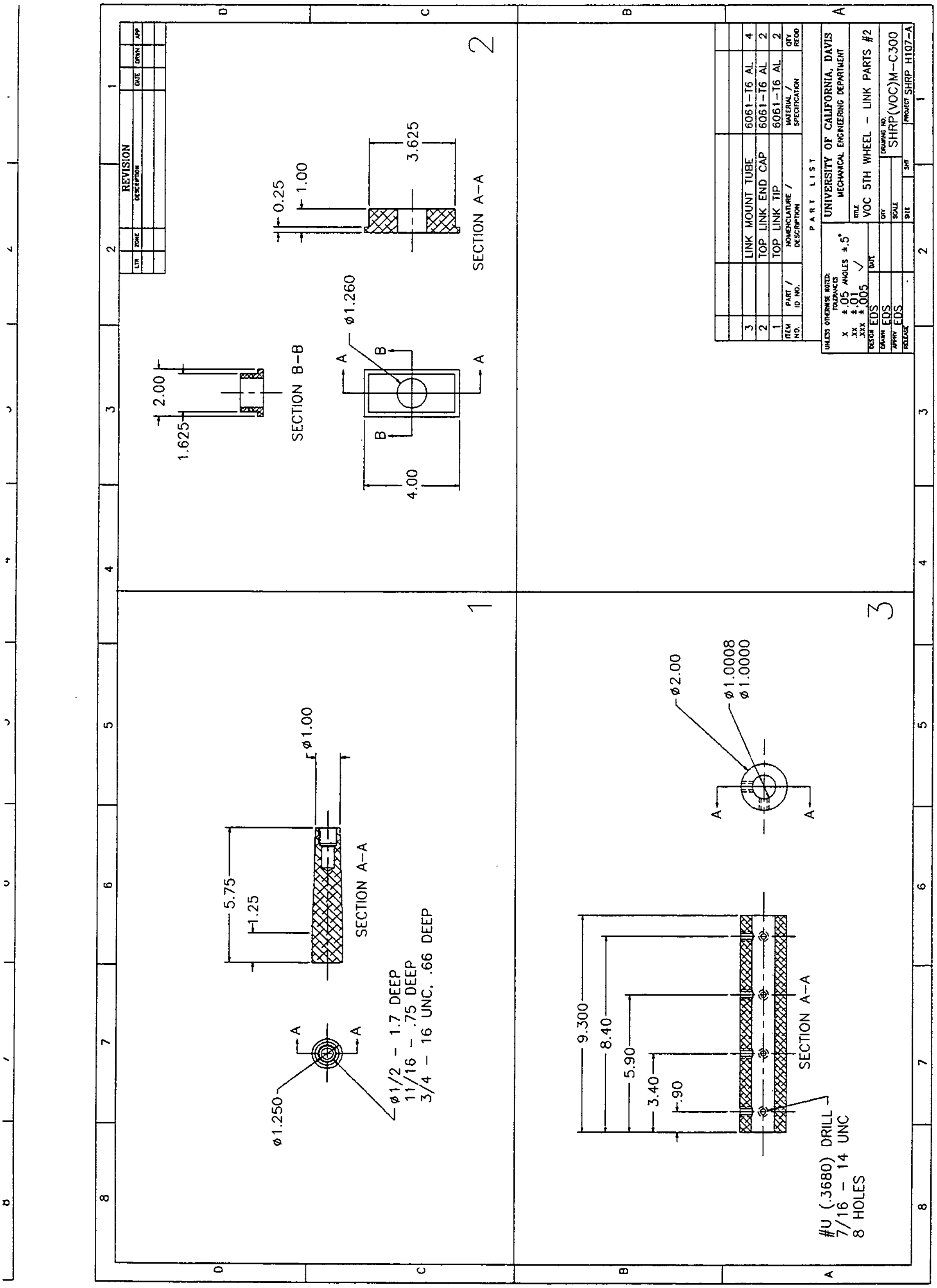


REVISION
THREAD INSERT ITEM #9
THREAD INSERT ITEM #8 8 REQ.
NOTES:
1) BREAK ALL SHARP EDGES
2) WELDS SHALL BE AS FOLLOWS:
A: V-GROOVE WELDS SHALL BE 3/16" IN SIZE WITH 60°-90° GROOVE ANGLE.
B: EDGE WELDS SHALL BE 3/16" AROUND
C: FILLET WELDS SHALL BE 3/16" IN SIZE
3) CONTACT UCD POINT OF CONTACT FOR WELDING INSTRUCTIONS.
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL - TOP LINK
SHRP(VOC)M-C100
PROJECT SHRP H107-A
25.81
21.31
9.25
11.15
7.15

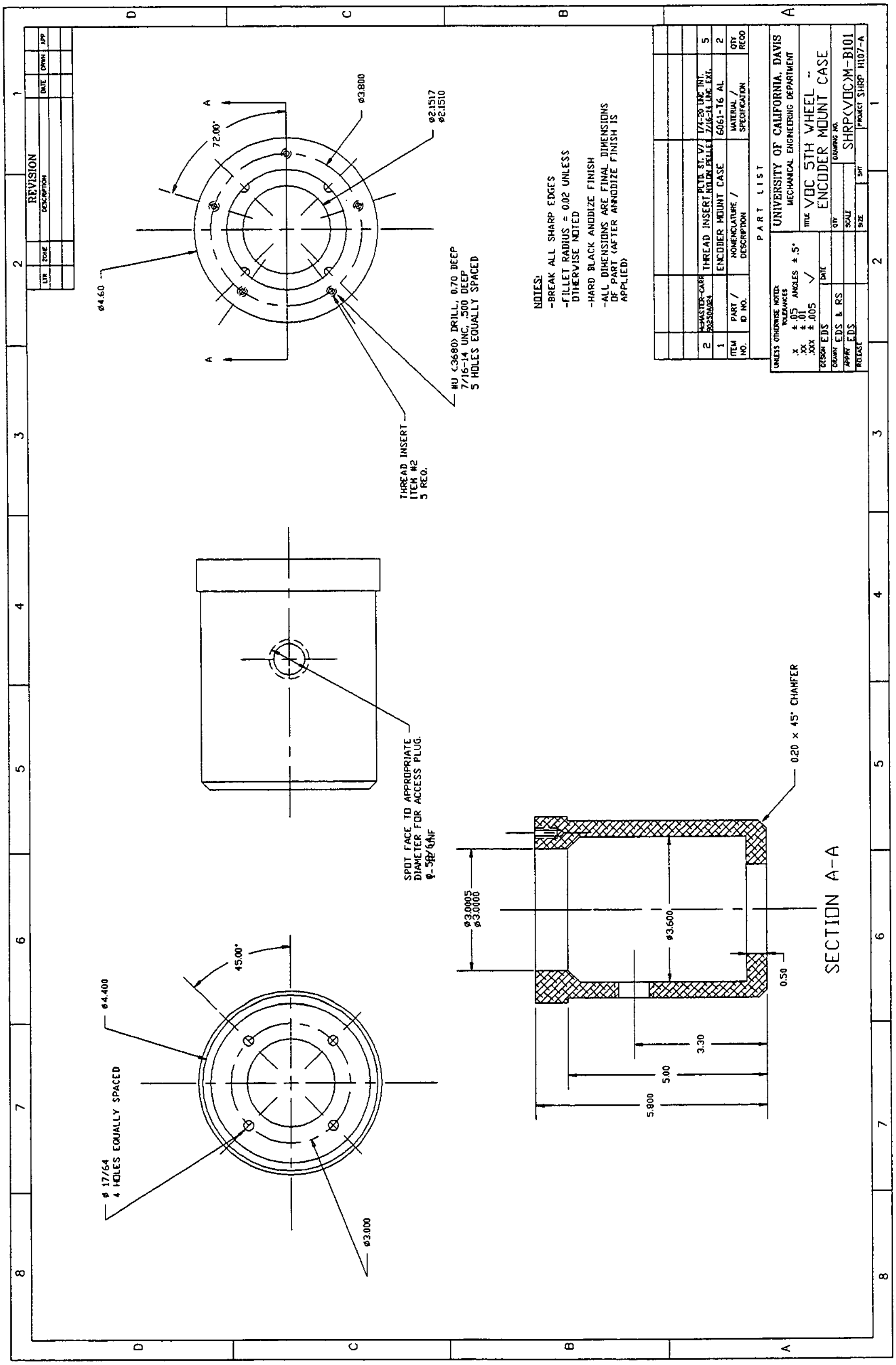
Drawing 7.18


REVISION
LINK GUSSET
TOP LINK - PART 3
TOP LINK - PART 2
TOP LINK - PART 1
6061-T6 AL RECT. BAR, 1/2 x 2
6061-T6 AL RECT. TUBE,2X4X3/16 WALL
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL - LINK PARTS #1
SHRP(VOC)M-C200
SHRP H107-A
EDS
RS
15.81
4.00
45.00°
135.00°
7.1
2.00
R 1.00
R 0.375
2 REQ.
9.250
1.00
0.75
3.25
6.500
10.500

Drawing 7.19

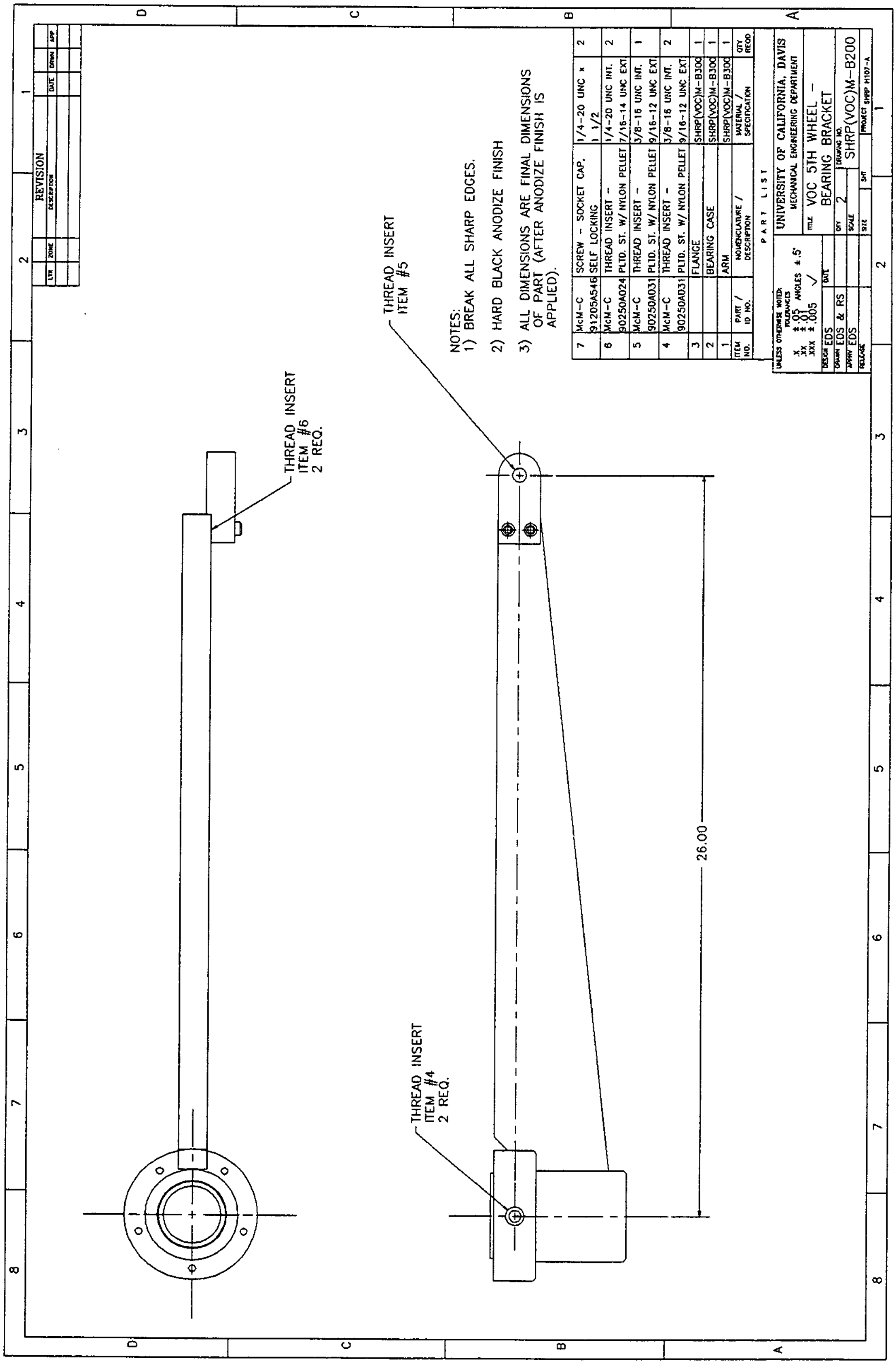

UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL - LINK PARTS #2
SHRP(VOC)M-C300
LINK MOUNT TUBE
TOP LINK END CAP
TOP LINK TIP
6061-T6 AL
PART LIST
REVISION
SECTION A-A
SECTION B-B

Drawing 7.20

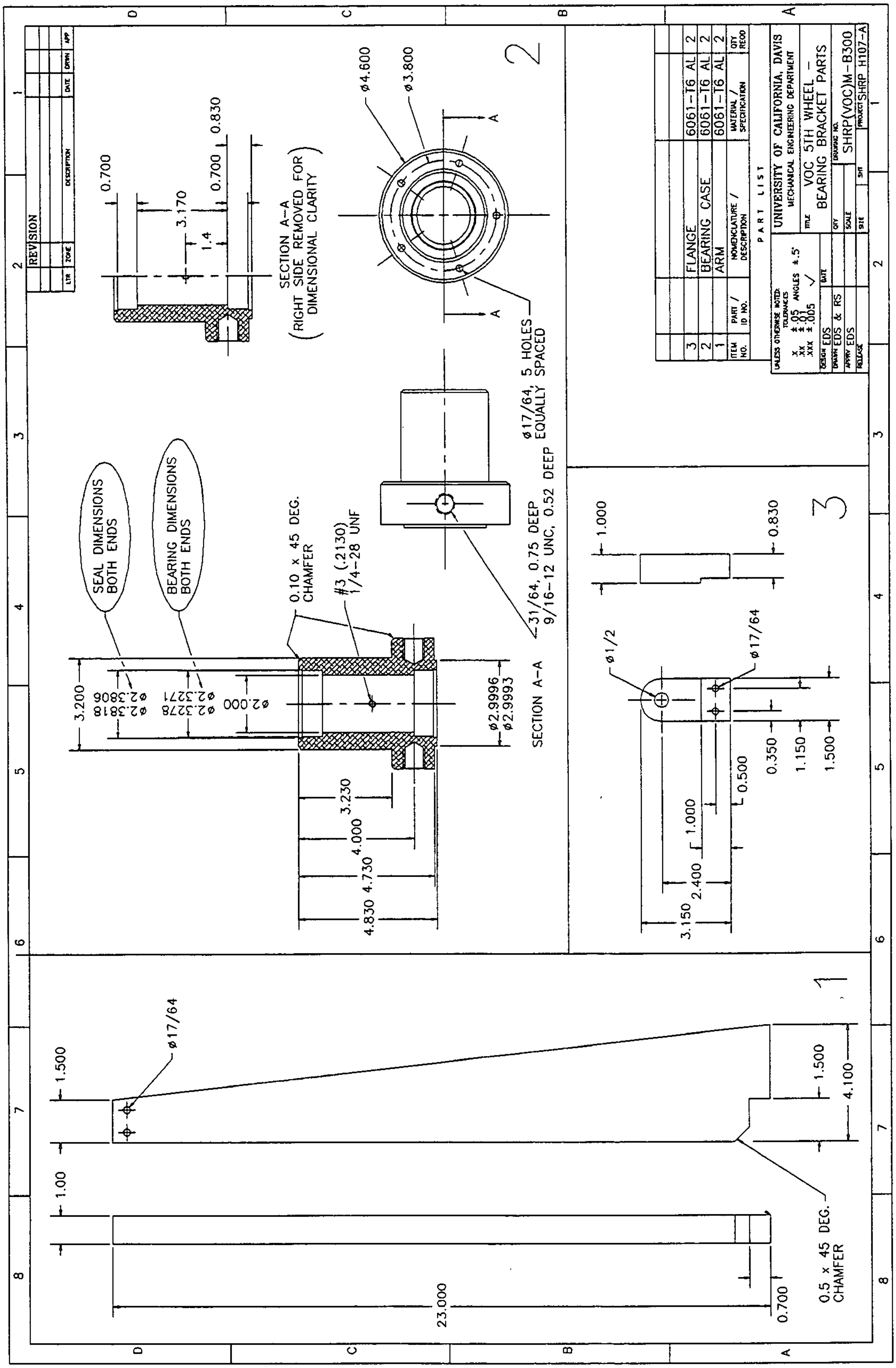


UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VDC 5TH WHEEL - ENCODER MOUNT CASE
SHRP(VDC)M-B101
PROJECT SHRP H107-A
PART LIST
THREAD INSERT
ENCODER MOUNT CASE
6061-T6 AL
NOTES:
-BREAK ALL SHARP EDGES
-FILLET RADIUS = 0.02 UNLESS OTHERWISE NOTED
-HARD BLACK ANODIZE FINISH
-ALL DIMENSIONS ARE FINAL DIMENSIONS OF PART (AFTER ANODIZE FINISH IS APPLIED)
REVISION
THREAD INSERT ITEM #2 5 REQ.
SPOT FACE TO APPROPRIATE DIAMETER FOR ACCESS PLUG.
0.20 x 45° CHAMFER
SECTION A-A
4 HOLES EQUALLY SPACED
5 HOLES EQUALLY SPACED

Drawing 7.21


THREAD INSERT ITEM #6 2 REQ.
THREAD INSERT ITEM #4 2 REQ.
THREAD INSERT ITEM #5
26.00
NOTES:
1) BREAK ALL SHARP EDGES.
2) HARD BLACK ANODIZE FINISH
3) ALL DIMENSIONS ARE FINAL DIMENSIONS OF PART (AFTER ANODIZE FINISH IS APPLIED).
REVISION
LTR ZONE DESCRIPTION DATE DRWN APP
7 McM-C 91205A546 SCREW - SOCKET CAP, SELF LOCKING 1/4-20 UNC x 1 1/2 2
6 McM-C 90250A024 THREAD INSERT - PLTD. ST. W/ NYLON PELLET 1/4-20 UNC INT. 7/16-14 UNC EXT 2
5 McM-C 90250A031 THREAD INSERT - PLTD. ST. W/ NYLON PELLET 3/8-16 UNC INT. 9/16-12 UNC EXT 1
4 McM-C 90250A031 THREAD INSERT - PLTD. ST. W/ NYLON PELLET 3/8-16 UNC INT. 9/16-12 UNC EXT 2
3 FLANGE SHRP(VOC)M-B300 1
2 BEARING CASE SHRP(VOC)M-B300 1
1 ARM SHRP(VOC)M-B300 1
ITEM NO. PART / ID NO. NOMENCLATURE / DESCRIPTION MATERIAL / SPECIFICATION QTY REQD
PART LIST
UNLESS OTHERWISE NOTED: TOLERANCES .X ±.05 .XX ±.01 .XXX ±.005 ANGLES ±.5°
DESIGN EDS
DRAWN EDS & RS
APPRV EDS
RELEASE
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
TITLE VOC 5TH WHEEL - BEARING BRACKET
QTY 2
DRAWING NO. SHRP(VOC)M-B200
PROJECT SHRP H107-A
SCALE SIZE SHT

Drawing 7.22


REVISION
SECTION A-A
(RIGHT SIDE REMOVED FOR DIMENSIONAL CLARITY)
SEAL DIMENSIONS BOTH ENDS
BEARING DIMENSIONS BOTH ENDS
0.10 x 45 DEG. CHAMFER
#3 (.2130) 1/4-28 UNF
31/64, 0.75 DEEP 9/16-12 UNC, 0.52 DEEP
ø17/64, 5 HOLES EQUALLY SPACED
ø4.600
ø3.800
ø2.9996
ø2.9993
ø2.000
0.5 x 45 DEG. CHAMFER
ø17/64
ø1/2
3 FLANGE 6061-T6 AL 2
2 BEARING CASE 6061-T6 AL 2
1 ARM 6061-T6 AL 2
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
VOC 5TH WHEEL – BEARING BRACKET PARTS
SHRP(VOC)M-B300
SHRP H107-A
EDS
EDS & RS

Drawing 7.23

Appendix B: Subsystem Components

Manufacturer	Component	Model
APS Components:		
Aeroquip	Hydraulic System Connections	Misc.
Allenair	Pneumatic Cylinders	
American Power Conversion	Uninterruptible Power Supply	Smart-UPS 2000
Bellofram	Pneumatic Transducer	I/P Type 1000
Berry	Melter	BMA-200
Control Technology Specialists	Burner Control System	
Dayton	3/4 HP DC Motor	2M169
Eclipse	Thermal Blast Burner	
EG & G Rotron	Debris Separator	IVM2000PF
Generac	25 KW Generator	SD025G
Hoffman	NEMA 12 Box with Window	20x16x8
Hydraulic Controls, Inc.	Hydraulic Pumping Unit	Custom
Kaydon	Angular Contact Ball Bearings	KA series
Maurey Instrument Corp.	Linear Motion Potentiometer	P1613-3-202
McMaster-Carr	Flex Shaft	442A36
Paxton	Centrifugal Blower	CB-87
Raytek	Infrared Pyrometer	ET3LT
Thompson	Linear Bearings	Super-8
UC Davis	72" Crimped Steel Wire Brush	Custom
Worcester	Positioner	Pm15 S
Worcester	Positioner Mounting Kit	MK 191
ICU Components:		
Computer Machinery Corp.	Ethernet Comm. Software Driver	CMC ENP-10 Driver
Computer Machinery Corp.	Ethernet Communications Card	CMC ENP-10
Heurikon Corporation	Backplane	HSE/17R-12V-W60-F3-S150
Heurikon Corporation	CPU Card	HK68H/V3E-16MB
Microware Corporation	OS-9 Professional	Ver. 2.4
Microware Corporation	Real-Time Audio Visual Environment (RAVE)	MM1250
Vigra Inc.	Multimedia Graphics Card	MM1250
Xycom	Analog I/O Card	XVME540
Xycom	Digital I/O Card	XVME201
Xycom	Software Driver	XVME982

LRPS Components:		
Bastech	LRPS Frame	Custom
Columbia Winch and Hoist	Hoist	H2000A1-01
Industrial Computer Solutions	Rackmount 486 PC System	
McMaster-Carr	Wheel Size Swivel Casters for LRPS	2443T32
Parker Hannifin	Digital Process Servo Valve Controller and Actuator	PMC 10
Parker Hannifin	F-Style Actuator, Proportional Valve, and Controller.	PLA2X12LF7M10NB10
Sony	13" Video/Data Monitor	GVM 1310
TDK	Bearing Rails	SR 35W
LSS Components:		
Modular Vision Systems, Inc.	Digital Signal Processing Board	SKY321-PC
Modular Vision Systems, Inc.	LaserVision Profile Board	LPB
Modular Vision Systems, Inc.	LaserVision Sensor	MVS-30
RPS Components:		
Fanuc Robotics	Robot Manipulator	A-510
Fanuc Robotics	Karel Controller	RH, "C" Size
Fanuc Robotics	KAREL software	Version 2.21
Fanuc Robotics	Servo Driven Robot Transport, linear slide	Custom, 50 " Travel
Fanuc Robotics	3.5" Serial Floppy Disk Drive	
Fanuc Robotics	AD Module	
Fanuc Robotics	8-Bit I/O Module	
Fanuc Robotics	Serial Communications Option for KAREL Controller.	
Vehicle Components:		
Amerigas	Propane Gas System	Custom
Bastech	Robot Mount	Custom
David Clark	Communication System	3800 Series
Harrington Plastics	Elevated Walkway	I-4015 Series
KT Design	Operator Booth Skid	Custom
T & N Manufacturing	Operator Booth	Custom
T & N Manufacturing	Truck Bed	Custom
White GMC	Truck	XPEDITOR Series

VOC Components:		
BEI Motion Systems	Shock Proof Optical Encoder	
Fafnir	Pillow Block Link Mount Bearing , 1" Dia.	YAS-1
R & K Industrial Wheels	Encoder Wheel	Custom
Timken	Tapered Roller Cone	LM67048
Timken	Tapered Roller Cup	LM67010
Xycom	Computer Counter Card	XVME230
VSS Components:		
DataCube	FeatureMax MKll	260-0369 Rev. 02
DataCube	Image Flow Software ver. 2.1.2	940-1001-HH-MM
DataCube	Max-Scan 10MHZ	260-0250 Rev. 05
DataCube	MaxGraph	260-0225 Rev. 04
DataCube	ROI Store 512	260-0243 Rev. 08
DataCube	ROI Store 2048	260-0243 Rev. 08
Datron Technology	Optical Encoder	Correvit WPT-4500
Hubble	Floodlight Fixture	QL505
JML	TV Lenses (12.5mm, F1.3)	P/N 71846
Loral Fairchild	Line Scan Camera	CAM1301R
PELCO	Pressurized Camera Enclosures	#EH8004/SPL
Phillips	500 Watt Tungsten Halogen Lamps	500T3Q/CL FCL
Radstone	3.5" Floppy Drive	
Radstone	4MByte, Dual Port Memory Module	8SB/201
Radstone	20 Slot Chassis with 1200W PSU, 6 Slot VSB Backplane	cs-20 2/001
Radstone	68-33/100 CPU Module with 4M RAM, 50 MHz	68-33/100
Radstone	170 MB Hard Drive	WK-3/300
Radstone	Ethernet Card	ENET-1/100 112
Radstone	OS-9 Professional	Rel. 5
Radstone	Tape backup, 60 MB	TK-1/100
Z-World	Little Giant Controller	SBC200-E

Appendix C: VOC Kinematics

C.1 - Introduction

To accomplish the task of tracking road cracks with respect to the crack sealing truck, it is necessary to develop the proper kinematics of the problem and incorporate them into the VOC computer program. The kinematics of the crack tracking problem are developed in the sections that follow. It is noted here that since the maximum speed of the truck during the crack sealing operation likely to be not more that 2 mph, dynamic effects of the truck and the various ACSM subsystems have a negligible effect on the crack tracking problem. Therefore, it is possible to get a very accurate solution to this problem by including only the kinematic equations of the systems involved.

C.2 - Definitions

Subscripts

[#/#] - Any subscript of the form [#/#] identifies the variable to which it is attached as having its particular value between step "[#/" and step "/#]" of the truck. An example is [4/5]. The variable to which this subscript is attached has its particular value between step 4 and step 5 of the truck. A general example is "[n-1/n]". The variable to which this subscript is attached has its particular value between step "n-1" and step "n" of the truck.

- Any subscript not contained within "[ ]" identifies the coordinate frame from which the value of the variable to which the subscript is attached is measured with respect to. For the example of "4" the variable to which this subscript is attached is measured with respect to the 4th moving coordinate frame (4th step of the truck). For the example of "n-1", the variable to which this subscript is attached is measured

with respect to the "n-1" moving coordinate frame. For the example of "0", the variable to which this subscript is attached is measured with respect to the "0" or fixed coordinate frame.

$_{[\#]}$ - Any subscript of the form [#] identifies the variable to which the subscript is attached as having the particular value for step "#" of the truck. An example is "[3]". The variable to which this subscript is attached has the particular value for step "3" of the truck. A general example is "[n]". The variable to which this subscript is attached has its particular value for step "n" of the truck.

Constants

D - The lateral distance (in the "y" direction) between the left encoder wheel and the right encoder wheel. Refer to C.1.

Ne - The total number of encoder pulses per revolution of the encoder wheel (fifth wheel).

Re - The radius of the encoder wheel.

W - The lateral distance (in the "y" direction) between the right encoder wheel and the point "B" located on the truck. Refer to C.1.

Variables

Angles

$b_{[\#]0}$ - The angle, about a vertical axis, from a line drawn through point "$B_{[n]}$" and parallel to the x-axis of the "0" (fixed) reference frame to a line drawn through point "$B_{[n]}$" and point "A". The subscript "[#]" denotes the step of the truck motion to which this value belongs. Refer to C.2. This angle is defined and used only for intermediate manipulation of the kinematics formulas. In the final equations it is eliminated through reverse substitution. This variable makes sense only when referring to the "$_0$" reference frame.

$f_{[\#]}$ - The angle, about a vertical axis, from a line drawn through point "$B_{[n]}$" and parallel to the x-axis of the "#-1" reference frame to a line drawn through point "$B_{[n]}$" and point "A". The subscript "[#]" denotes the step of the truck motion to which this value belongs. Refer to C.2. This angle is defined and used only for intermediate manipulation of the kinematics formulas. In the final equations it is eliminated through reverse substitution.

$y_{[\#-1/\#]}$ - The angle, about a vertical axis, from a line drawn through point "$B_{[\#-1]}$" and point "$B_{[\#]}$" to the x-axis of the "#-1" reference frame. The subscript "[#-1/" refers to point "$B_{[\#-1]}$". The subscript "/#]" refers to point "$B_{[\#]}$". Refer to C.2. The value of this angle is independent of the reference frame with respect to which it is measured. This angle is defined and used only for intermediate manipulation of the kinematics formulas. In the final equations it is eliminated through reverse substitution.

$q_{[\#]}$ - The angle, about a vertical axis, through which the truck rotates. The subscript "[#]" denotes the step of the truck motion at which this rotation occurred. This angle is commonly referred to as the "yaw angle". The value of this angle is independent of the reference frame with respect to which it is measured. Refer to C.2.

qTotal - The sum of all "$q_{[\#]}$" values up to and including the present step of truck motion.

Points

A - The point, located on the road surface, that is being tracked. Refer to C.1.

$B_{[\#]}$ - The point (on the truck), located on the center line of the right and left encoders, at a distance "W" to the left of the right encoder. The subscript identifies the variable to which it is attached as belonging to the [#] step. Refer to C.1.

Miscellaneous Variables

$A_{[\#]}$ - The distance between a point "A" and the point "$B_{[\#]}$". Refer to C.5.

$Ax_{[\#]\#}$ - The "x" distance, measured with respect to a particular reference frame (denoted by the subscript "#"), between a point "A" and the origin of the [#] reference frame. The subscript [#] denotes the step of the truck to which this value belongs. Refer to C.4.

$Ay_{[\#]\#}$ - The "y" distance, measured with respect to a particular reference frame (denoted by the subscript "#"), between a point "A" and the origin of the [#] reference frame. The subscript [#] denotes the step of the truck to which this value belongs. Refer to C.4.

$ARCl_{[\#/\#]}$ - The length of the arc traversed by the left encoder from step "[#/" to step "/#]". Refer to C.1.

$ARCr_{[\#/\#]}$ - The length of the arc traversed by the right encoder from step "[#/" to step "/#]". Refer to C.1.

$B_{[\#/\#]}$ - The distance between one point "B" (denoted by the subscript "[#/") and another point B (denoted by the subscript "/#]. Refer to C.5.

$Bx_{[\#/\#]\#}$ - The "x" distance, measured with respect to a particular reference frame (denoted by the subscript "#"), between one point "B" (denoted by the subscript "[#/") and another point B (denoted by the subscript "/#]. Refer to C.3.

$Bx(cum)_0$ - The cumulative sum of all "$Bx_{[\#/\#]0}$" values up to and including the value for the last step of the truck. This variable makes sense only when referring to the "$_0$" reference frame.

$By_{[\#/\#]\#}$ - The "y" distance, measured with respect to a particular reference frame (denoted by the subscript "#"), between one point "B" (denoted by the subscript "[#/") and another point B (denoted by the subscript "/#]. Refer to C.3.

$By(cum)_0$ - The cumulative sum of all "$By_{[\#/\#]0}$" values up to and including the value for the last step of the truck. This variable makes sense only when referring to the "$_0$" reference frame.

n - The variable "n" refers to either the current step of the truck or the current moving coordinate frame depending on the context in which it is used. Additionally, "n-1" refers to the previous step or moving coordinate frame, "n-2" refers to the step or moving coordinate frame previous to the "n-1" step or moving coordinate frame, etc.

$Nl_{[\#/\#]}$ - The number of encoder pulses counted by the left encoder from step "[#/" to step "/#]".

$Nr_{[\#/\#]}$ - The number of encoder pulses counted by the right encoder from step "[#/" to step "/#]".

$Rb_{[\#/\#]}$ - The length of the radius between step "[#/," and step "/#]" of the truck drawn from the center of rotation of the truck and the arc traced by the point "B" (on the truck). Refer to C.1.

$Rl_{[\#/\#]}$ - The length of the radius between step "[#/," and step "/#]" of the truck drawn from the center of rotation of the truck and the arc traced by the left encoder wheel. Refer to C.1.

$Rr_{[\#/\#]}$ - The length of the radius between step "[#/," and step "/#]" of the truck drawn from the center of rotation of the truck and the arc traced by the right encoder wheel. Refer to C.1.

C.3 - Kinematics

General Kinematics

First equations for several of the basic variables are derived. From C.1, it can be easily shown that:

$$ARCl_{[n-1/n]} = 2 \times p \times Re \left(\frac{Nl_{[n-1/n]}}{Ne}\right) \qquad (C.1)$$

and

$$ARCr_{[n-1/n]} = 2 \ x \ p \ x \ Re\left(\frac{Nr_{[n-1/n]}}{Ne}\right). \tag{C.2}$$

Next, a formula for $Rr_{[n-1/n]}$ is derived. From C.1, it can be seen that:

$$\frac{ARCr_{[n-1/n]}}{Rr_{[n-1/n]}} = \frac{ARCl_{[n-1/n]}}{Rl_{[n-1/n]}} \tag{C.3}$$

and

$$Rl_{[n-1/n]} = Rr_{[n-1/n]} + D. \tag{C.4}$$

Substituting Eqns. C.4 into C.3 and rearranging,

$$Rr_{[n-1/n]} = \left(\frac{(ARCr_{[n-1/n]})\ D}{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}\right). \tag{C.5}$$

Also, from C.1,

$$Rb_{[n-1/n]} = Rr_{[n-1/n]} + W, \tag{C.6}$$

$$q_{[n]} = \left(\frac{ARCr_{[n-1/n]}}{Rr_{[n-1/n]}}\right), \tag{C.7}$$

and

$$q_{[n]} = \left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right). \tag{C.8}$$

From C.2,

$$f_{[n]} = \tan^{-1}\left(\frac{Ay_{[n-1]\ n-1} - By_{[n-1/n]\ n-1}}{Ax_{[n-1]\ n-1} - Bx_{[n-1/n]\ n-1}}\right). \tag{C.9}$$

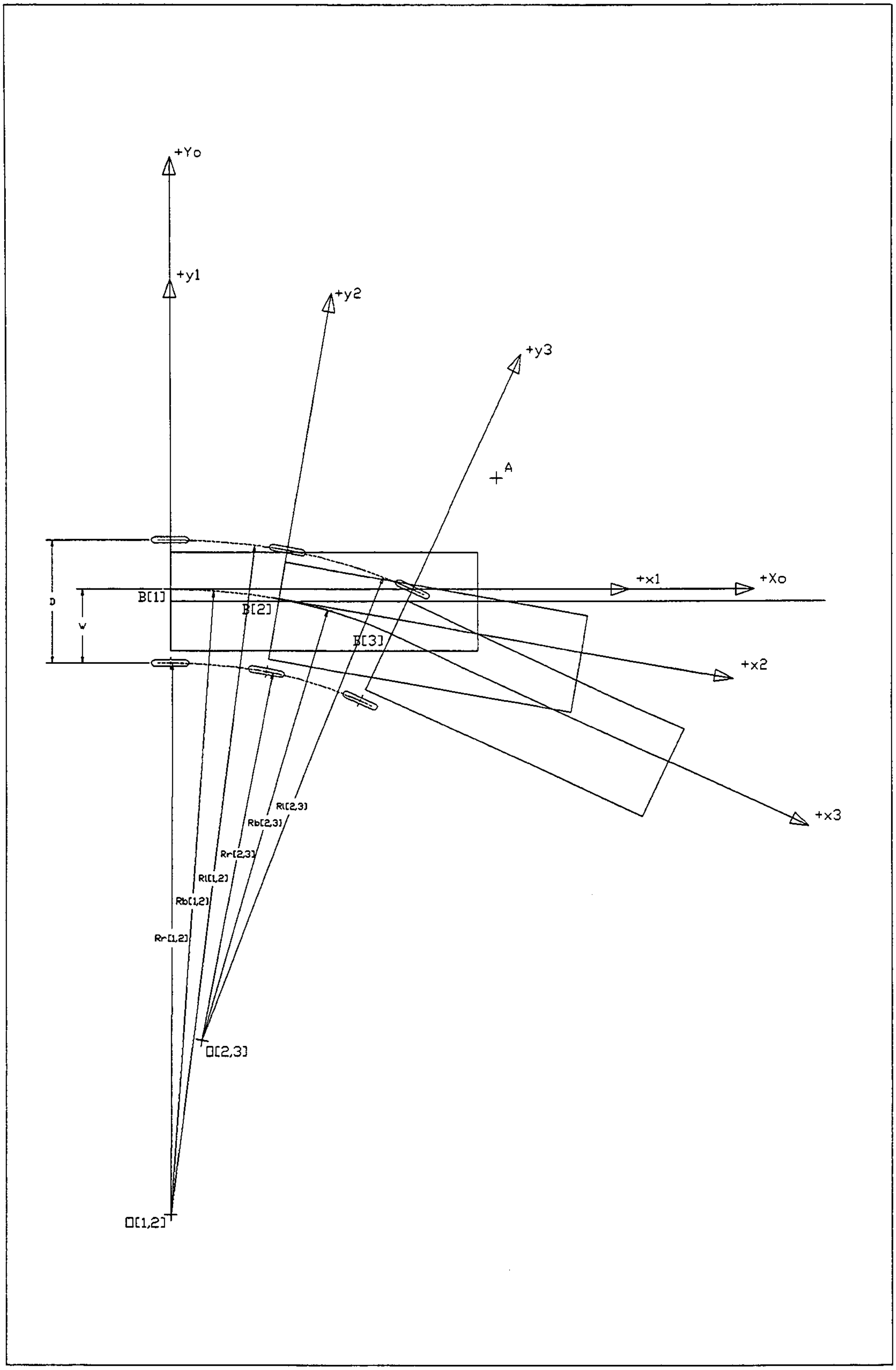


Figure C.1 - VOC system kinematics - Plate 1.

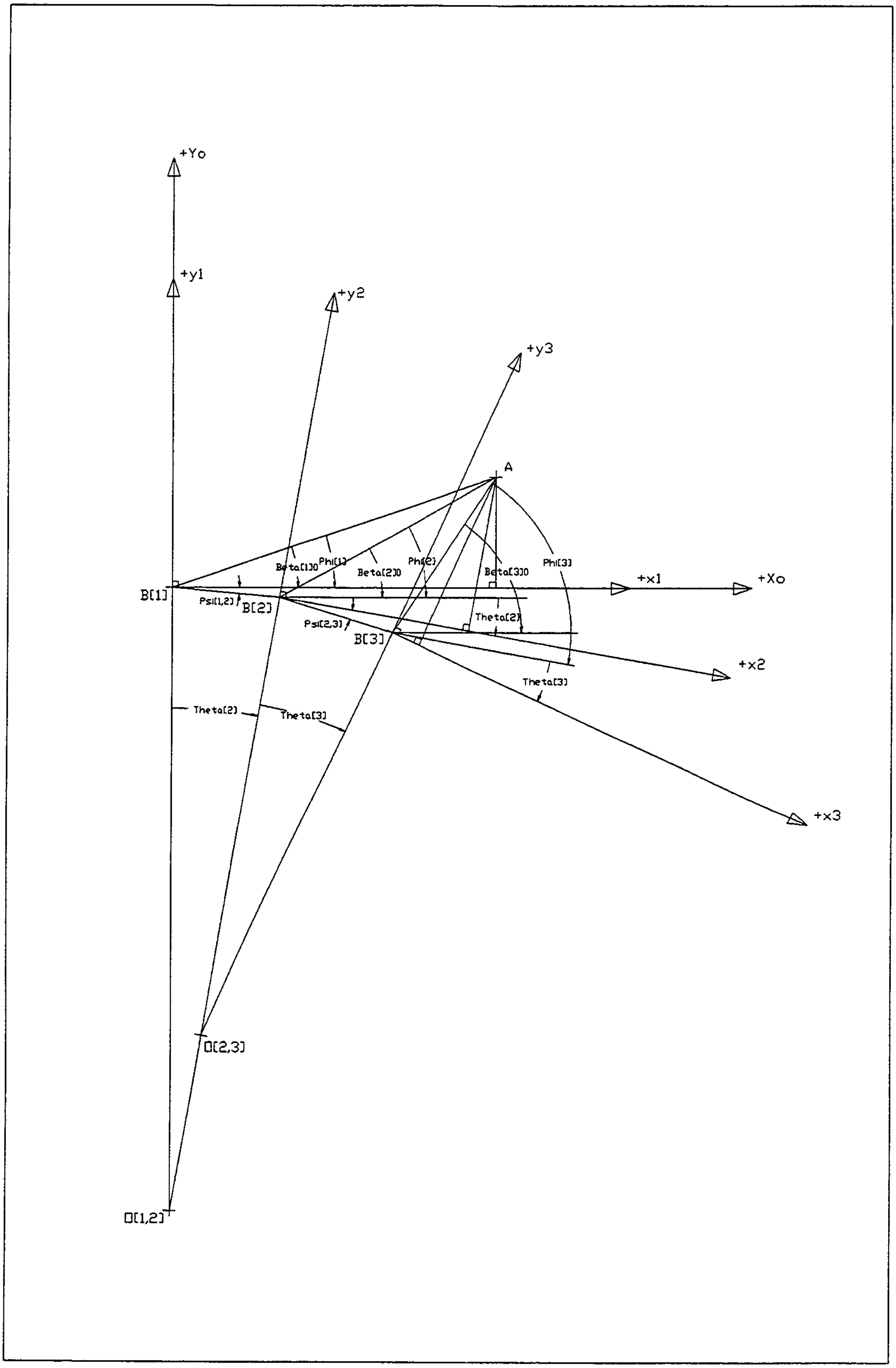


Figure C.2 - VOC system kinematics - Plate 2.

Kinematics with respect to Local Reference Frame

Now, from C.3 it can be seen that:

$$DBx_{[n-1/n]\ n-1} = Rb_{[n-1/n]} \sin(q_{[n]}) \tag{C.10}$$

and

$$DBy_{[n-1/n]\ n-1} = Rb_{[n-1/n]} (1 - \cos(q_{[n]})). \tag{C.11}$$

Now substitute Eqn. C.5 into Eqn. C.6. Then substitute Eqns. C.6 and C.8 into Eqns. C.10 and C.11,

$$DBx_{[n-1/n]\ n-1} = \left(\frac{(ARCr_{[n-1/n]})\ D}{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}} + W\right) \sin\left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right) \tag{C.12}$$

refer to C.3

and

$$DBy_{[n-1/n]\ n-1} = \left(\frac{(ARCr_{[n-1/n]})\ D}{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}} + W\right)\left(1 - \cos\left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right)\right). \tag{C.13}$$

refer to C.3

Now develop equations for point A. Referring to C.4,

$$Ax_{[n]\ n} = \left(\sqrt{(Ax_{[n-1]\ n-1} - DBx_{[n-1/n]\ n-1})^2 + (Ay_{[n-1]\ n-1} - DBy_{[n-1/n]\ n-1})^2}\right) \cos(f_{[n]} + q_{[n]}) \tag{C.14}$$

and

$$Ay_{[n]\ n} = \left(\sqrt{(Ax_{[n-1]\ n-1} - DBx_{[n-1/n]\ n-1})^2 + (Ay_{[n-1]\ n-1} - DBy_{[n-1/n]\ n-1})^2}\right) \sin(f_{[n]} + q_{[n]}). \tag{C.15}$$

Substituting Eqns. C.8 and C.9 into Eqns. C.14 and C.15,

$$Ax_{[n]\ n} = \left(\sqrt{(Ax_{[n-1]\ n-1} - DBx_{[n-1/n]\ n-1})^2 + (Ay_{[n-1]\ n-1} - DBy_{[n-1/n]\ n-1})^2}\right) \times \tag{C.16}$$

$$\cos\left(\tan^{-1}\left(\frac{Ay_{[n-1]\,n-1} - DBy_{[n-1/n]\,n-1}}{Ax_{[n-1]\,n-1} - DBx_{[n-1/n]\,n-1}}\right) + \left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right)\right)$$

refer to C.4

and

$$Ay_{[n]\,n} = \left(\sqrt{(Ax_{[n-1]\,n-1} - DBx_{[n-1/n]\,n-1})^2 + (Ay_{[n-1]\,n-1} - DBy_{[n-1/n]\,n-1})^2}\right) \times \tag{C.17}$$

$$\sin\left(\tan^{-1}\left(\frac{Ay_{[n-1]\,n-1} - DBy_{[n-1/n]\,n-1}}{Ax_{[n-1]\,n-1} - DBx_{[n-1/n]\,n-1}}\right) + \left(\frac{ARCl_{[n-1/n]} - ARCr_{[n-1/n]}}{D}\right)\right).$$

refer to C.4

Kinematics w/Respect to Global Reference Frame

Referring to C.2, it can be seen that:

$$y_{[n-1/n]} = \tan^{-1}\left(\frac{-DBy_{[n-1/n]\,n-1}}{DBx_{[n-1/n]\,n-1}}\right) \tag{C.18}$$

and

$$qTotal = q_{[1]\,0} + \ldots + q_{[n-1]\,n-2} + q_{[n]\,n-1}. \tag{C.19}$$

From C.5:

$$B_{[n-1/n]} = \sqrt{(DBx_{[n-1/n]\,n-1})^2 + (DBy_{[n-1/n]\,n-1})^2}. \tag{C.20}$$

Now, referring to C.3,

$$DBx_{[n-1/n]\,0} = B_{[n-1/n]} \cos(y_{[n]\,n-1} + qTotal + q_{[n]\,n-1}) \tag{C.21}$$

and

$$DBy_{[n-1/n]\,0} = B_{[n-1/n]} \sin(y_{[n]\,n-1} + qTotal + q_{[n]\,n-1}). \tag{C.22}$$

Note that the correct signs (+/-) of $DBx_{[n-1/n]\,0}$ and $DBy_{[n-1/n]\,0}$ in Eqns. C.21 and C.22 may not be preserved since $B_{[n-1/n]}$ (which was calculated in Eqn. C.20) was calculated by squaring $DBx_{[n-1/n]\,n-1}$ and $DBy_{[n-1/n]\,n-1}$, adding them, and taking their square root. This must be taken into account in the computer program.

Substituting Eqns. C.8, C.18, C.19, and C.20 into Eqn. C.21,

$$DBx_{[n-1/n]\,0} = \left(\sqrt{(DBx_{[n-1/n]\,n-1})^2 + (DBy_{[n-1/n]\,n-1})^2}\right) \; x \tag{C.23}$$

$$\cos\left(\tan^{-1}\left(\frac{-DBy_{[n-1/n]\,n-1}}{DBx_{[n-1/n]\,n-1}}\right) + \left(\frac{ARCl_{[1/2]} - ARCr_{[1/2]}}{D}\right) + \ldots + \left(\frac{ARCl_{[n-2/n-1]} - ARCr_{[n-2/n-1]}}{D}\right)\right).$$

refer to C.3

Similarly, substituting Eqns. C.8, C.18, C.19, and C.20 into Eqn. C.22,

$$DBy_{[n-1/n]\,0} = \left(\sqrt{(DBx_{[n-1/n]\,n-1})^2 + (DBy_{[n-1/n]\,n-1})^2}\right) \; x \tag{C.24}$$

$$\sin\left(\tan^{-1}\left(\frac{-DBy_{[n-1/n]\,n-1}}{DBx_{[n-1/n]\,n-1}}\right) + \left(\frac{ARCl_{[1/2]} - ARCr_{[1/2]}}{D}\right) + \ldots + \left(\frac{ARCl_{[n-2/n-1]} - ARCr_{[n-2/n-1]}}{D}\right)\right).$$

refer to C.3

Now we develop equations for point "A". First,

$$DBx(cum)_0 = DBx_{[1/2]\,0} + \ldots + DBx_{[n-2/n-1]\,0} + DBx_{[n-1/n]\,0} \tag{C.25}$$

and

$$DBy(cum)_0 = DBy_{[1/2]\,0} + \ldots + DBy_{[n-2/n-1]\,0} + DBy_{[n-1/n]\,0}. \tag{C.26}$$

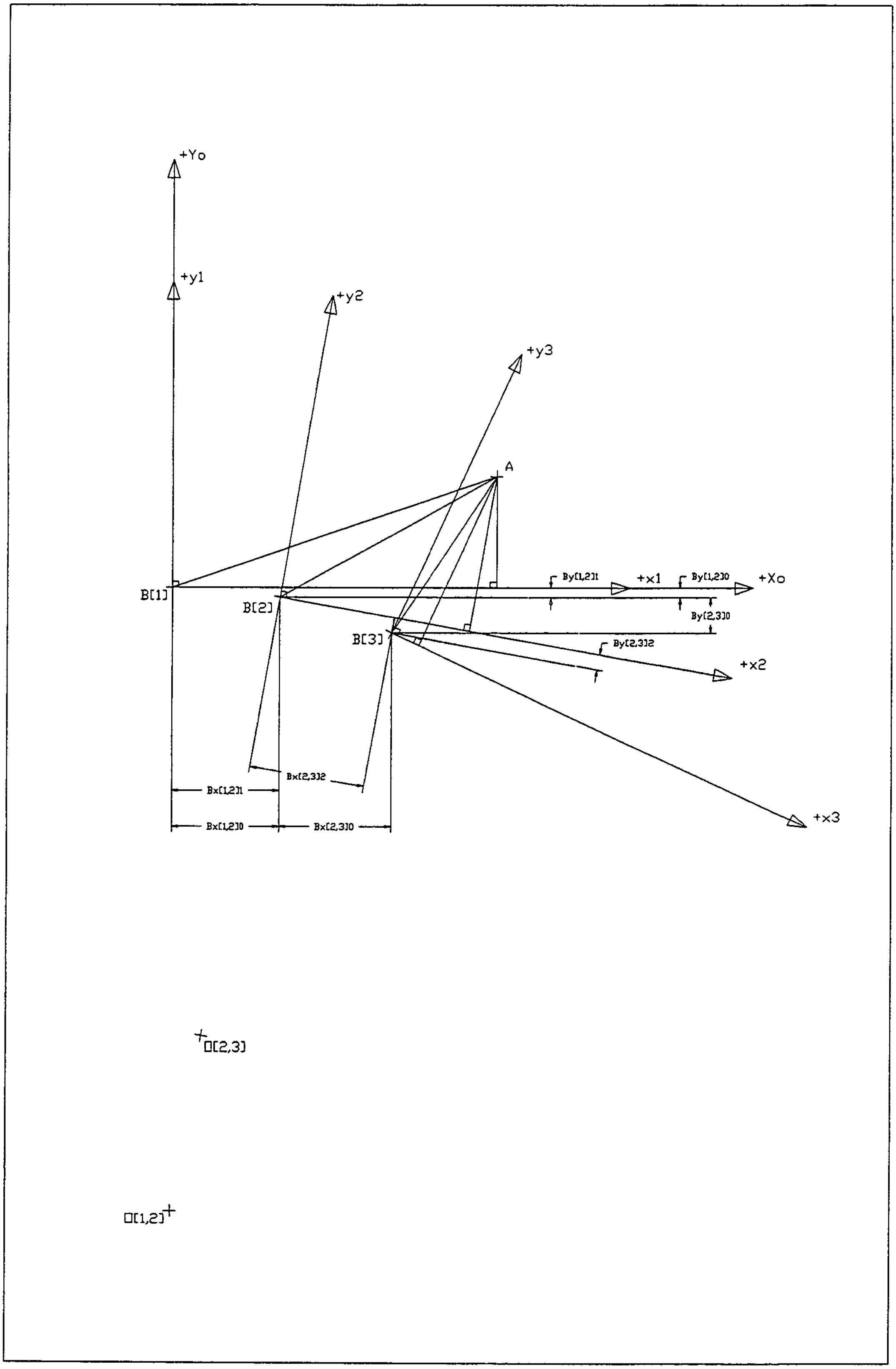


Figure C.3 - VOC system kinematics - Plate 3.

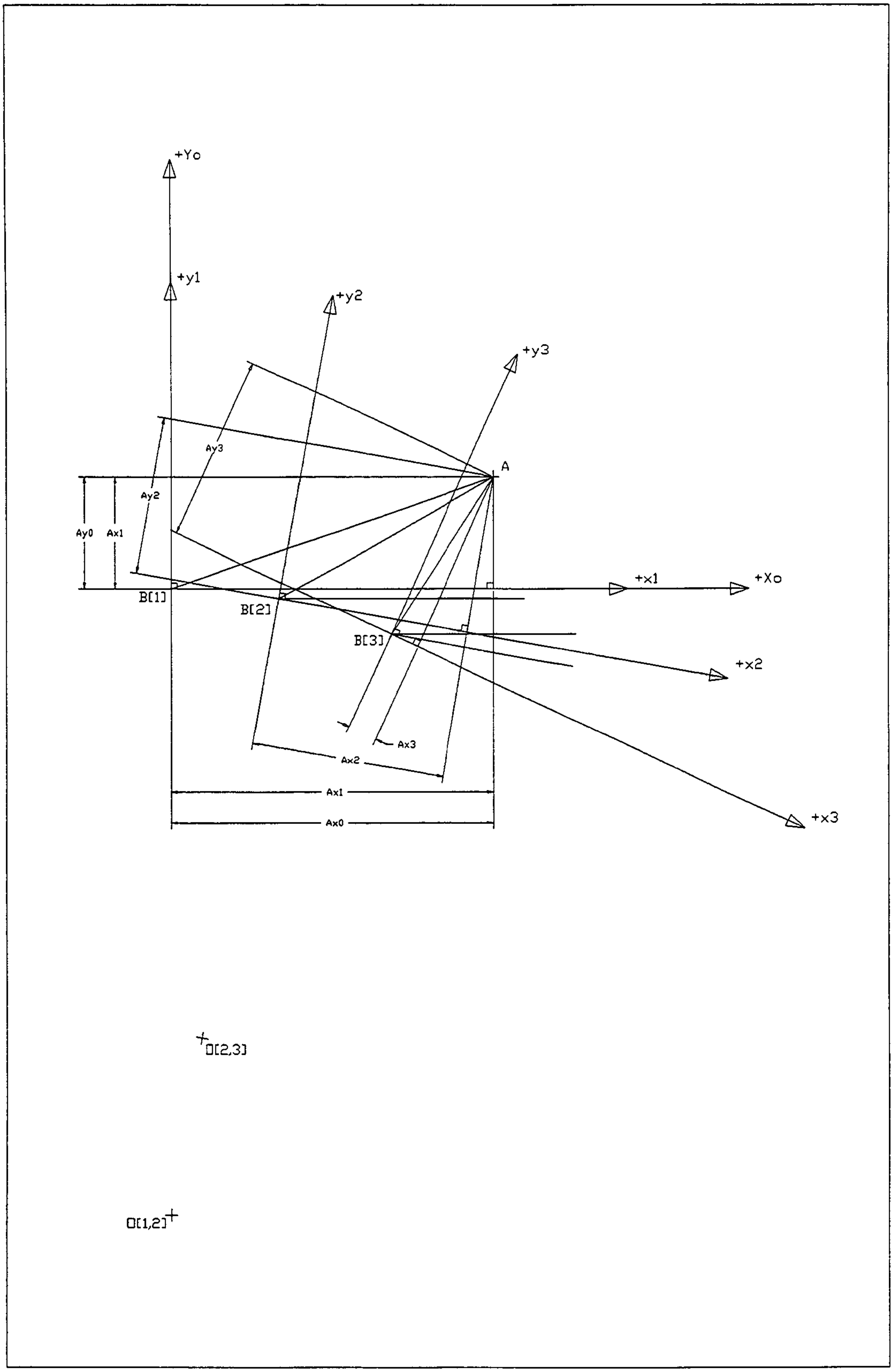


Figure C.4 - VOC system kinematics - Plate 4.

From C.2, it is seen that:

$$b_{[n]0} = \left(\frac{Ay_{[1]0} - DBy(cum)_0}{Ax_{[1]0} - DBx(cum)_0}\right). \tag{C.27}$$

Now, referring to C.4:

$$Ax_{[n]0} = \left(\sqrt{(Ax_{[1]0} - DBx(cum)_0)^2 + (Ay_{[1]0} - DBy(cum)_0)^2}\right) \cos(b_{[n]0}) \tag{C.28}$$

and

$$Ay_{[n]0} = \left(\sqrt{(Ax_{[1]0} - DBx(cum)_0)^2 + (Ay_{[1]0} - DBy(cum)_0)^2}\right) \sin(b_{[n]0}). \tag{C.29}$$

Substituting Eqn. C.27 into Eqns. C.28 and C.29,

$$Ax_{[n]0} = \left(\sqrt{(Ax_{[1]0} - DBx(cum)_0)^2 + (Ay_{[1]0} - DBy(cum)_0)^2}\right) \times \tag{C.30}$$

$$\cos\left(\frac{Ay_{[1]0} - DBy(cum)_0}{Ax_{[1]0} - DBx(cum)_0}\right).$$

refer to C.4

Similarly,

$$Ay_{[n]0} = \left(\sqrt{(Ax_{[1]0} - DBx(cum)_0)^2 + (Ay_{[1]0} - DBy(cum)_0)^2}\right) \times \tag{C.31}$$

$$\sin\left(\frac{Ay_{[1]0} - DBy(cum)_0}{Ax_{[1]0} - DBx(cum)_0}\right).$$

refer to C.4

Appendix D: Machine Subsystem Costs

TRUCK

	MTL	LBR HRS
White GMC Truck	$89,000	9
Truck Bed	$3,600	40
Operator Booth	$6,402	3
Operator Booth Skid	$850	8
Robot Mount (RPS)	$350	10
Communication System	$900	2
Elevated Walkway	$1,100	11
Propane Gas System	$350	5
	$102,552	88

Sell Price TRUCK $179,781

APS

1. Debris Removal System		MTL	LBR HRS
	Debris Separator (1)	$2,681	
	Blower (1)	$3,432	
	Misc. PVC Pipe, 3" dia.	$80	
	Misc. Flex. Hose, 2-3" ID	$268	
	Misc. Plumbing Connectors & Fasteners	$80	
	Misc. Hydraulic Hose & Fittings	$107	
	Misc. Electrical Wiring & Connectors	$27	
	Router Vacuum Hood (Custom made)	$50	8.6
		---------------	---------------
	sub total	$6,726	8.6
2. Burner			
	Fuel Train & Flame Safeguard System		
	Control Panel		
	Gas Pressure Switches		
	Gas Modulator		
	Ignition Transformer	$6,381	
	Burner		
	Eclipse Thermal Blast Air Heater/		
	CAT. No. 84-14TBH, 400 cfm	$5,000	
	Nozzle		
	Materials	$698	
	Welding/Machining		8
	Misc. Hardware/Plumbing		
	Est. Cost	$200	30
		---------------	---------------
	sub total	$12,280	38
3. Router			
	Router Assembly (assembled at UCD)	$1,200	96
	Hydraulic Motor	$234	
	Swivel casters Wheel Size (4 ea)	$191	
	Linear Actuator 3" stroke	$225	
		---------------	---------------
	sub total	$1,849	96

(APS continued next page)

APS continued

4 Sealant Applicator			
	Sealer Comp. replacement part	$7,200	
	1Worcester Pm15 S Positioner and 1 MK 191 Mtg Kit	$572	
	6 thompsom super-8 bearings	$95	
	2 Kaydon KA series angular contact ball bearings	$917	
	helicolies, etc.	$111	
	1 Bellofram I/P Type 1000 transducer	$268	
	Pneumatic cylinders	$170	
	1 90 turn intern pipe	$200	
	10 sst. spring #3 mixed assortment	$28	
	72" crimped steel wire brush	$207	
	linerar motion potentiometer	$212	
	O-ring assortment	$105	
	6 extension springs,20spring anchors	$43	
	1 flex shaft	$249	
	1 3/4 HP DC motor	$271	7.5
	sub total	$10,648	7.5
5. Generator System			
	25 KW Generator Model SD025G	$10,122	
	20x16x8 NEMA 12 Box with Window	$270	
	raceways, etc.	$863	
	labor		100
	sub total	$11,255	100
6. Sealant Melter			
	sub total	$25,450	24
7. Hydraulics			
	Hydraulic Pumping Unit	$19,620	4
	Hydraulic System Connections	$2,000	17
	sub total	$21,620	21

Sell Prices

Sealant Applicator	$18,556
Debris Removal	$11,983
Router	$9,643
Burner	$23,389
Generator system	$25,856
Sealant Melter	$44,762
Hydraulics	$38,067

RPS

	MTL	LBR HRS
1. GMF A-510 manipulator with 4 axes, inverted configuration	$56,250	5
2. A-510 RH KAREL Controller "C" size with KAREL software V.2.21	$31,250	2
3. Servo driven Robot Transport Unit with 50" of travel	$25,000	1
4. Serial Communications Option for KAREL controller	$1,000	1
5. 3.5" Serial Floppy Disk Drive	$3,750	
6. AD Module	$715	1
7. 8 bit DO module	$325	1
	---------------	---------------
	$118,290	11

Sell Prices		
For Commercial machine	RPS	$201,235
For unit designed for application		$143,927

LRPS

	MTL	LBR HRS
1.1 Longitudinal Machine Mechanical Assembly		
A. LRPS Frame Assembly Includes all items except Caster and Actuator.	$5,014	
B. Casters (Quantity 2)	$102	
C. Bearing Rails	$600	10
1.2 Hoist Frame and Hoist		
A. Frame-Materials precut(est. $100)	$100	
Labor for welding (in house) (estimate at 6 hrs ea.)		6
B. Hoist (2000 lb) Columbia Winch and Hoist H2000A1-01	$1,113	8
	$6,929	24
2.1 Control Computer/Hydraulics		
Rackmount 486 PC System	$2,150	3
Enclosure for 14" monitor	$195	
Upgrade Motherboard to 256K Cache	$85	
3.5" 1.44 NB Teac Floppy Drive	$48	
Sony GVM 1310 13" Video/Data Monitor	$992	
Inline VGA Cable for Sony GVM 1310	$38	
Actuator. Parker Hannifin F-style, Actuator, proportional valve and controller-PLA2X12LF7M10NB10	$7,684	3
	$11,192	6

Sell Prices	
Longitudinal Mach. Assy	$13,371
Control computer	$19,376

ICU

COMPUTER		
1. Hardware Components:	MTL	LBR HRS
Backplane (HSE/17R-12V-W60-F3-S150-Ethernet Cables)	$7,110	2
CPU Card (HK68H/V3E-16MB)	$8,700	
ANALOG I/O CARD (XVME540)	$1,800	1
DIGITAL I/O CARD (XVME201)	$375	1
COMMUNICATIONS CARD (CMC ENP-10)	$2,195	1
REAL TIME AUDIP VISUAL ENVIRONMENT (RAVE) AND MULTI MEDIA GRAPHICS CARD (MM1250)	$5,871	2
VT100 TERMINAL	$300	2
	$26,351	9
2. Software Components:		
OPERATING SYSTEM (OS-9 PROFESSIONAL VER. 2.4)	$1,950	2
SOFTWARE DRIVERS (ENP-10 AND XVME982)	$1,500	2
	$3,450	4
Grand Total	$29,801	13
ELECTRICAL INTEGRATION		
POWER		
Feeders		
raceways, etc.	$180	
conductors	$135	
labor		60
Loadcenter		
panel	$126	
breakers	$91	
labor		32
General Wiring Construction		
raceways, etc.	$3,195	
labor		200
Uninteruptible Power Supplies		
Smart-UPS 2000; American Power Conversion	$1,331	
labor		4
ELECTRONICS		
Electronics		
cable, connectors, components, etc.	$765	
labor		130
LPS MACHINE		
General		
labor		40
	$5,823	466

Sell Price ICU Computer $51,391 Electrical Integration $41,463

VSS

	MTL	LBR HRS
CAMERAS		
Line Scan Cameras Loral Fairchild CAM1301R, 2 ea	$3,100	5
PELCO Pressurized Camera Enclosures #EH8004/SPL, 2 ea	$968	
TV Lenses, JML P/N 71846 (12.5mm, F1.3), 2 ea	$200	
LIGHTFRAME		
Construction of lightframe and camera mounts	$9,975	
Floodlight fixture Hubble 14 ea @ $35.00	$490	
500 wat tunsten halogen lamp(clear); Phillips 500T3Q/CL FCL, 14 ea @ $12	$168	
RADSTONES		
OS-9 Development System	$22,320	2
cs-20 2/001 20 slot chassis with 1200W PSU, 6 slot VSB Backplane, WK-3/300 170MBYTE Hard Disk		1
68-3/300 CPU module with 4M RAM, 50 MHz		
OS-9 Professional Software		
ENET-1/100 112 Ethernet Card		
Memory Module, 8SB/201, 4MByte, Dual Port	$2,300	
Tape backup	$1,600	2
DATACUBE image processing system		
MAX-SCAN 10MHZ, 1 ea	$3,750	1
ROI STORE 2048, 2 ea @ $6750	$13,500	2
ROI STORE 512, 2 EA @ $3750	$7,500	2
FEATUREMAX MKII, 1 ea	$6,500	1
MAXGRAPH , 1 ea @ $1750	$1,750	1
8 MByte Memoty Module, 1 ea	$2,395	
cables	$350	
Manuals for all of the above	$150	
SOFTWARE		
IMAGE FLOW , 940-1001-HH-MM, 1 ea @$6,000	$6,000	4
CAMERA CONTROLLER BLOCK DIAGRAM		
Vibration Filter		
Etc.		
Totals	$83,016	21

Sell Price VSS $142,128

LSS

LOCAL SENSOR			MTL	LBR HRS
	Laser Vision System			
		Modular Vision Systems, Inc. Part # MVS-30	$24,035	
		Software		2
		Comunication		1
		Install Hardware		1
		Mounting Hardware		8
			--------------	--------------
			$24,035	12

Sell Price LSS	$41,550

VOC

VOC System			MTL	LBR HRS
	Custom parts fabricated by machine shop		$5,294	
	Encoder Wheel, 2 ea @ $135		$290	
	Encoder, 2 ea @ $700		$1,502	
	Bearing - Encoder Shaft			
		Timken- tapered roller, cup, 4 ea @ $5	$21	
		Timken- tapered roller, cone, 4 ea @ $10	$43	
	Seal- Encoder Shaft, 1.5" ID, 4 ea @ $3		$13	
	Spacer- Encoder Shaft, 1.25" ID, 1.5"ODx0.4" long, 4 ea @ $2		$9	
	Bearing - Link Mount, Pillow block, 1" DIA., 8 ea @$24		$206	
	Computer Counter Card, XVME 230 , 1 ea @ $1500		$1,609	5
	Computer Cable, 1 ea @ $50		$50	1
			--------------	--------------
			$9,036	6
	Install on truck			15
			--------------	--------------
		Grand Total	$9,036	21

Sell Price VOC	$16,739

Appendix E: Cost/Benefit Analysis Spreadsheet

◦ COST SAVINGS ANALYSIS ◦

Crack Sealing System

Crack Sealing System	Current System Costs	Proposed System Costs
• Platform	$0	$250,000
• Additional Equipment	$0	$300,000
• Operational Cost	$45,000	$45,000
• Material Cost	$90,000	$90,000

ASSUMPTION

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

DIFFERENTIAL COST BETWEEN SYSTEMS = $550,000

◦ COST SAVINGS ANALYSIS ◦

CASE 1

ASSUMPTIONS	
NO SPEED ADVANTAGE (1-2 Miles per Day)	
(1) EXISTING AVERAGE NUMBER OF PERSONS / CREW	8
(2) AVERAGE LABOR COST / PERSON / YEAR	$50,000
PROPOSAL	
(3) NEW AVERAGE NUMBER OF PERSONS/ CREW	4
RESULTS	
(4) EXISTING AVERAGE LABOR COST / YEAR = [(1)*(2)]	$400,000
(5) NEW AVERAGE LABOR COST / YEAR = [(2)*(3)]	$200,000
AVERAGE LABOR COST SAVINGS / YEAR = [(5)-(4)]	**$200,000**

CASE 2

ASSUMPTIONS	
SPEED ADVANTAGE (Up to 4 Miles per Day)	
(6) NEW AVERAGE LABOR COST / YEAR	$200,000
PROPOSAL	
(7) % LABOR COST REDUCTION DUE TO SPEED ADVANTAGE	30.00%
RESULT	
ADDITIONAL NEW AVERAGE LABOR COST SAVINGS / YEAR = [(6)*(7)]	**$60,000**

◦ COST SAVINGS ANALYSIS ◦

CASE 3

	Time	Year	% Time / Year
ASSUMPTIONS			
BETTER QUALITY OF PERFORMANCE (Reduced frequency of operation)			
(8) AVERAGE FREQUENCY OF MAINTENANCE	1	2	50.00%
PROPOSAL			
(9) NEW FREQUENCY OF MAINTENANCE	1	3	33.33%
RESULTS			
(10) % FREQUENCY MAINTENANCE SAVINGS / YEAR = [(9)-(8)]	16.67%		
(11) MATERIAL COST / YEAR	$90,000		
FREQUENCY MAINTENANCE MATERIAL COST SAVINGS / YEAR = [(10)*(11)]	**$15,000**		

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

◦ SUMMARY ◦

ASSUMPTIONS

Inflation Rate (e) = 5.00%

Cost of Money (i) = 10.00%

Corrected Value (i') = i + e + ie = 15.50%

CASE 1

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
AVERAGE LABOR COST	$400,000	$420,000	$441,000	$463,000
LABOR COST SAVINGS	$200,000	$210,000	$221,000	$232,000
DIFFERENTIAL COST / YEAR	$550,000	($368,000)	($166,000)	
ACTUAL SAVINGS /YEAR	($350,000)	($158,000)	$55,000	$232,000
NET PRESENT VALUE = A(P/A, i'%, n) - Initial Investment	$437,000			

CASE 2

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
NEW AVERAGE LABOR COST	$200,000	$210,000	$221,000	$232,000
ADDITIONAL LABOR COST SAVINGS	$60,000	$63,000	$66,000	$70,000
DIFFERENTIAL COST / YEAR	$550,000	($305,000)		
ACTUAL SAVINGS /YEAR	($290,000)	($32,000)	$287,000	$302,000
NET PRESENT VALUE = A(P/A, i'%, n) - Initial Investment	$733,000			

◦ SUMMARY ◦

CASE 1

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

CASE 2

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

◦ SUMMARY ◦

CASE 1

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

CASE 2

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

◦ SUMMARY ◦

CASE 3

	YEAR 1	YEAR 2	YEAR 3	YEAR 4
LABOR COST SAVINGS	$200,000	$210,000	$221,000	$232,000
ADDITIONAL LABOR COST SAVINGS	$60,000	$63,000	$66,000	$70,000
MATERIAL COST	$90,000	$95,000	$100,000	$105,000
MATERIAL COST SAVINGS	$15,000	$16,000	$17,000	$18,000
SYSTEM SAVINGS / YEAR	$275,000	$289,000	$304,000	$320,000
DIFFERENTIAL COST / YEAR	$550,000	($289,000)		
ACTUAL SAVINGS /YEAR	($275,000)	$0	$304,000	$320,000
NET PRESENT VALUE = A(P/A, i'%, n) - Initial Investment	$807,000			

◦ SUMMARY ◦

CASE 3

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

◦ SUMMARY ◦

CASE 3

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

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