TACTILE DISPLAY SYSTEM

for a WHOLE-ARM MANIPULATOR

Phase II SBIR Final Report

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TACTILE DISPLAY SYSTEM

for a WHOLE-ARM MANIPULATOR

Phase II SBIR Contract NAS9-18901

Project Summary

The objective of this Phase II program was to design a second-generation Tactile Display System (TDS) suitable for teleoperator control of a dual whole-arm manipulator (WAM) and other teleoperation or simulation tasks involving tactile interaction with real or virtual environments. The principal tasks performed were: (1) Design a complete WAM TDS based on the experience and results obtained in Phase I; (2) Fabricate and assemble the new TDS; (3) Evaluate the performance of the TDS using synthetic and/or real tactile sensor signals. These tasks and program objectives were achieved and a complete turnkey TDS was fabricated and delivered to the sponsoring organization.

The tactile display consisted of an elastic fabric suit worn on the upper torso, and contained a total of 512 tactile display elements (taxels) housed in eight modular display panels distributed over the forearms (2 panels), upper arms (2), upper chest (2) and stomach (2). Each taxel measured ∅11.8 mm by 5 mm high, and was operated in a vibratory mode (4.5 Hz) with a variable displacement amplitude from 0-3.5 mm. The taxels were attached to the suit fabric by removable clips, thereby allowing great flexibility in creating taxel distributions optimized for particular applications. The TDS suit could be donned/doffed in 10/2 minutes, respectively, and was found to generate robust tactile stimulation signals even through multiple layers of intervening fabric.

Potential commercial markets for this technology include remote manipulation of large objects in vacuum, toxic, underwater, or thermally-extreme environments, e.g., space operations involving satellite deployment, capture, and repair, space habitat construction and maintenance, or space exploration; handling of toxic chemical or biological materials; undersea mining or salvage operations; handling of hot objects during manufacture; and various operations in cold-weather regions.

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GLOSSARY

DPS	"Display Power Supply," referring to the separate 24 VDC supply used to power only the tactile display valves.
PCB	"Printed Circuit Board"
PWM	"Pulse Width Modulation:" a general control scheme in which the duty cycle (ON time) is varied during each control period. For the tactile display valves, the duty cycle is limited by hardware to vary between 0-10%, whereas the control period is 222 ms (4.5 Hz).
SCSI	"Small Computer System Interface."
SMT	"Surface Mount Technology"
Taxel	Abbreviation for "tactile element" that represents a touch display or touch sensing element, depending on the context. Term chosen for close analogy with the visual term "pixel" which represents a "picture element" in a visual sensor or display unit.
TDP	"Tactile Data Processors," referring to the four processors used to directly generate or to acquire, calibrate, process, and output real or synthetic tactile data to the tactile display drivers.
TDS	"Tactile Display System," referring to the system developed and delivered on this program.
WAM	"Whole-Arm Manipulator," referring to a telemanipulation system that utilizes multiple arms to perform remote grasping and manipulation tasks under human control.

1. INTRODUCTION

1.1 Program Objectives:

The objective of this Phase II program was to design and fabricate a second-generation Tactile Display System (TDS) suitable for teleoperator control of a whole-arm manipulator (WAM).

1.2 Program Tasks:

The principal tasks addressed in this project were:

1. Design of a second-generation TDS, concentrating on optimizing such factors as the taxel performance, taxel mounting methods, and suit design amenable to convenient system use, maintenance, and repair at the customers facility.

2. Fabrication of a TDS for the upper torso and arms suitable for extended use in a telerobotics research facility.

3. Evaluation of the TDS system with regard to proper functionality of each taxel.

1.3. Program Results:

A photograph of the successfully-completed TDS with 512 taxels is shown in **Figure 1**, and the general display system characteristics summarized in **Table 1**. The basic tactile display elements consisted of inflatable pneumatic bladders packaged into small, independently-mountable plastic disc-shaped bodies (∅11.8 mm x 5 mm thick). The taxels were mountable by means of metal snaprings (C-Clips), and were capable of generating an analog vibratory tactile output (3.5 mm maximum displacement) through PWM control at a base frequency of 4.5 Hz. The taxels were grouped into display modules or panels containing 64 taxels each, and the panels attached by zippers and/or Velcro straps to the surface of the suit (which could be any elastic fabric garment, such as a long-sleeved SPANDEX bicycling shirt) to cover the forearms, upper arms, chest, and stomach areas of the wearer. After the initial custom-fitting of the zippered panels to each user's personal undergarment, it is possible to achieve assisted suit donning/doffing times of 15/5 minutes. The display accepts analog driver signals (0-5 VDC) from external real or virtual sources (e.g., tactile sensor arrays, or a VR system), or can generate them internally for system testing purposes. Qualitative testing indicated the taxel stimulation intensity were very high, being readily perceptible even through multiple layers of fabric on the wearer's body.

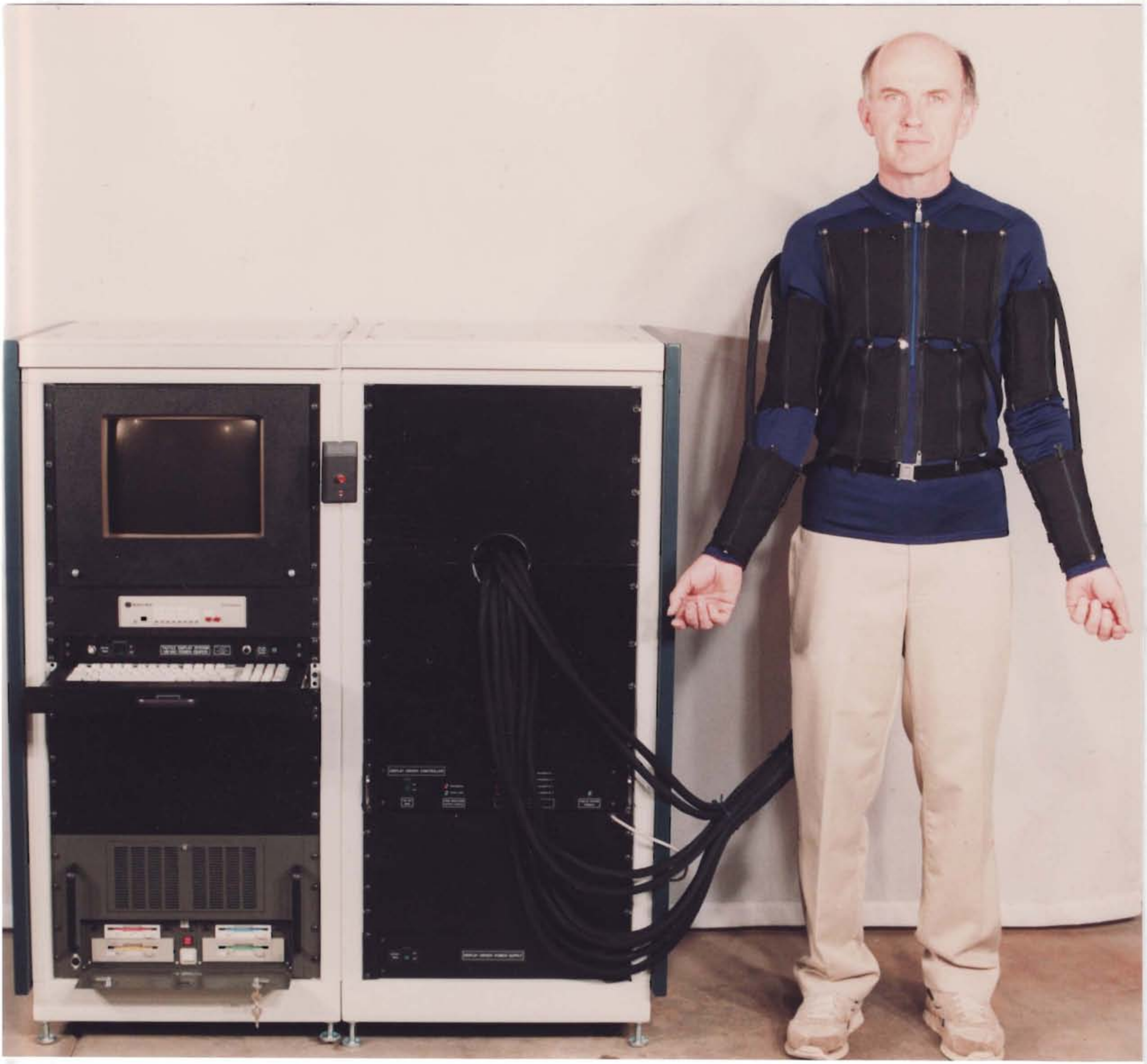


Figure 1: Tactile Display System developed under this Phase II program. Shown are the tactile display suit (right), tactile display driver cabinet (center) and tactile sensor data signal conditioner cabinet (left). The tactile display suit contains 512 taxels distributed over the arms, chest, and stomach areas by display panels containing 64 taxels each. Photo WAM-200696A-16.

Table 1: General features and performance characteristics of the Tactile Display System developed during this contract.

Display Array Configuration	Elastic fabric suit covering front of torso and arms
Number of Taxels	512 total
Taxel Dimensions	Ø11.8 mm x 5 mm thick
Taxel Actuation Mechanism	Pneumatic inflation of a silicone membrane. Inflation amplitude regulated by PWM control at 4.5 Hz. Maximum duty factor set in hardware to 10% corresponding to maximum permitted taxel inflation level (3.5 mm).
Taxel Operating Pressure	650 kPa (95 psi). Vacuum may be optionally applied at the display driver exhaust port to improve response time.
Taxel Actuation Displacement	0-3.5 mm (max)
Taxel Control Signal	Analog voltage 0-5 VDC
Taxel Mounting	Attached via snaprings to any location on an elastic fabric display garment or display panel module
Taxel Distribution	Eight display array panels containing 64 taxels, each panel capable of being zippered into position on the arms, chest, or stomach areas
Taxel Panel Description	64 taxels arranged on a 6 x 11 array 15 mm center-to-center taxel spacing Zippers on side for rapid donning/doffing of suit
Taxel Panel Placement	R and L Forearms: 2 (64 taxels per arm) R and L Upper arms: 2 (64 taxels per arm) Chest: 2 (one panel per side) Stomach: 2 (one panel per side)
Panel Attachment Methods	Arms: Zipper into adjustable Velcro straps Chest and Stomach: Zippered directly onto front of suit
Suit Fitting	Each suit user has own elastic fabric garment to which zipper tabs are attached in a custom manner reflecting desired positioning of display panels. Garment may be laundered in normal manner to maintain high levels of personal hygiene among multiple operators.
Donning/Doffing Time	Donning of fitted suit: 10 minutes with assistance Doffing of suit: 2 minutes with assistance
Operator Ranging Distance	1.2 m from display driver cabinet

In addition to the features mentioned above, the development and use of individually-mountable taxels was the primary technical innovation responsible for a variety of other important display suit features. In contrast to the Phase I TDS, the taxels are individually repairable at the customers facility without the need for assistance or return of the suit to the manufacturer. To minimize the need for repair, the taxel lifetime was improved during this program from a few hours for the Phase I design to a minimum of 2000 hours at the maximum activation amplitude of 3.5 mm, thereby insuring long and trouble-free service in a R&D environment. Additionally, the size and distribution of the taxels over the display undergarment is theoretically unlimited because of the snapring mounting method, thereby allowing considerable flexibility to address present and future TDS applications , e.g., WAM teleoperator control and tactile feedback from synthetic environments.

Section 2 describes work performed developing a new taxel and display suit for the Phase II program, and Section 3 describes the design and fabrication of new tactile display driver modules. The electrical and computer control components are described in Section 4 and 5 respectively. The conclusion are presented in Section 6, and suggestions for future research and work summarized in Section 7. Appendix A, B, and C contain the detailed mechanical and electrical drawings pertaining to various components of the TDS, whereas Appendix D contains a brief Users Manual pertaining to the operation of the TDS.

2. TAXEL DEVELOPMENT

2.1. Review of Past Work

The Phase-I effort preceding this work resulted in the implementation of a first-generation tactile display for the forearm, as shown in **Figure 2** and **Figure 3**, respectively. This prototype successfully demonstrated the feasibility of the tactile display concept and was able to produce robust tactile stimulation of the skin even through one or more layers of clothing. However, after evaluation of the display during development and subsequent customer feedback, several design deficiencies were noted:

1. The taxel lifetime was found to be only 5-10 hours at the maximum actuation level, with failure occurring by the gradual growth of the effective taxel diameter until neighboring taxel failure zones on the taxel strip intersected. This failure mechanism was attributed to the presence of high crack-root stresses at the bond line that resulted in tear-failure of the silicone adhesive material.

2. The taxels were susceptible to failure by ballooning from inadvertent over-pressurization or valve controller failure.

3. The approach of using a modular tactile display strip to array fabrication significantly limited the array flexibility and the selection of taxel size, location, and density. A system allowing for relatively unrestricted placement of variously-sized taxels would be much preferred.

4. Donning and doffing the display array required assistance and was slow due to the large number of VELCRO® straps that had to be adjusted for each dressing operation.

5. No provisions were made for the maintenance of adequate levels of personal hygiene, as the display attachment straps were not removable or conveniently launderable.

To address these problems, a new taxel was eventually developed based on the concept of a removable taxel disc or button attached to an elastic fabric substrate or garment using expandable metal snaprings (also called cliprings or C-clips). The new taxel, coupled with a new garment design, effectively addressed the above deficiencies:

1. The taxel lifetime was extended to be in excess of 2000 hours at maximum excursion, or over one year of continuous use 8 hours per day.

2. Taxel ballooning was effectively constrained by the elastic fabric to which the taxel was attached. Once a relatively fixed amount of fabric expansion had occurred, the elastic fabric stopped stretching, thereby limiting further expansion by the underlying taxel membrane.

3. The taxel buttons could be produced in a great variety of sizes and shapes, and could be placed anywhere on the display undergarment or panel. (However, for reasons of convenience, only one taxel size measuring ∅11.8 mm was chosen and distributed over a rectangular array pattern in this Phase II program).

4. The assisted donning and doffing time for a 512 taxel display garment was found to be only 10 and 2 minutes, respectively, and was achieved through the use of eight modular tactile display panels attached by zippers sewn onto the display undergarment.

5. High levels of personal hygiene are possible, as the display undergarment (i.e., the fabric actually in contact with the skin) is separated from the display panels during every donning and doffing operation, and is constructed to be readily launderable.

The following sections present the details of the development effort and the results obtained.

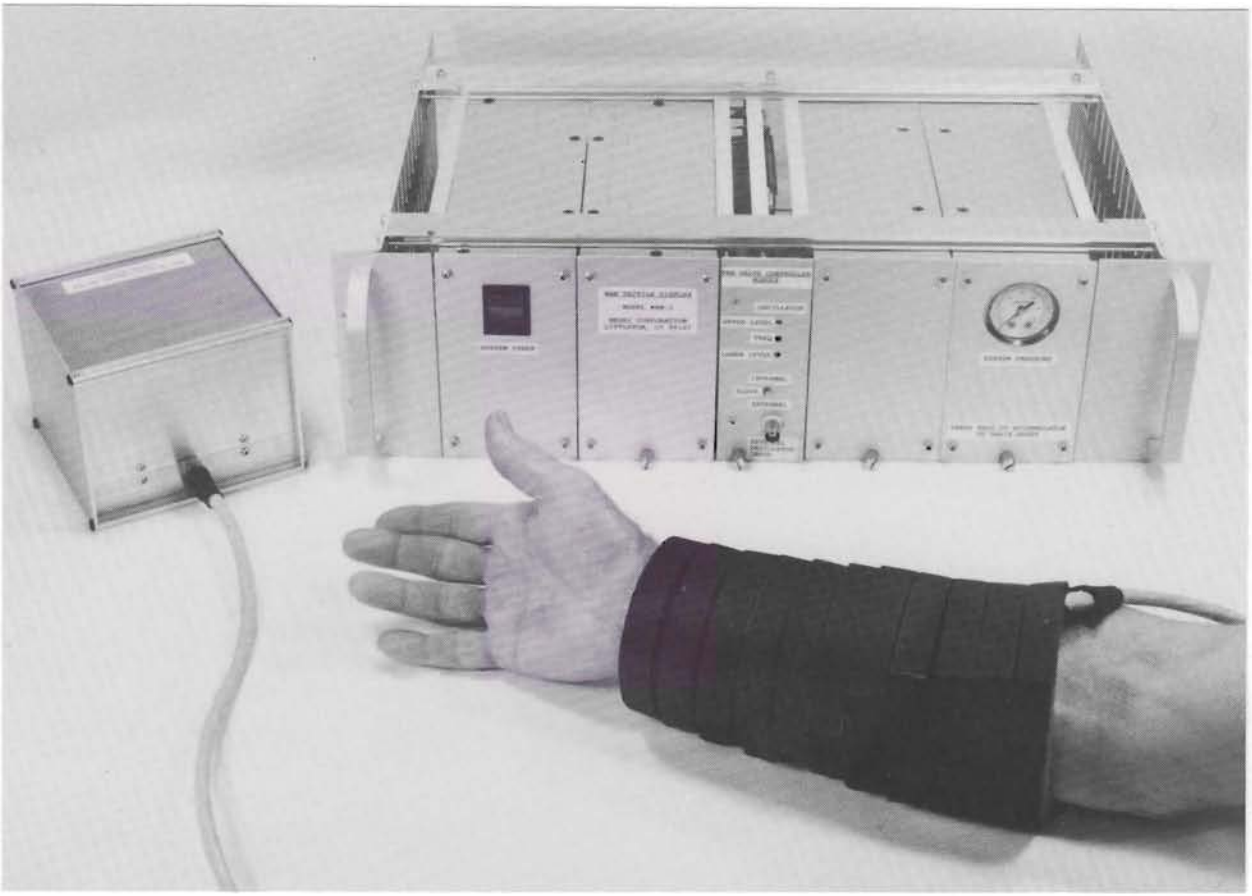


Figure 2: Phase I version of the WAM forearm tactile display being worn by an operator. The 55 taxel display consisted of 11 independent strips, each strip containing 5 taxels, and was designed to maintain taxel registry with the skin during wrist and arm rotations. Photo WAM-070892-25.

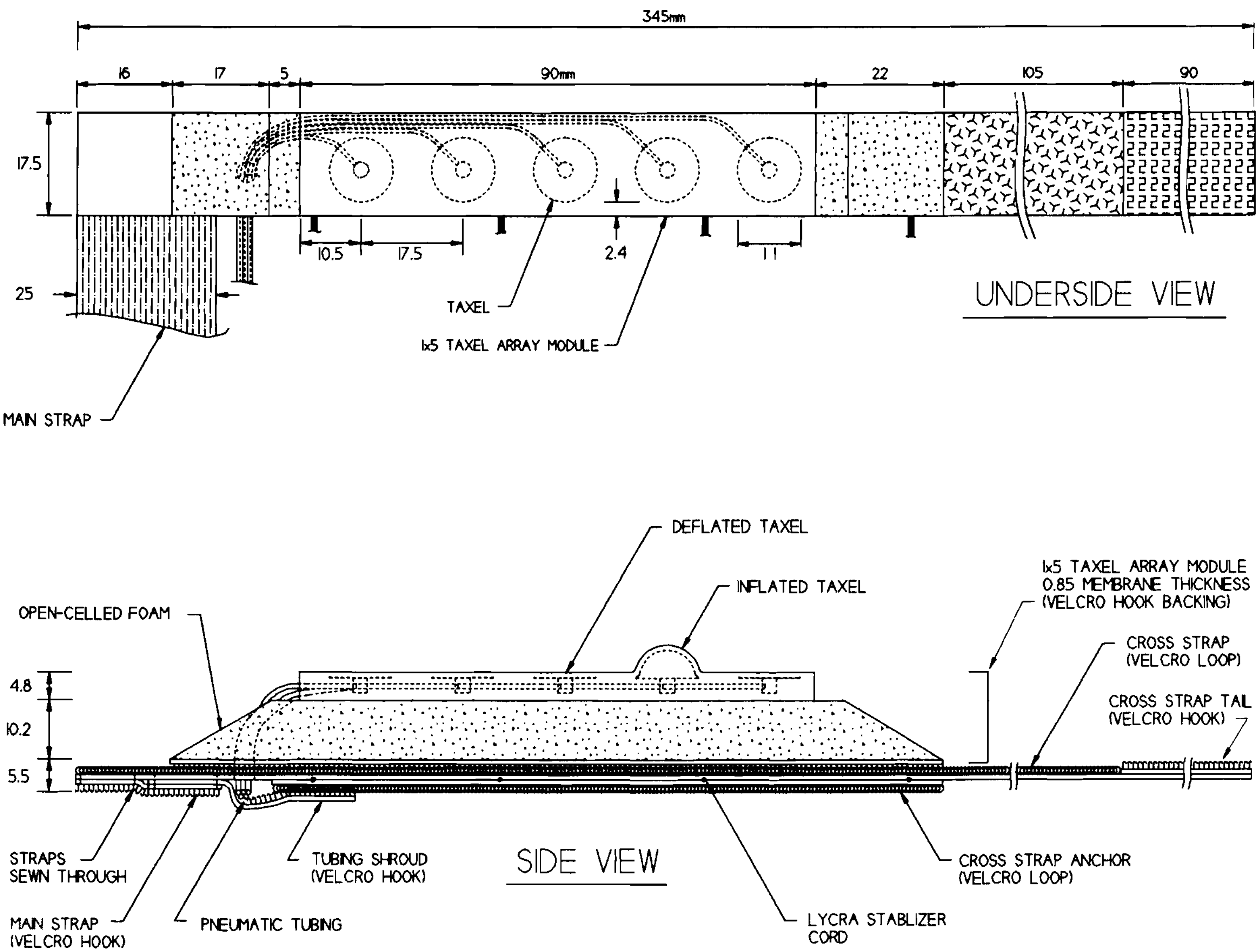


Figure 3: Each tactile display strip in the Phase I WAM tactile display was a module containing 5 taxels integrally bonded to a foam backing pad and VELCRO® attachment straps. The effective taxel diameter was 11.0 mm, with both the taxel membrane and body being fabricated from silicone sheet stock. Drawing WAM-TD03.

2.2. Taxel Evaluation Tools

During the Phase I effort, it was realized that a necessary taxel evaluation tool would be a method for monitoring the profile or height of the taxel during operation. A simple mechanical cantilever sensor was utilized in Phase I to give qualitative results useful for comparison purposes, but this was considered insufficiently accurate for the Phase II effort where a measurement range of -2 mm to +8 mm with a frequency response of DC - 250 Hz was deemed necessary.

Various approaches to measuring the membrane height were considered and/or evaluated. Any system involving mechanical contact was quickly dismissed due to the possibility of mechanical interference during measurement and relatively slow response time. A video system was also considered in which the silhouette or shadow of the inflated taxel dome was captured and analyzed, but this approach was also abandoned as it was too expensive to procure a high frame-rate video system. A simplified version using a linear CCD to monitor only the shadow of the dome peak was also considered, but eventually also abandoned due to the difficulty of positioning such a device in close proximity to a completed taxel array and the impossibility of measuring negative excursions (concavities) in the taxel dome structure.

The method finally selected to measure taxel dome motions was a laser displacement sensor by manufactured by KEYENCE, sensor head Model LB-12 and controller LB-72. This main features of this device are summarized below:

Measurement Method:	Optical triangulation using 3 mW laser
Standoff Distance:	40 mm
Displacement Measurement Range:	+/- 10 mm
Displacement Resolution:	0.015 mm
Measurement Spot Size	1 mm
Frequency Response Range	0 - 200 Hz
Linearity:	1% of Full Scale

The sensor was mounted on a vertical linear slide and the taxel under test placed underneath the laser measurement spot. The sensor output (+/- 4 VDC) was fed into a PC-based digitizing scope card (COMPUSCOPE CS LITE) for data viewing and storage. The taxels under test and evaluation were driven by a single valve manifold specifically assembled for this purpose, where the PWM base frequency could be conveniently varied by means of a stable function generator (HEWLETT PACKARD 3310A).

An initial concern with this type of optical sensor was that the surface of most elastomers under evaluation as candidates as taxel membranes were partially translucent and thus would not provide a well-defined image spot. However, in practice this did not prove to be a problem as it was possible to attach a small white piece of paper to the center of each taxel, thereby providing a standard target regardless of the specific taxel construction details.

In addition to allowing characterization of taxels under development, the laser displacement station was used to perform accelerated lifetime tests on taxels to evaluate such issues as adhesive strength and interfacial abrasion between the taxel membrane and associated elastic cover fabric. In such cases, the PWM frequency was increased from 5 Hz to 12 Hz and the amplitude of the taxel displacement adjusted to the maximum value (3.5 mm). In order to minimize the possibility of adverse thermal effects from frictional heating of the taxel cover and membranes, a fan was used to direct cooling air over the taxel during lifetime testing.

2.3. Initial Taxel Design

Taxel development began with a list of general features and performance requirements pertinent to this Phase II program:

- Taxels must generate very high tactile displacements (2.5 mm minimum) with sufficient force to be readily perceptible through several layers of clothing or intervening fabric.

- Tactile display must be repairable by the customer at the customer's facility.

- Long taxel lifetime (1 year of continuous use).

- Rapid donning and doffing of the display suit (preferably without the use of an assistant)

- Cognizance of personal hygiene issues (i.e., few would care to don an item of clothing previously worn for several weeks straight by another co-worker).

The initial concept that emerged from consideration of this list was that of an elastic fabric suit to which modular, discrete taxels could be readily attached or removed. This permitted every user to have their own display suit garment which could, if necessary, be removed from the system and laundered after each use, thereby maintaining a relatively high level of personal hygiene. The specific taxel design or mechanism of attachment was not clear, however, and much of the subsequent development work concentrated on refining this suit concept and developing the means of implementing it in a practical manner. The expandable elastic fabric substrate was considered an integral part of the taxel, and was designed to provide a physical restraint against uncontrolled taxel membrane inflation (a common mode of failure of past taxels).

A significant effort was devoted early in this program to developing a simple but reliable method of attaching the taxel to the elastic fabric. Many types of circular attachment hardware was considered, procured and/or fabricated, and examined (e.g., shim washers, metallic rings, spiral rings and snaprings) until two candidates remained, these being the flexible metallic ring (dubbed the "flexring") and the ubiquitous snapring. The flexring approach was initially favored for the aesthetically compact and eye-pleasing appearance of the installed taxel arrays and for the elegant method of ring installation (which required simultaneously rolling, bending, and pushing the ring over the cloth into the taxel groves). However, as revealed in the following sections, the flexring technology could not be satisfactorily developed with the available resources, and was eventually eclipsed and replaced by the bulkier and less visually aesthetic snapring approach that was undergoing parallel development and evaluation.

2.4. Flexring Taxel Version

Figure 4 to **Figure 7** illustrate the final design of the flexring taxel and associated components. The term "flexring" comes from the use of a thin, smooth rings to attach the taxel to the elastic fabric of the display undergarment (or intermediate display panel) and - in the conceptual design discussed here - to also attach a cover garment to the back of the taxel to hide the pneumatic tubing from view and to provide a more aesthetic appearance to the tactile display suit. The chief advantages of the flexring approach to taxel attachment were pleasing visual aesthetics after installation and light weight.

The taxel body may be fabricated from any common plastics, as prototypes had been machined from ABS, hard urethane, and polycarbonate, as well as cast from various epoxies. The taxel membrane disc was cut from standard, commercially-available silicone sheet stock (CHR-300, 0.76 mm thick) and bonded to the inside cavity of the taxel with silicone gel adhesive (DOW 732). Significant effort was devoted to developing an adhesive application procedure utilizing a motor-driven syringe dispenser system, but the large size of the dispenser head and lack of adequate flow control led to the eventual abandonment of this approach. Satisfactory yields were eventually obtained using a simple manual syringe to apply adhesive to a taxel body mounted on a miniature, motorized rotary stage.

Commercial sources of flexrings were initially considered, but the cost and lead-time to procure the minimum quantities of rings in an appropriate range of sizes needed for this program were deemed inappropriate for the R&D phase of taxel development the program was in. For this reason, various methods of fabricating the flexrings in-house were developed.

The flexring illustrated in **Figure 7** was fabricated by lathe-cutting thin rings from a brass tube of the appropriate inner and outer dimensions. Deburring the rings proved to be a very difficult problem, however. Another approach to flexring fabrication was to make them from rings of music wire with the ends brazed together: This approach avoided much of the deburring problem, as the round wire and smooth joint did not require much if any finishing. However, it was difficult to achieve repeatable ring dimensions, avoid thermally damaging the ring material, and to maintain the necessary brazing skills.

The most troublesome aspect of developing a flexring fabrication procedure was removal of sharp burrs at the ring edges. Traditional methods such as tumbling or vibration in various media were initially tried, but the rings were found to be too delicate and it was not possible to find tumbling parameters (e.g., media type and mix, tumbling speed, vibration intensity, and time) that would provide the needed deburring without also bending or twisting the rings. More time-consuming manual methods involving wire-wheels, filing, and sandpaper mandrels were also tried and found to be more successful, but still not entirely satisfactory due to the difficulty of holding the relatively delicate ring while processing it. The best process that was developed involved placing a number of rings on a mandrel (e.g., a threaded rod) rotating at high speed and allowing the rings to bounce around for an hour or so. Even this was not ideal, as approximately half of the rings still needed to be completed manually due to the non-uniform nature of edge burring.

After significant investment of development time, the full difficulty of the flexring development task was more clearly realized. It was discovered that a large number of variables had to be carefully balanced for proper taxel retention:

- Elastic fabric thickness and its behavior as a function of strain
- Taxel flexring groove dimensions and edge radii
- Taxel material mechanical properties (stiffness)
- Flexring mechanical properties (stiffness)
- Flexring dimensions and edge radii.

The reliability of taxel retention was found to be a delicate function of these parameters, and it was not possible to find a combination that would provide taxel retention with the range of SPANDEX® thicknesses that were expected to be encountered. This raised the undesirable scenario of requiring a variety of snapring sizes to accomplish taxel mounting on various substrate fabrics. Additionally, even a well-sized flexring was found to require significant skill and mechanical dexterity to install and uninstall without damaging the ring, the fabric, or the underlying taxel.

In conclusion, the competition between the two taxel retention methods was eventually won by the snapring design primarily because such taxels could be reliably anchored to a wide variety of cloth substrate weights (thicknesses), in addition to the ready availability and low cost of snaprings from numerous commercial sources.

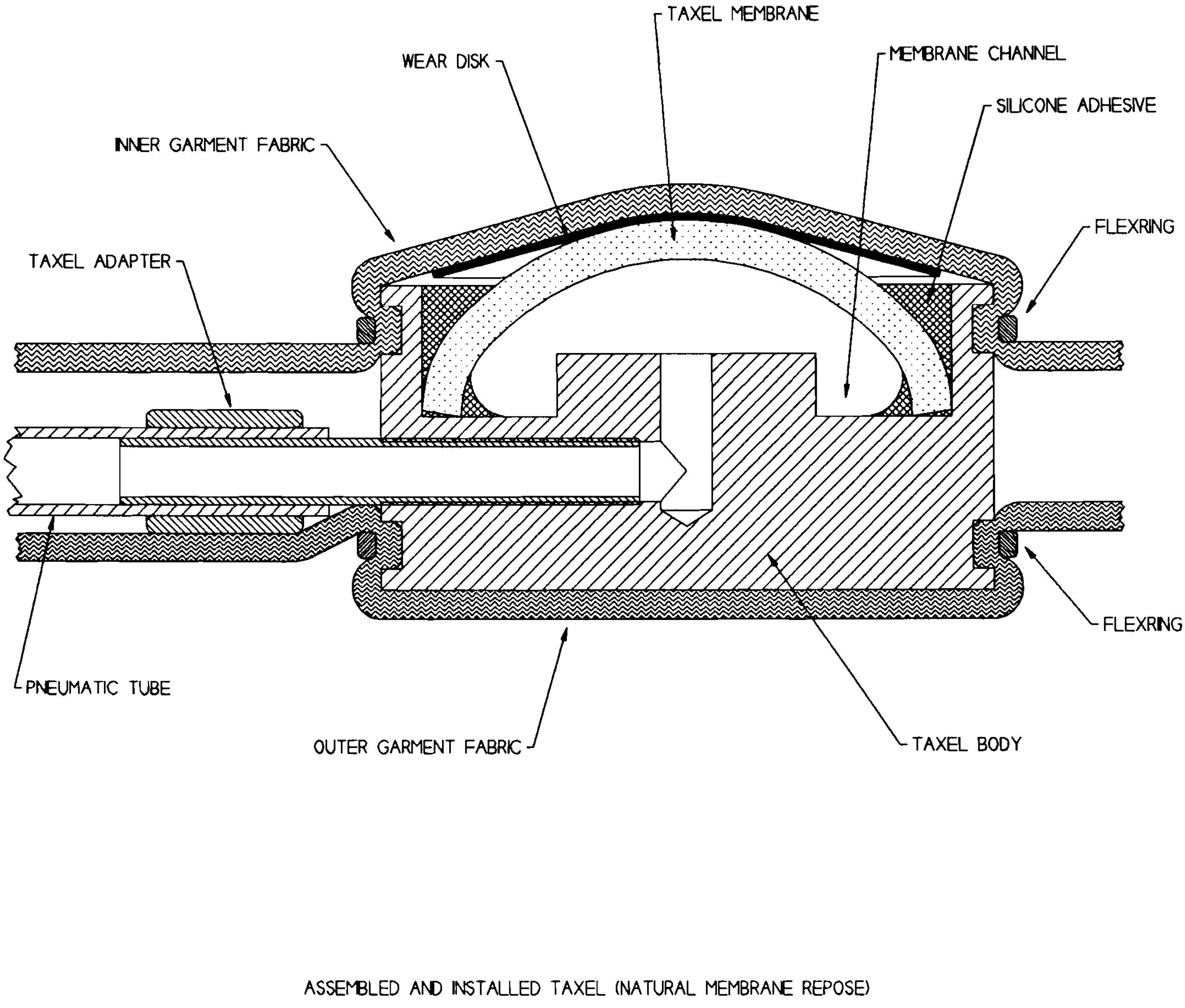


Figure 4: Flexring version of a tactile display element in which both the front and back panels of the mounting fabric are directly attached to the taxel using flexrings. Scale 8X. Drawing TDRV3128-2.

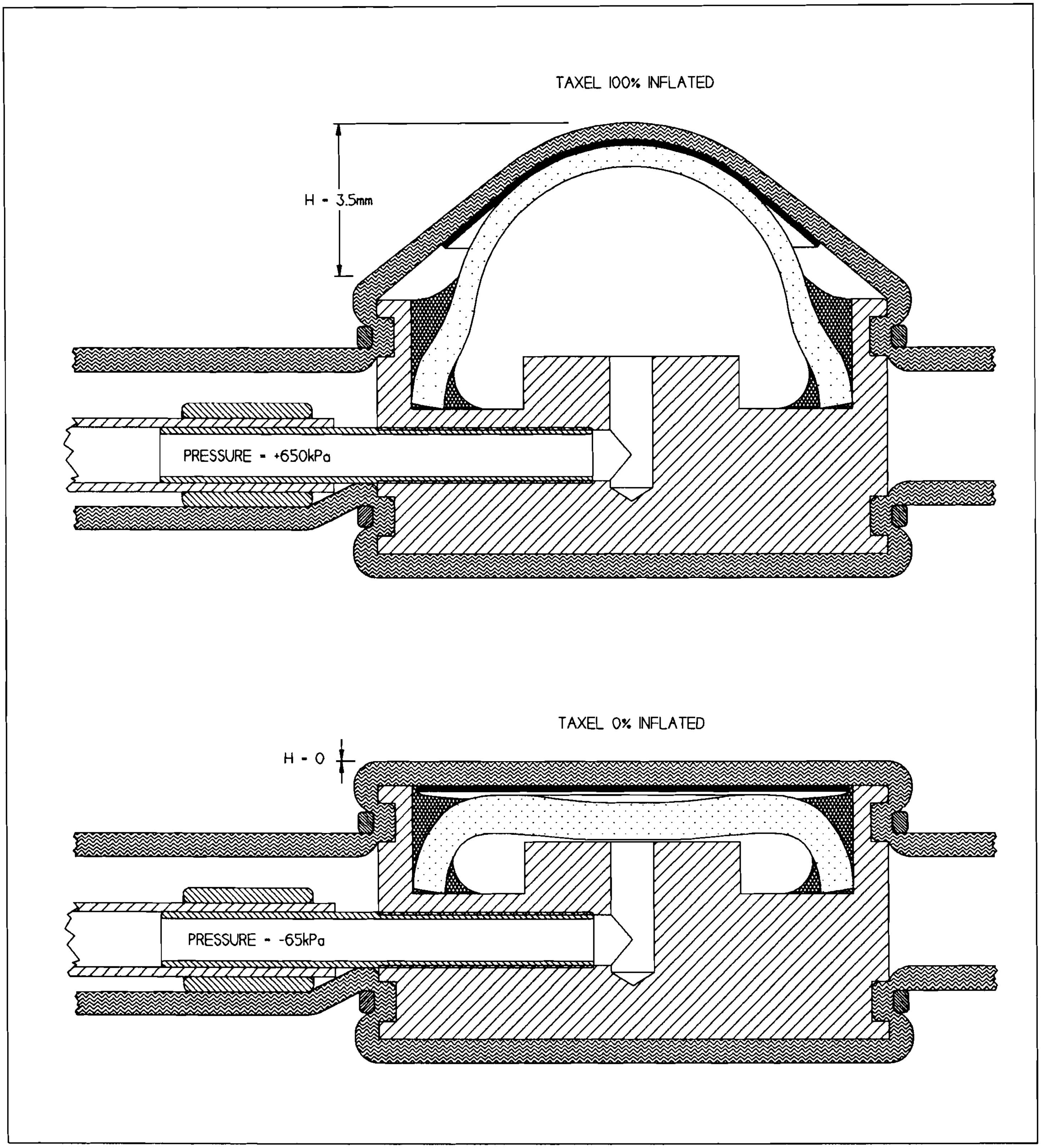
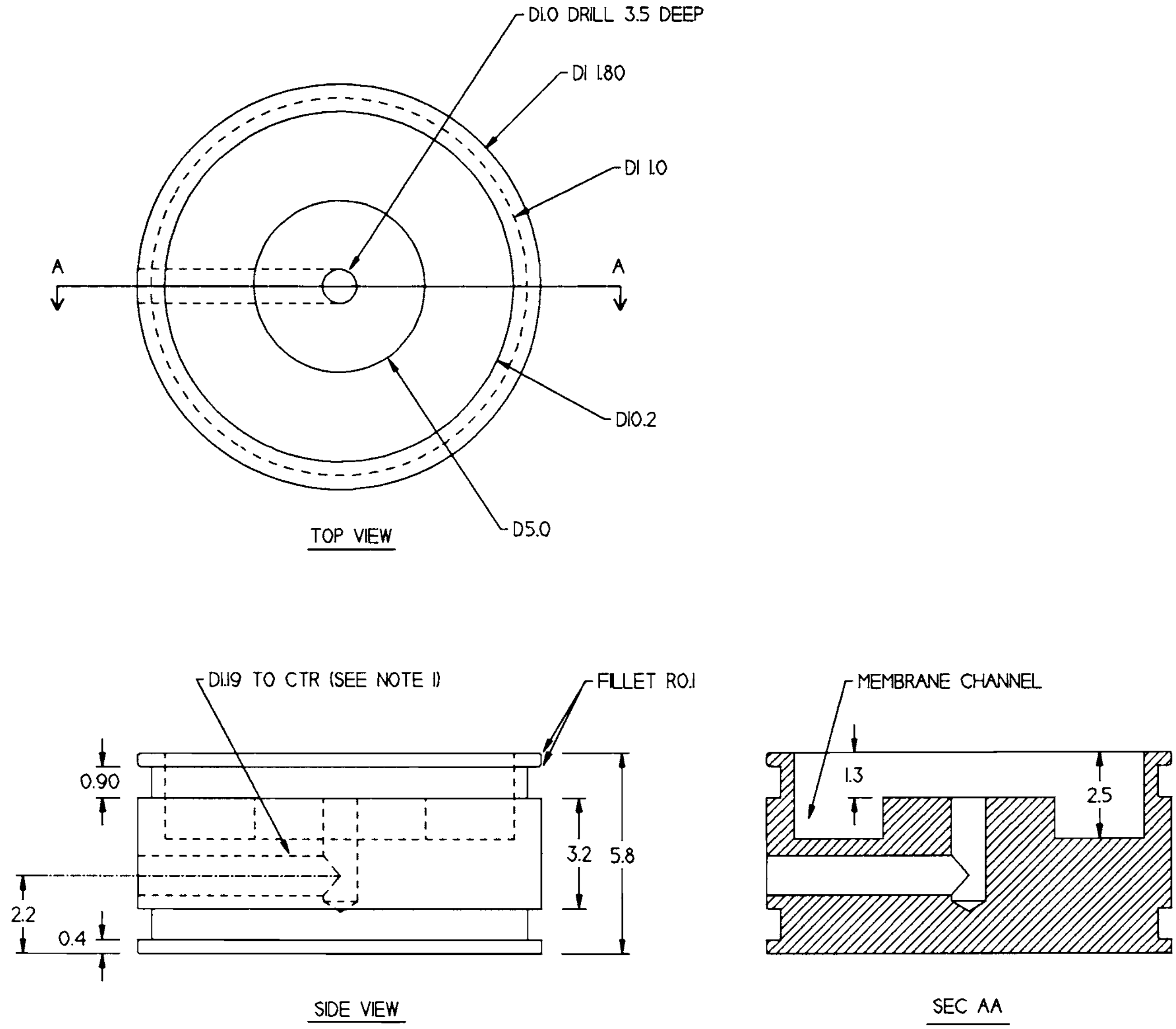


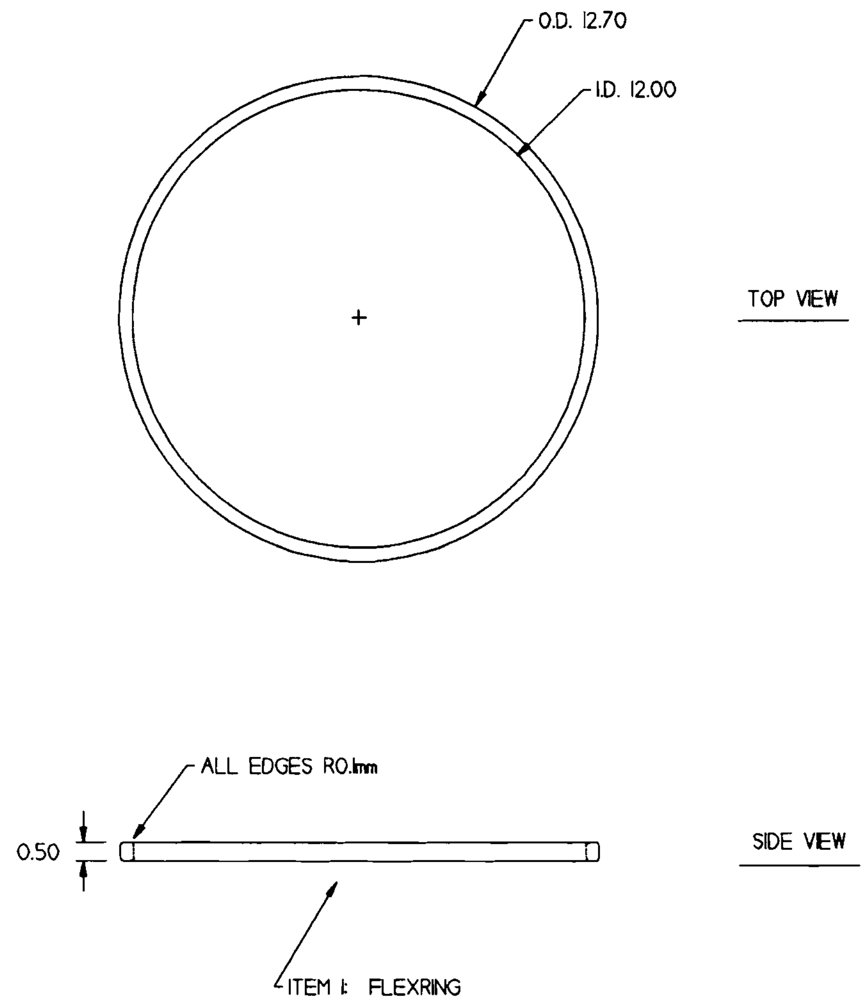
Figure 5: Appearance of the flexring taxel during minimum and maximum inflation. Scale 8X. Drawing TDRV3128-3.



NOTES:
1. FOR PART FABRICATED BY MACHINING. USE 1.0mm DIA DRILL FIRST FOLLWED BY HAND REAMING WITH 1.19mm DIA DRILL.

QTY	BC PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
1	TDRV3128-PRT01	TAXEL BODY (URETHANE. D75 HARDNESS. HEADWAY IND 1-134-001-7 OR EQUIV.)		1
PARTS LIST (ONE TAXEL)				

Figure 6: Dimensions of the flexring version of the display taxel body. Drawing TDRV3128-1.



NOTES:
1. ROUND RING EDGES ON KNURLED MANDREL ROTATING AT HIGH SPEED.
2. INSTALL ON TAXEL BY FIRST INSERTING ONE SIDE IN GROOVE. THEN ROLLING RING INTO REMAINDER OF GROOVE.

2	TDRV3131-PRT01	TAXEL FLEXRING (CUT FROM BRASS TUBE 12.68 O.D. x 11.98 I.D.. SMALL PARTS CO No. Q-TTRB-15)	1
QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	ITEM NO.
PARTS LIST (ONE TAXEL)			

Figure 7: Flexring dimensions. Drawing TDRV3131.

2.5. Snapring Taxel Version

The snapring version of the WAM TDS display element was developed in parallel with the flexring version and overcame the two main deficiencies of the former. First, being a spring-like element it could readily accommodate much greater variations in fabric thickness and taxel dimensional tolerances, and secondly, the snaprings were simple modifications of readily-available commercial items. **Figure 8** through **Figure 13** illustrate the final design of the snapring taxel and associated components.

The taxel body and membrane are very similar to the snapring taxel version previously discussed and shown in **Figure 4** to **Figure 6**. The snapring is shown in **Figure 11**, and is a modified, commercially-available stainless-steel unit. The principal modifications entail trimming and rounding the installation ears, burnishing all edges in a high-speed wire brush wheel to remove burrs and flash, and squeezing the snapring together so it has no gap in its new natural repose. Stainless steel was chosen to avoid corrosion problems associated with use in environments characterized by high-humidity and the presence of corrosive body sweat.

Taxel wear discs are shown in **Figure 13**, and were used to reduce the abrasion between the taxel membrane and fabric cover during taxel operation. Initially, materials with lubricative properties were explored (e.g., polyethylene and TEFLON®), but such wear disks disintegrated relatively quickly, presumably due to a lack of sufficient elasticity. Tougher, more elastic materials were then tried, and satisfactory results obtained with a urethane film approximately 0.13 mm thick. This wear disk was augmented with a thin coating of silicone vacuum grease (an inert, long-term, persistent lubricant) between the membrane and weardisk interface, and resulted in taxel lifetimes exceeding 2000 hours at maximum amplitude (3.5 mm). This corresponds to approximately one year of full-time use, 8 hours per day.

Graphs showing typical taxel membrane displacements are shown in **Figure 14** through **Figure 19**. Measurements were taken with the laser displacement sensor described earlier using a complete taxel assembly, i.e., taxel, snapring, wear disc, silicone lubricant, and elastic fabric cover. Taxel inflation was noted to be much more rapid than deflation by a factor of approximately 6, causing the exhaust side of the taxel inflation cycle to be the prime determinant of the maximum permissible PWM base frequency. For the taxel developed for this program, this frequency was 4.5 Hz with a maximum duty cycle of approximately 10%. Higher duty factors failed to permit sufficient time for taxel evacuation and the taxel becomes permanently inflated, but no additional increase in p/p taxel inflation occurs. It is the latter dynamic tactile component that is responsible for the perceived tactile stimulation.

Applying a vacuum to assist in exhausting a taxel was found to shorten the exhaust time or raise the maximum p/p displacement value by 5-15%.

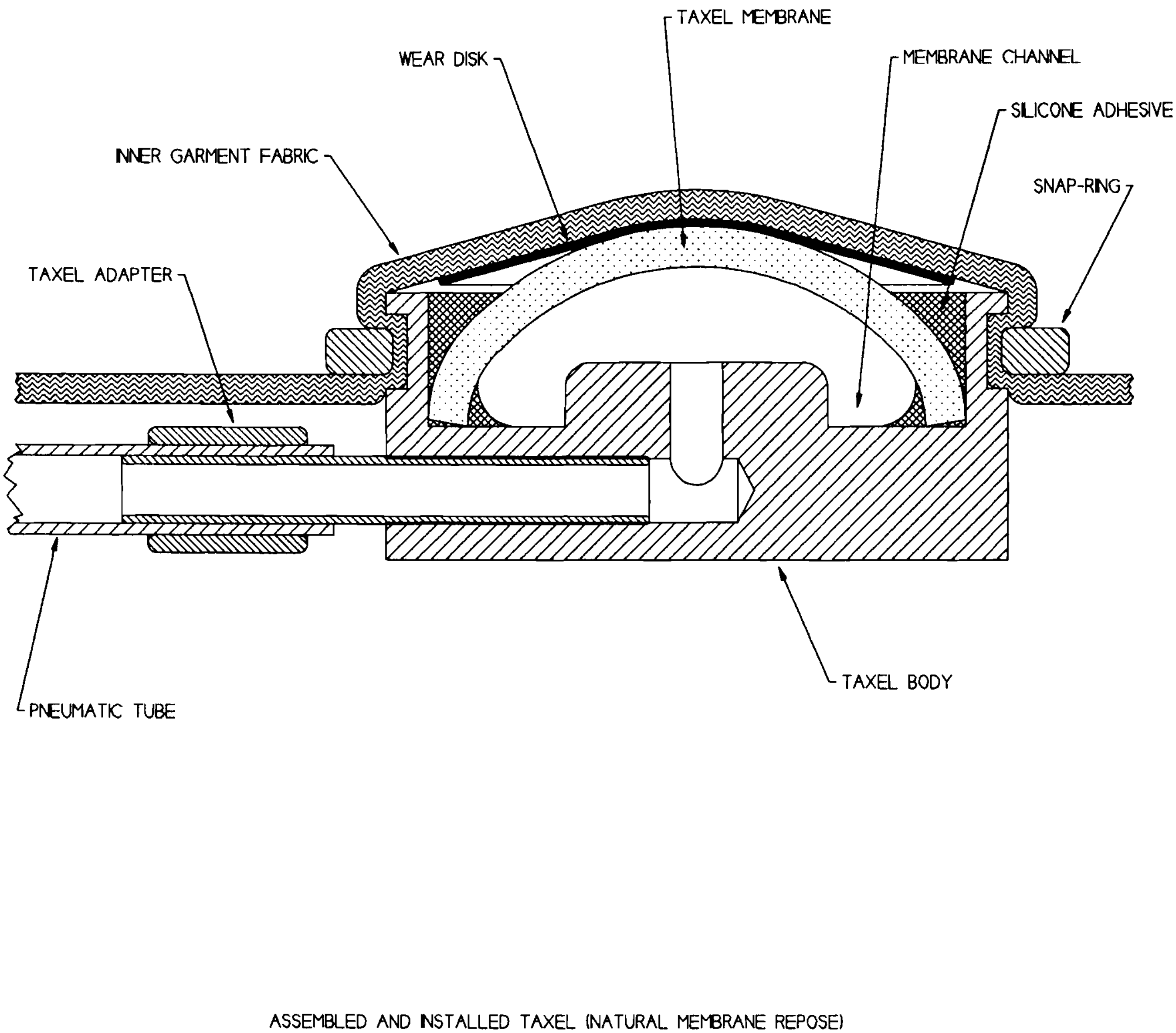


Figure 8: Snapring version of tactile display taxel. Taxel membrane is show in the natural repose position approximately 0.5 mm taller than when fully retracted by a vacuum applied to the exhaust port. Scale 8X. Drawing TDRV128-2.

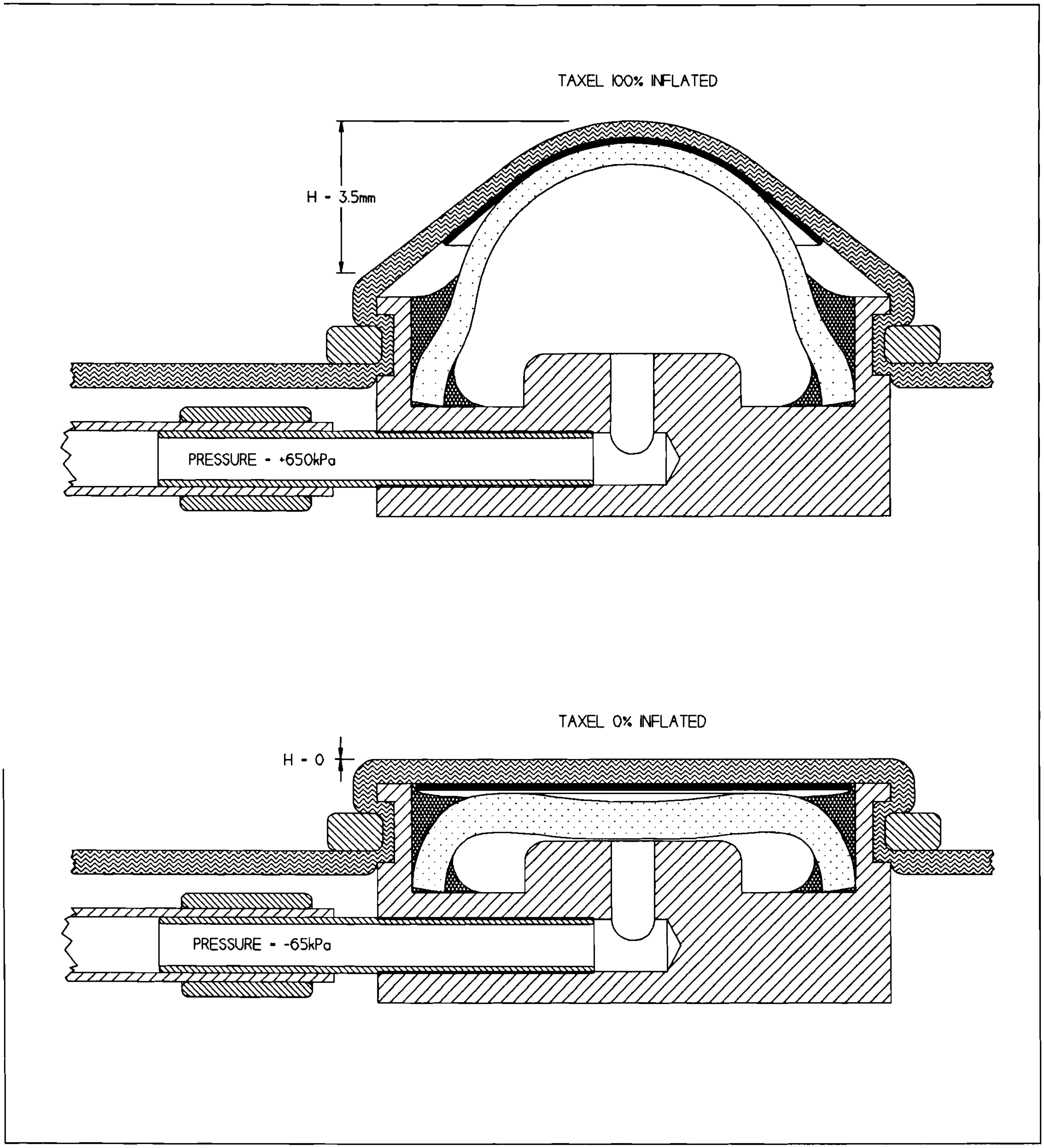
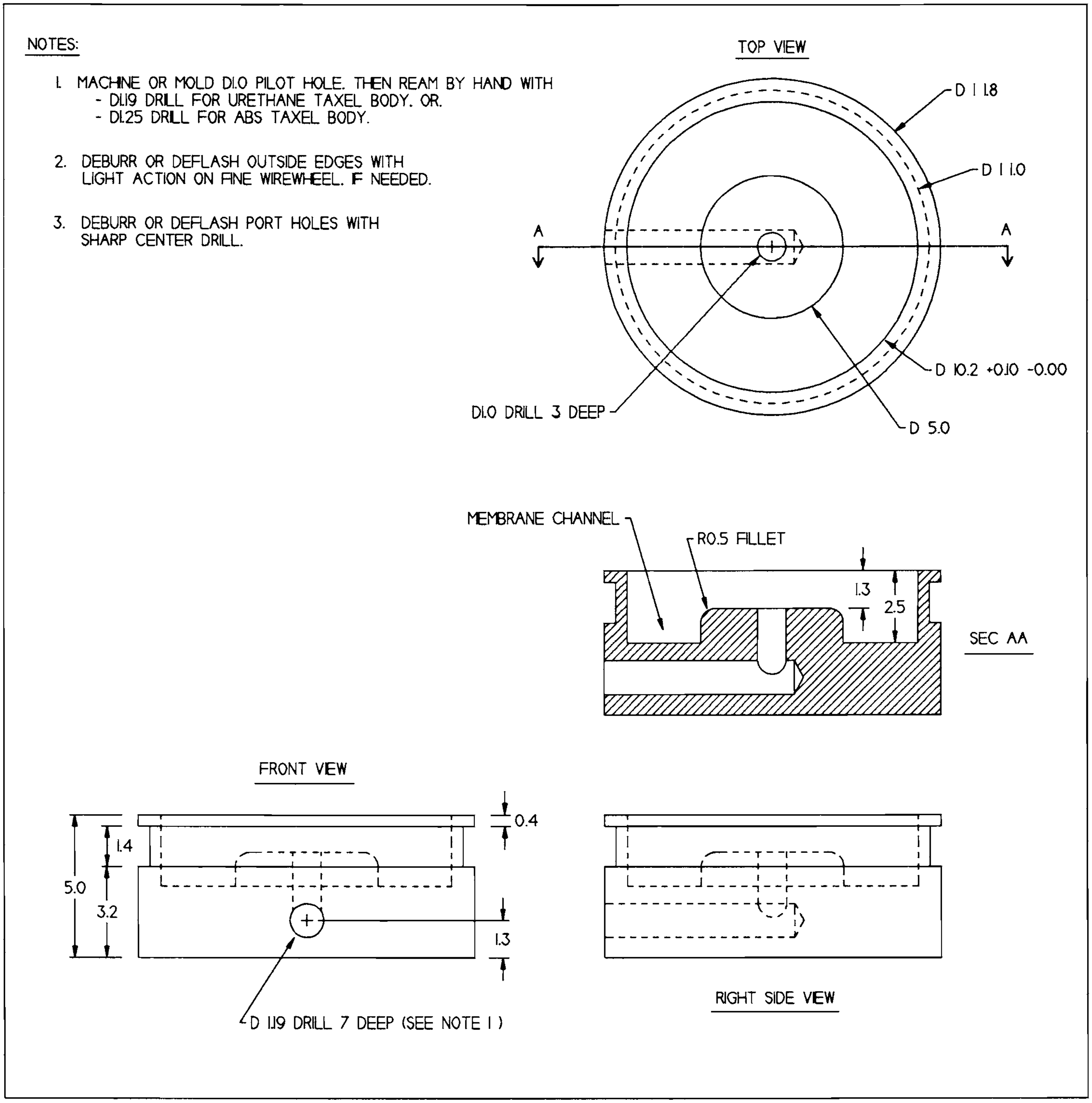
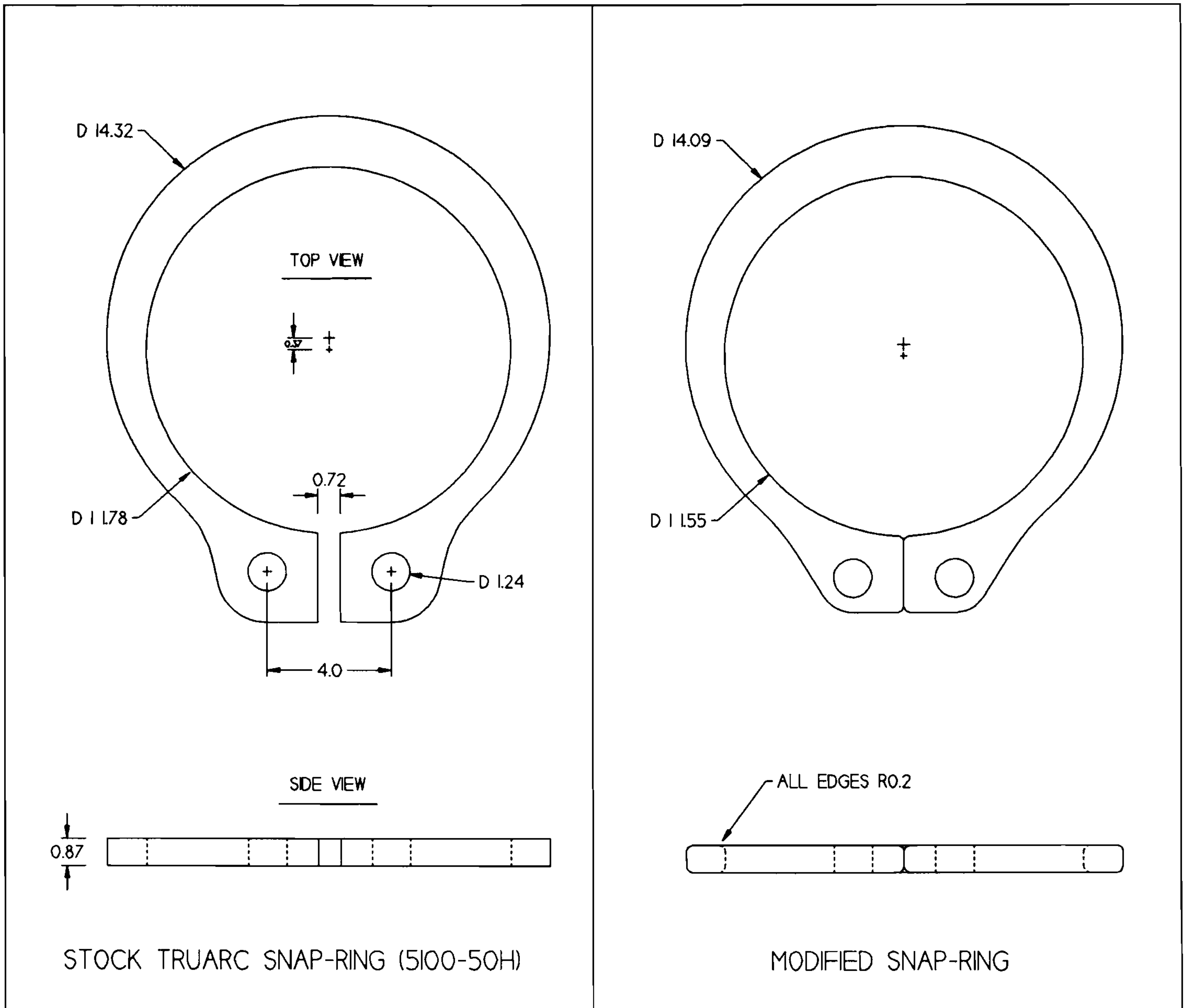


Figure 9: Appearance of the snapring taxel during minimum and maximum inflation. Scale 8X. Drawing TDRV3128-3.



1	TDRV3128-PRT01	TAXEL BODY: (1) URETHANE 75D HARDNESS. (2) ABS. (3) POLYCARBONATE		1
QTY	BC PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
PARTS LIST (ONE TAXEL)				

Figure 10: Dimensions of the snapring version of the display taxel body. Scale 5X. Drawing TDRV3128-1.

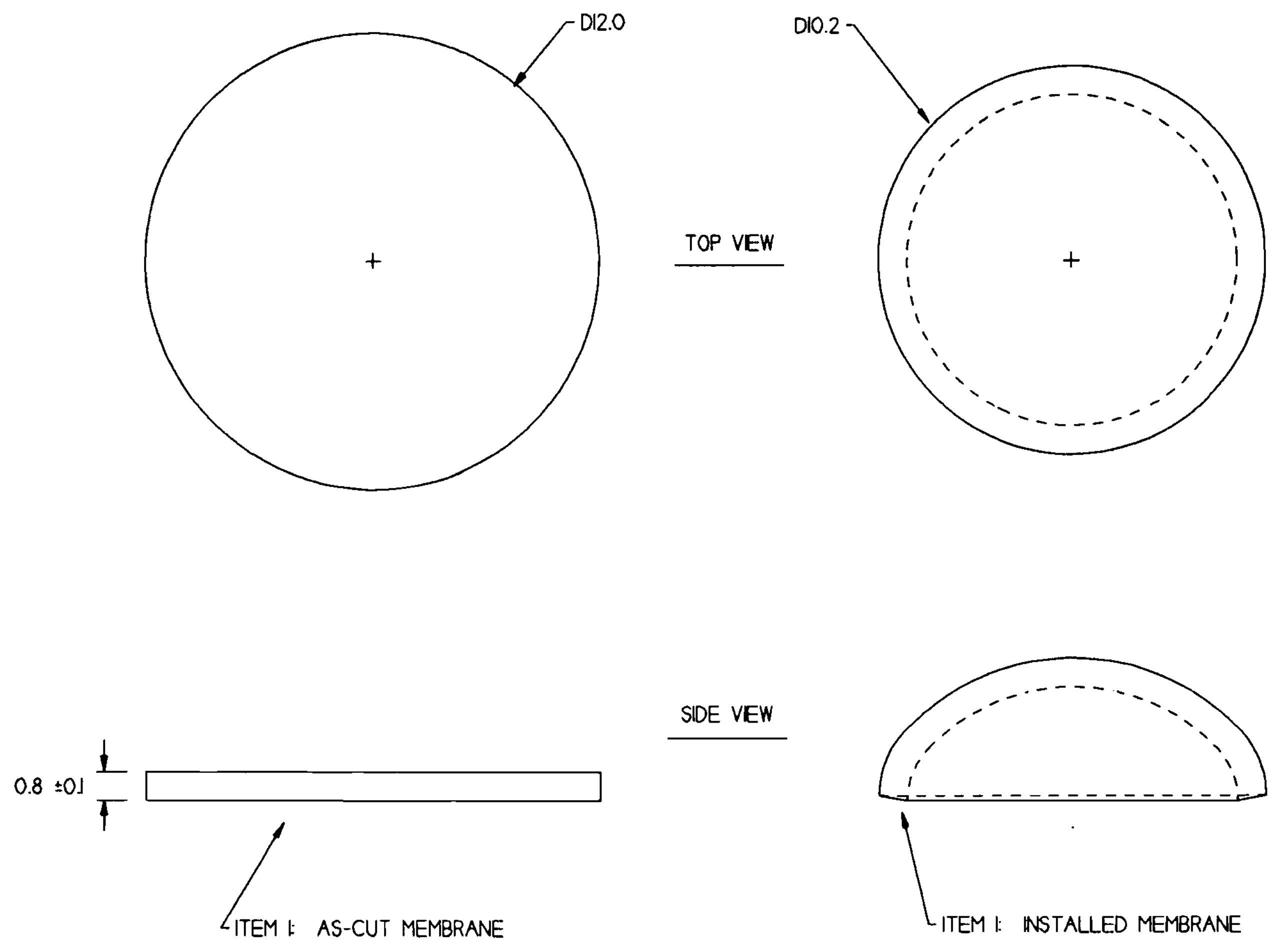


NOTES REGARDING SNAP-RING MODIFICATION:

1. TRIM APPROXIMATELY 0.5mm FROM EAR HEIGHT AND RE-ESTABLISH CURVED FORM.
2. DEBURR AND ROUND ALL EDGES WITH HIGH-SPEED STEEL WIRE WHEEL (ESPECIALLY INSIDE RING AND GAP).
3. PINCH SNAP-RING IN VISE UNTIL GAP IS ELIMINATED IN RELAXED POSITION.

1	TDRV3131-PRT01	TAXEL SNAP-RING (WALDRON TRUARC 5100-50H, STAINLESS STEEL)	1
QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	ITEM NO.
PARTS LIST (ONE TAXEL)			

Figure 11: Snapring dimensions before and after modification of commercially-available unit. Scale 5X. Drawing TDRV3135.

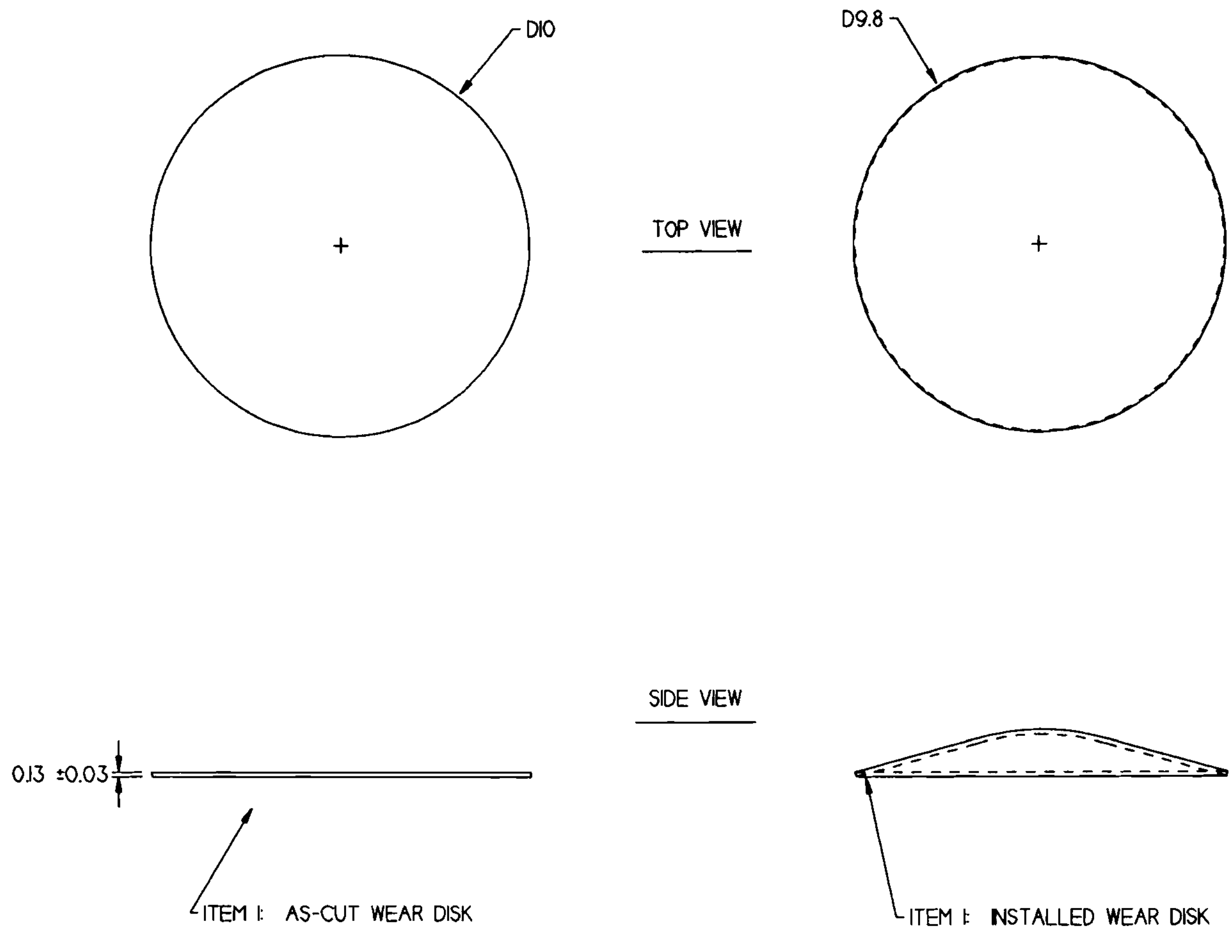


NOTES:

1. CLEAN SURFACE OF SILICONE STOCK WITH ACETONE. RUBBING TO REMOVE FACTORY SURFACE CONTAMINATION.
2. CUT SILICONE MEMBRANES WITH STATIONARY OR ROTARY "COOKIE-CUTTER" TOOL.

QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	ITEM NO.
1	TDRV3129-PRT01	TAXEL MEMBRANE (SILICONE, CHR-300, NOMINAL 0.76mm THICKNESS)	1
		PARTS LIST (ONE TAXEL)	

Figure 12: Silicone taxel membrane dimensions in natural repose state and installed state. Scale 5X. Drawing TDRV3129.



NOTES:
1. PUNCH-OUT URETHANE WEAR DISK WITH "COOKIE-CUTTER" TOOL.
2. PLACE THIN LAYER OF KRYTOX LUBRICANT (DUPONT CO.) BETWEEN DISK AND MEMBRANE DURING ASSEMBLY.

1	TDRV3130-PRT01	TAXEL WEAR DISK (URETHANE, RHODE ISLAND TEXTILE CO No. 3913, NOMINAL 0.13mm THICKNESS)	1
QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	ITEM NO.
PARTS LIST (ONE TAXEL)			

Figure 13: Wear disk dimensions. The wear disk was interposed between the taxel membrane and elastic cloth cover to minimize abrasive wear. Scale 5X. Drawing TDRV3130.

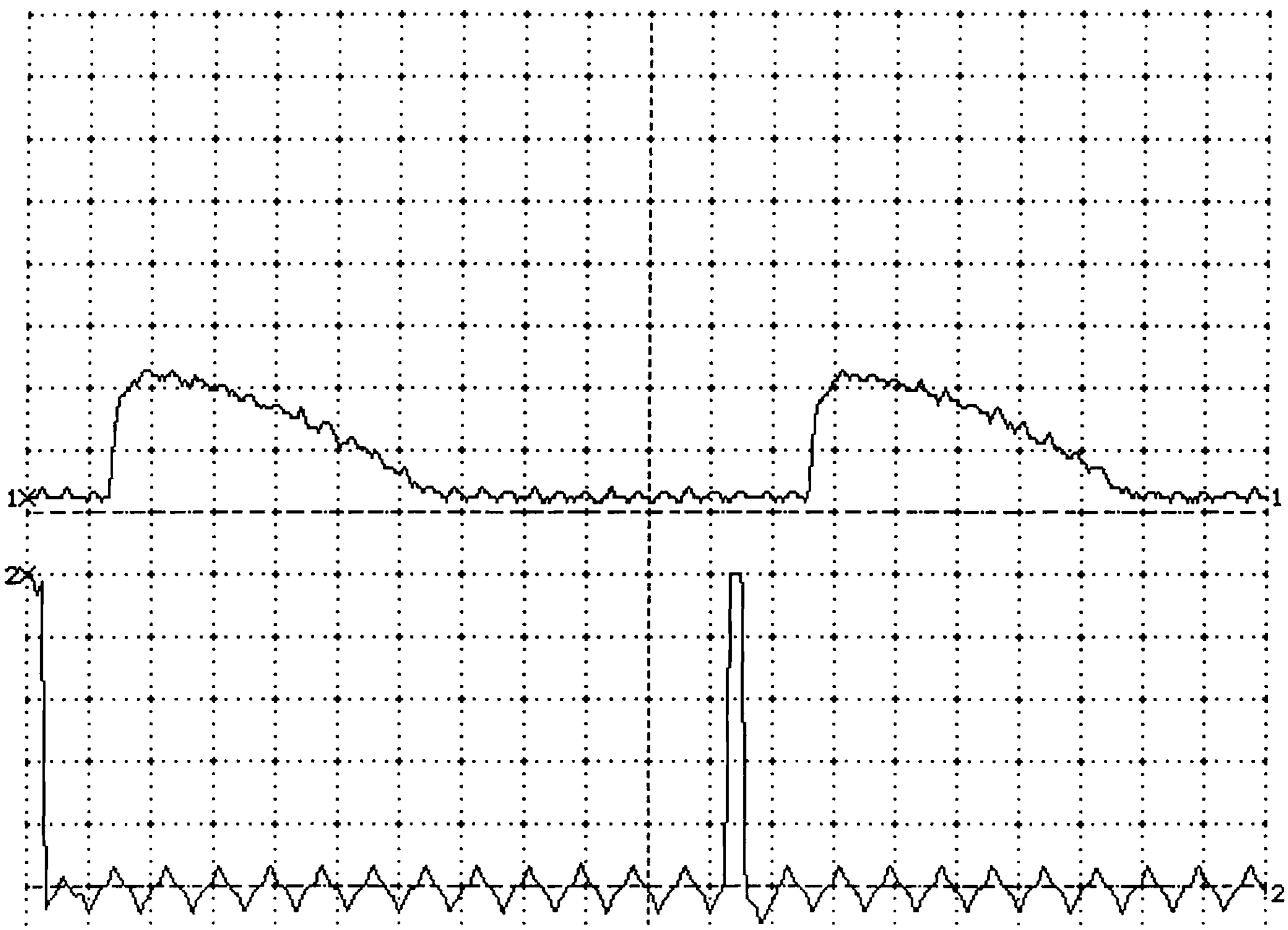


Figure 14: Top graph shows typical taxel displacement (0.5 mm per vertical division) measured by the laser displacement sensor, and shows a peak displacement of 1.0 mm. Bottom graph is driver voltage (0-24 VDC) applied to taxel valve. Horizontal time axis: 20 ms/div. Drive pressure: 700 kPa (101 psi). Evacuation pressure: -53 kPa (-8 psi). Taxel 181194A, Run 2.

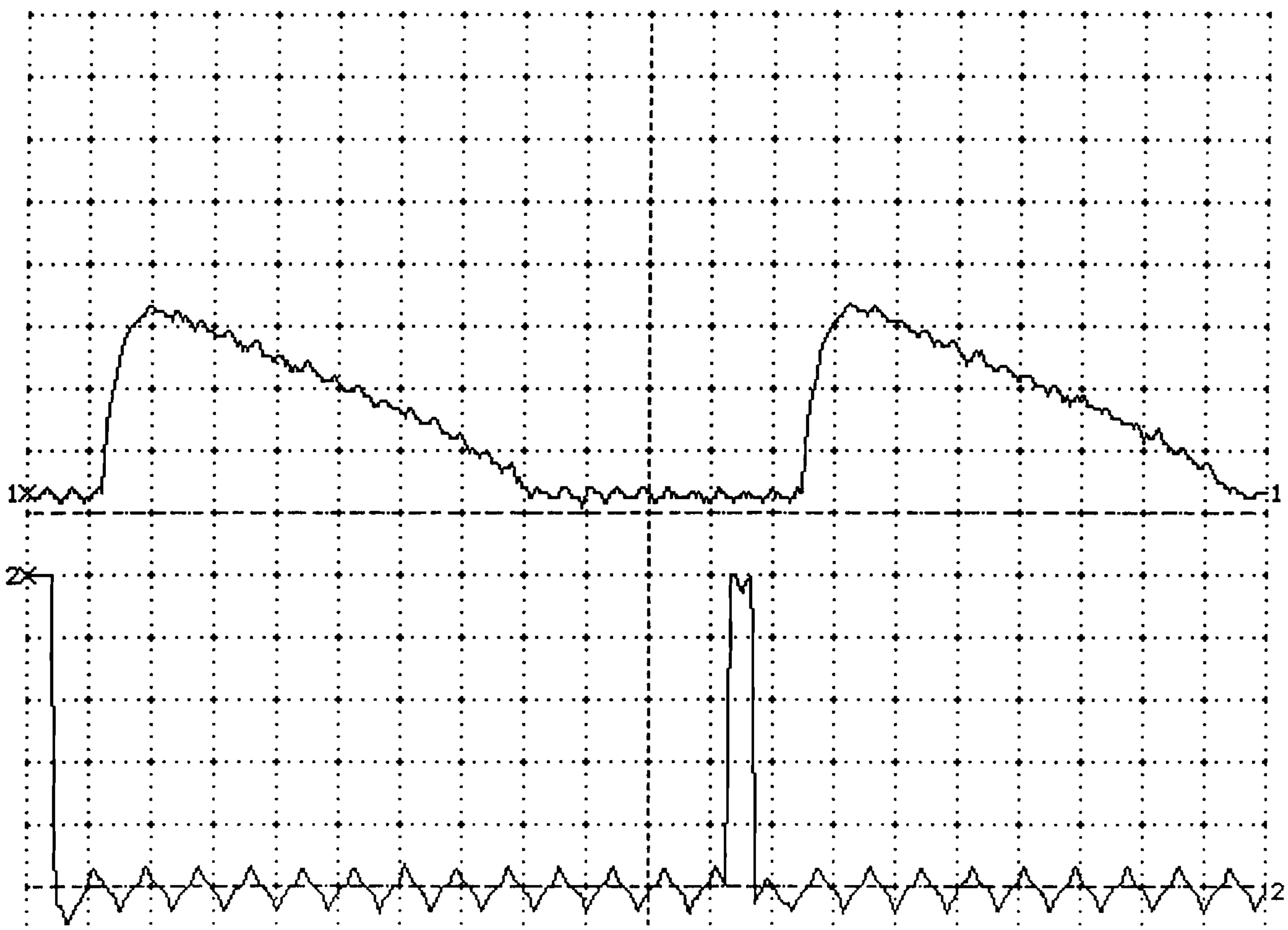


Figure 15: Same as **Figure 14**, except taxel displacement is increased to 1.5 mm by lengthening the PWM duty factor.

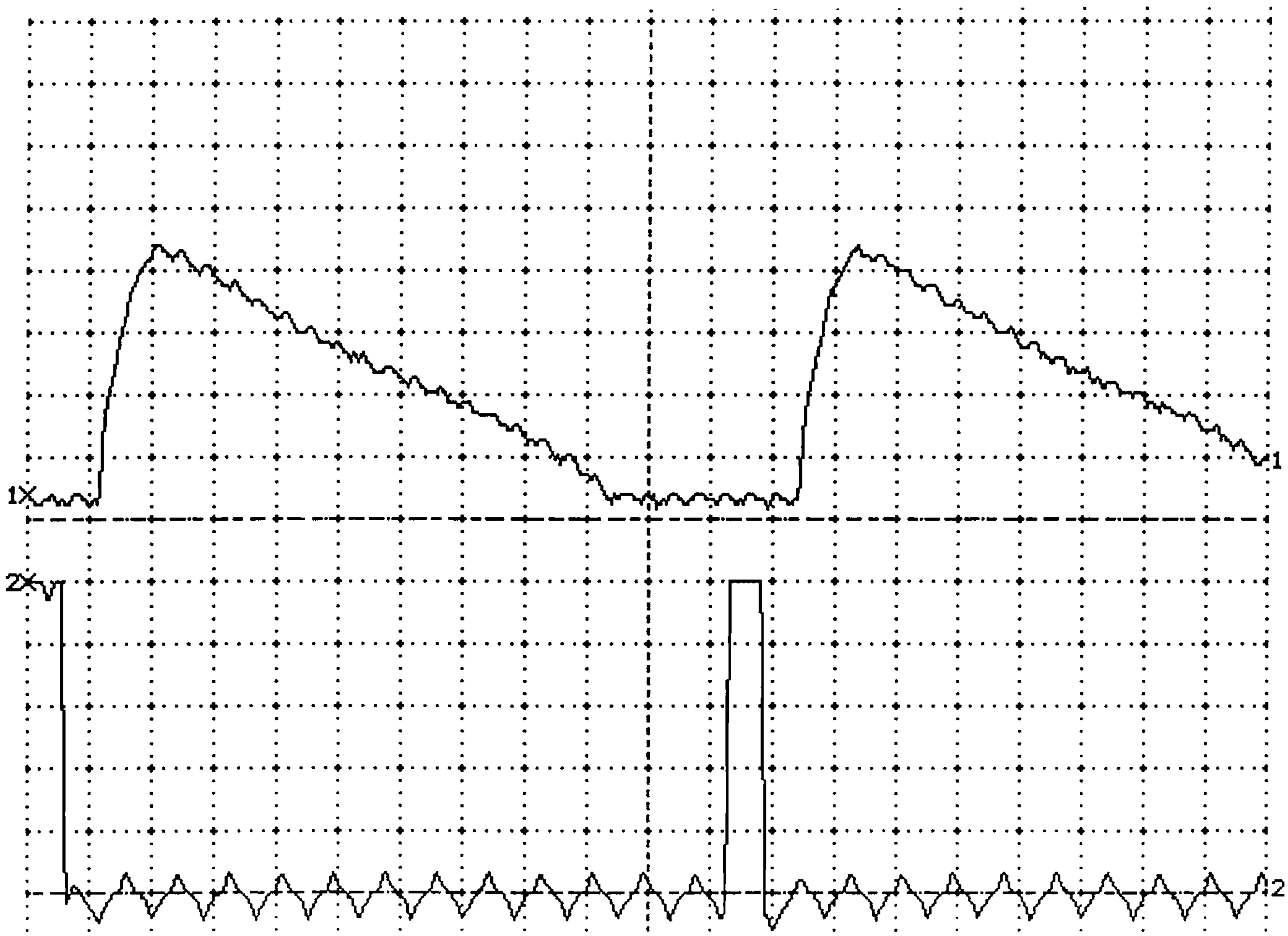


Figure 16: Same as **Figure 14**, except taxel displacement is 2.0 mm.

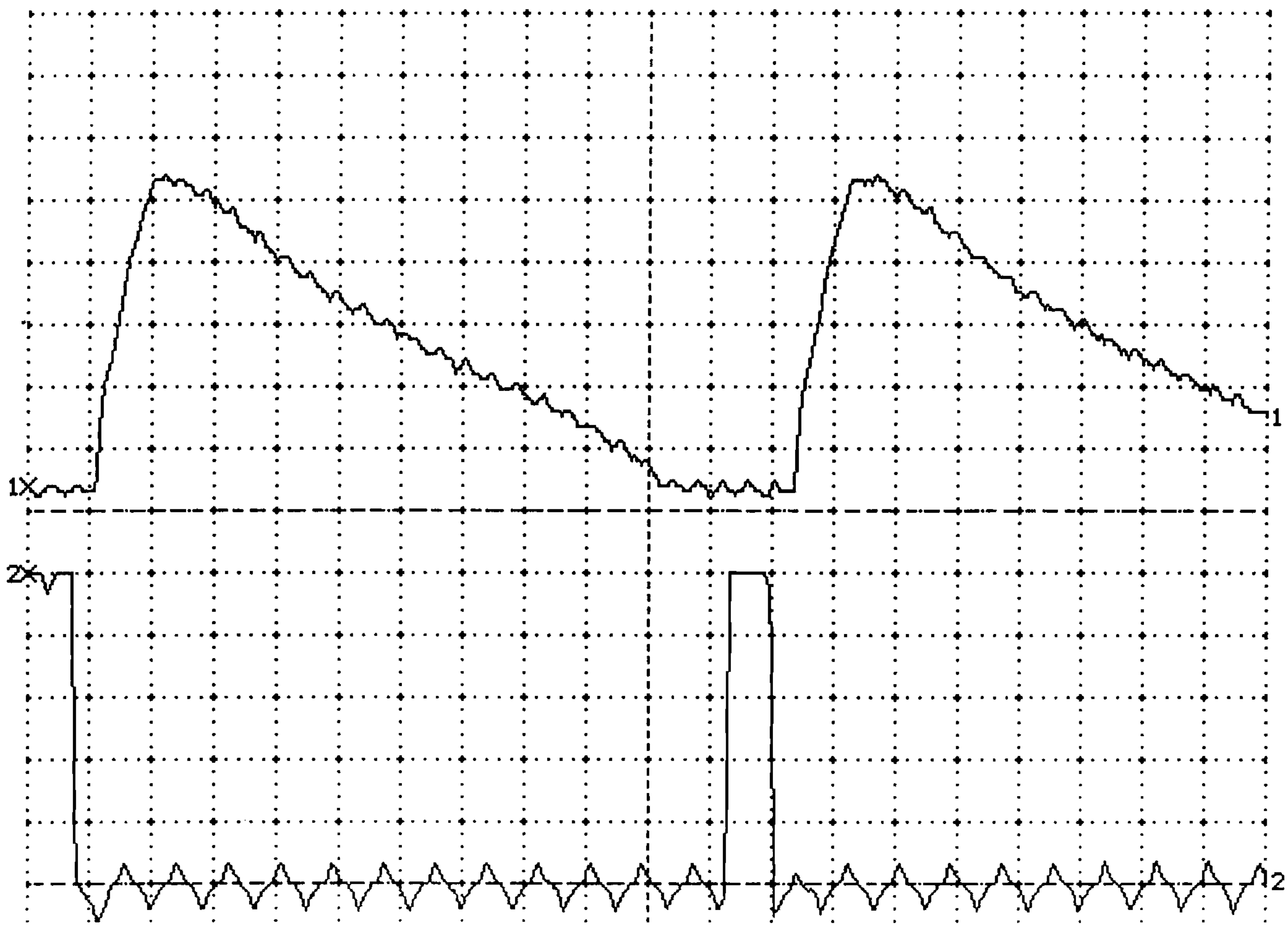


Figure 17: Same as **Figure 14**, except taxel displacement is 2.5 mm.

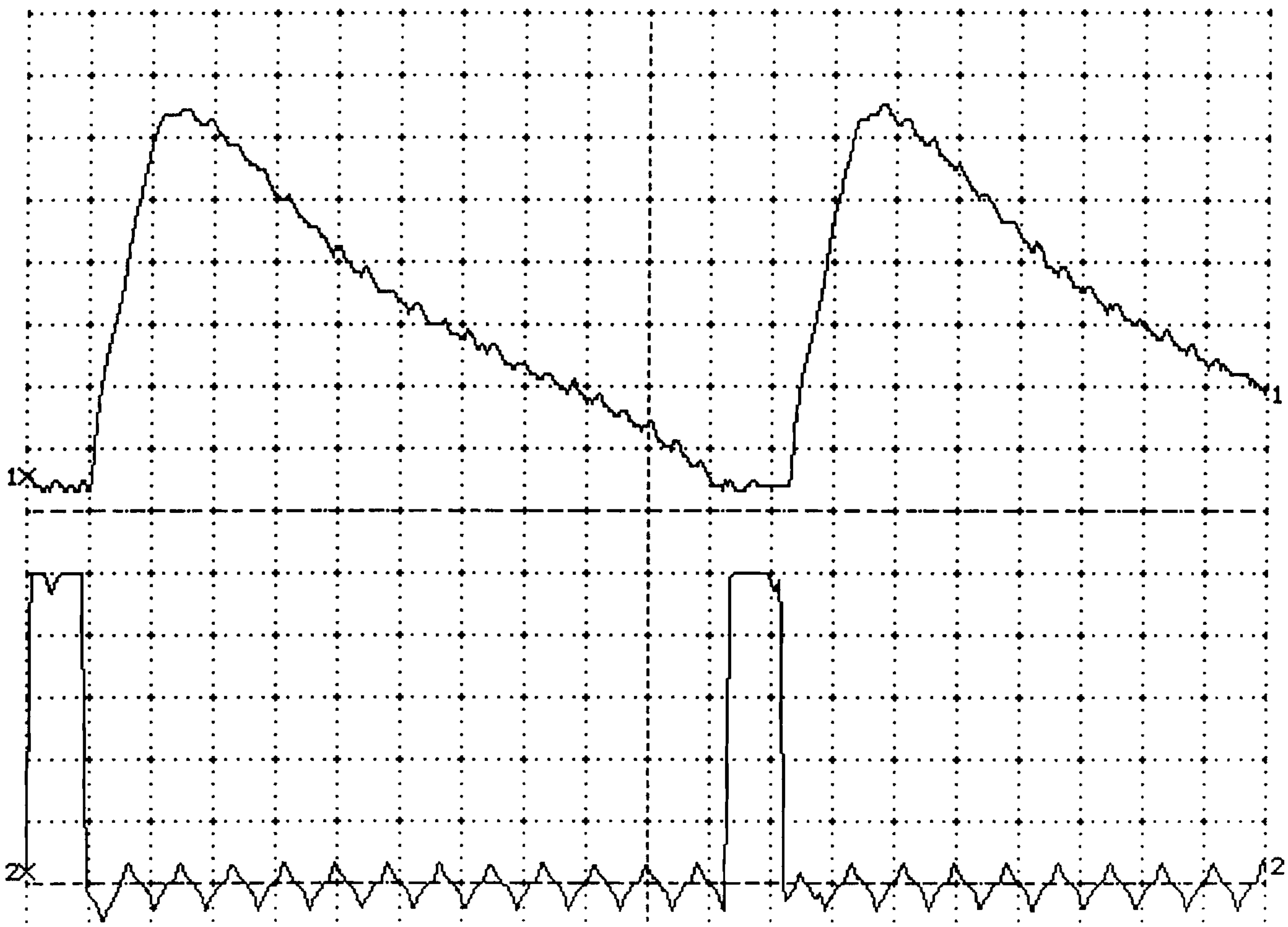


Figure 18: Same as **Figure 14**, except taxel displacement is 3.0 mm.

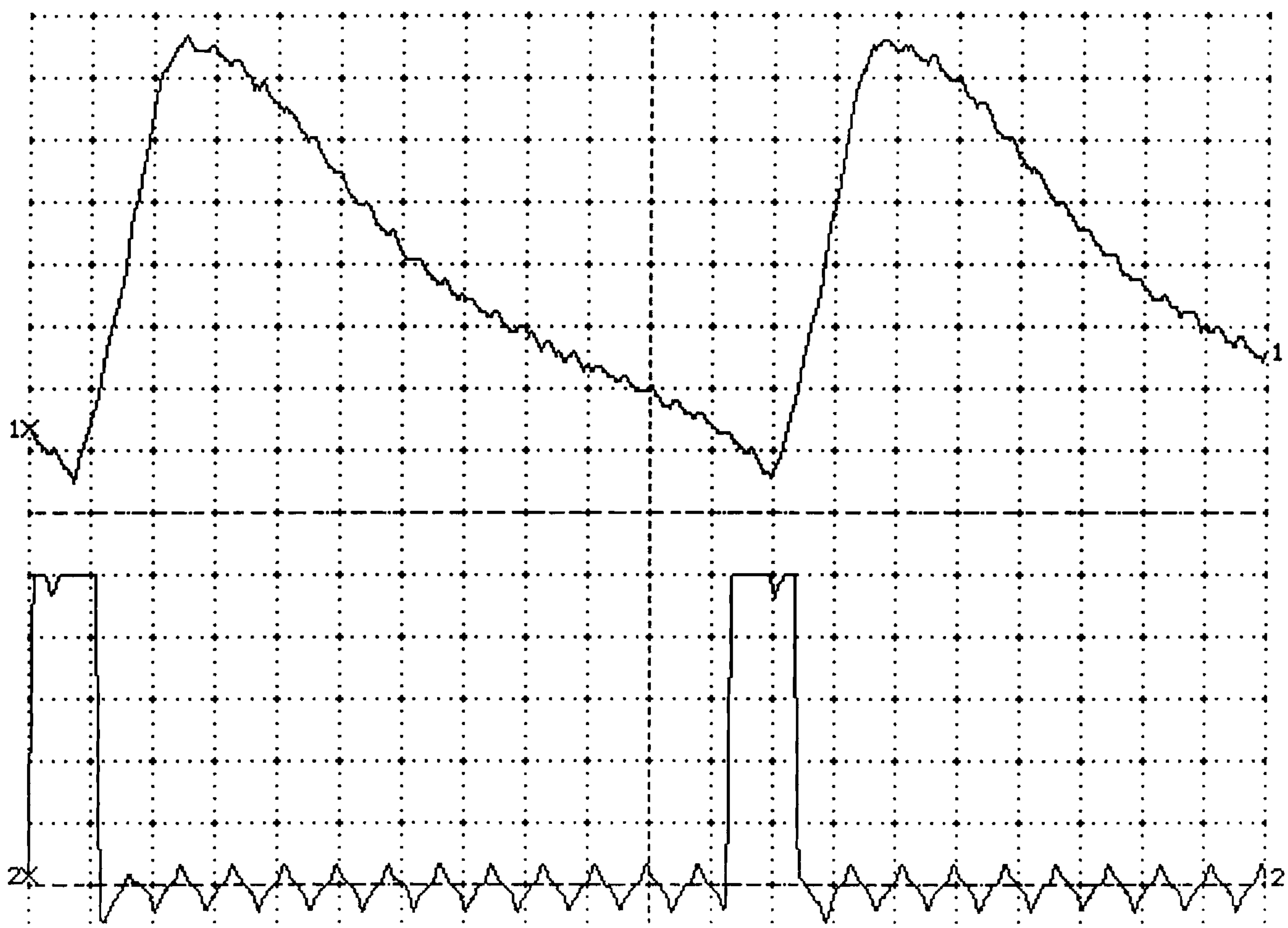


Figure 19: Same as **Figure 14**, except taxel displacement is the maximum amount, or 3.5 mm.

2.6. Pneumatic Tubing and Connectors

The pneumatic tubing for the display system was selected in parallel with the taxel development effort. The important tubing parameters were length, tubing diameter, and kink resistance. A minimum tubing length of 3 m was chosen which (after subtraction of routing overhead on each end) resulted in a operator "roaming distance" of approximately 1.5 m from the tactile display driver cabinet. A study was then undertaken with TEFLON®, PVC, and KYNAR® tubing to determine that the minimum tubing bore size that would permit adequate tactile stimulation by the taxel was approximately 20 AWG. A larger bore size permitted longer tubing to be used for a larger ranging distance, but this would have come at the expense of a larger pneumatic cable diameter and associated increase in cable weight and stiffness. A tubing size of 20 AWG was considered a good compromise, yielding a total sheathed cable diameter of approximately 50 mm (512 taxels).

Fabrication of tactile arrays in the past had relied heavily on obtaining KYNAR® stock from solid wire stripped to produce 24-30 AWG tubing. This material was used for the following reasons:

- Its inherent high strength resulted in a very thin-walled tube, with a corresponding savings in both pneumatic cable diameter and weight,
- KYNAR®-insulated wire was readily available,
- KYNAR® was very easy to bond with a wide variety of adhesives, thereby greatly simplifying the problem of attaching the tubing material to the manifold adapters and taxel body.

However, from the samples investigated, it was concluded that 20 AWG KYNAR® tubing was insufficiently kink and crush resistant, and might fail under the cable-bending conditions expected to be encountered during use of the tactile display suit. For this reason, other tubing materials were considered, e.g., TEFLON®, nylon and PEEK®. TEFLON® was found to possess good anti-kink properties and was readily available in thin-walled form, and its slick surface acted to prevent tubing damage due to stiction-induced kinking within the pneumatic tubing cable. However, the latter property also presented the significant problem of terminating the TEFLON® tubing at the display driver manifolds and taxel body.

The problem of terminating the TEFLON® tubing was solved by developing a slip-on collar connector system that mechanically retained the tubing onto an abraded internal core. Drawings of the tubing adapters for the display driver manifold and taxels utilizing this approach are shown in **Figure 20** to **Figure 24**. Despite the slick surface and cold flow properties of TEFLON®, this approach to tubing connection was found to be surprisingly reliable. The connectors readily withstood static pressures in excess of 830 kPa (120 psi), and the collared tubing could not be pulled off the connector core without breaking the tubing first.

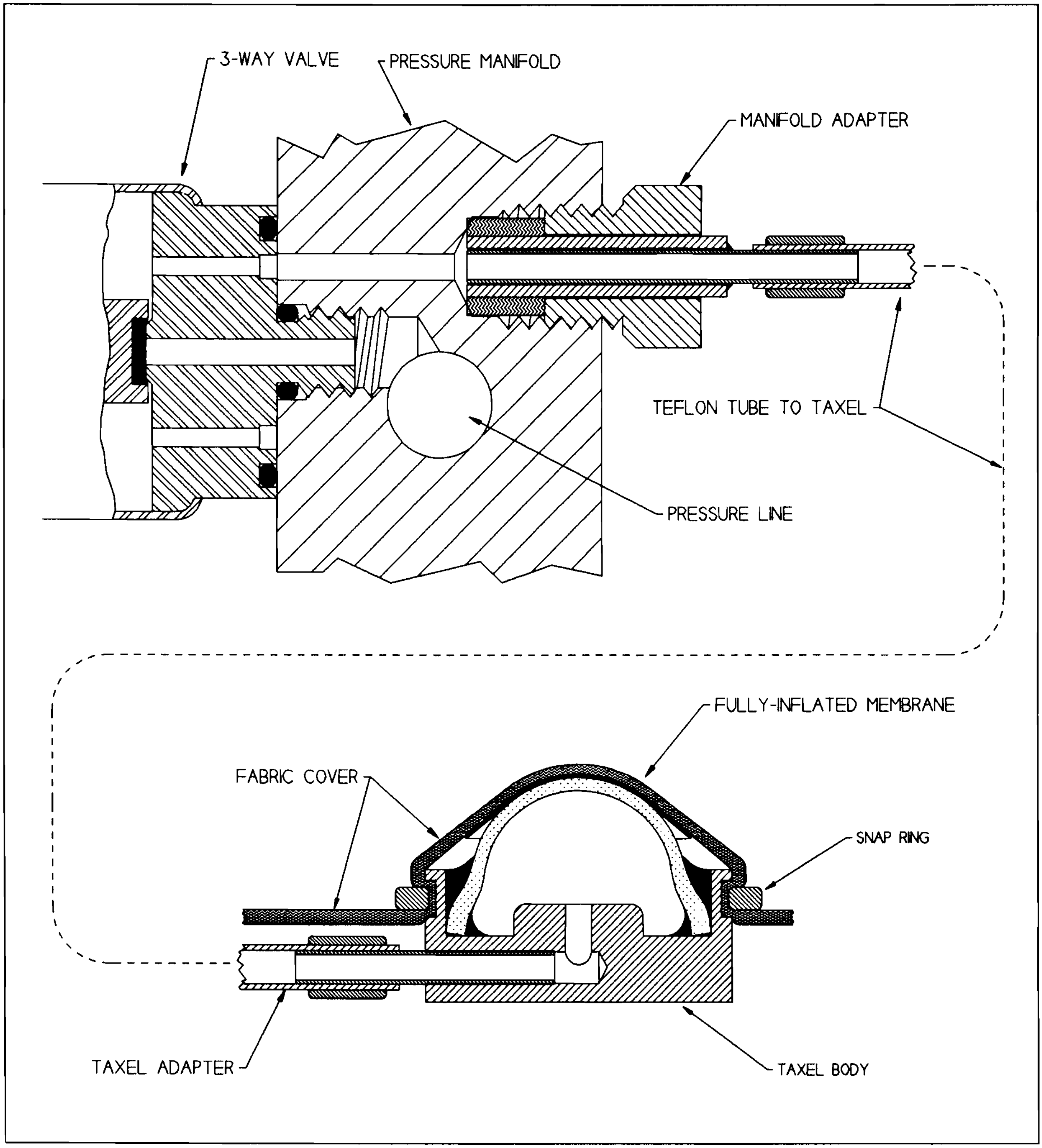
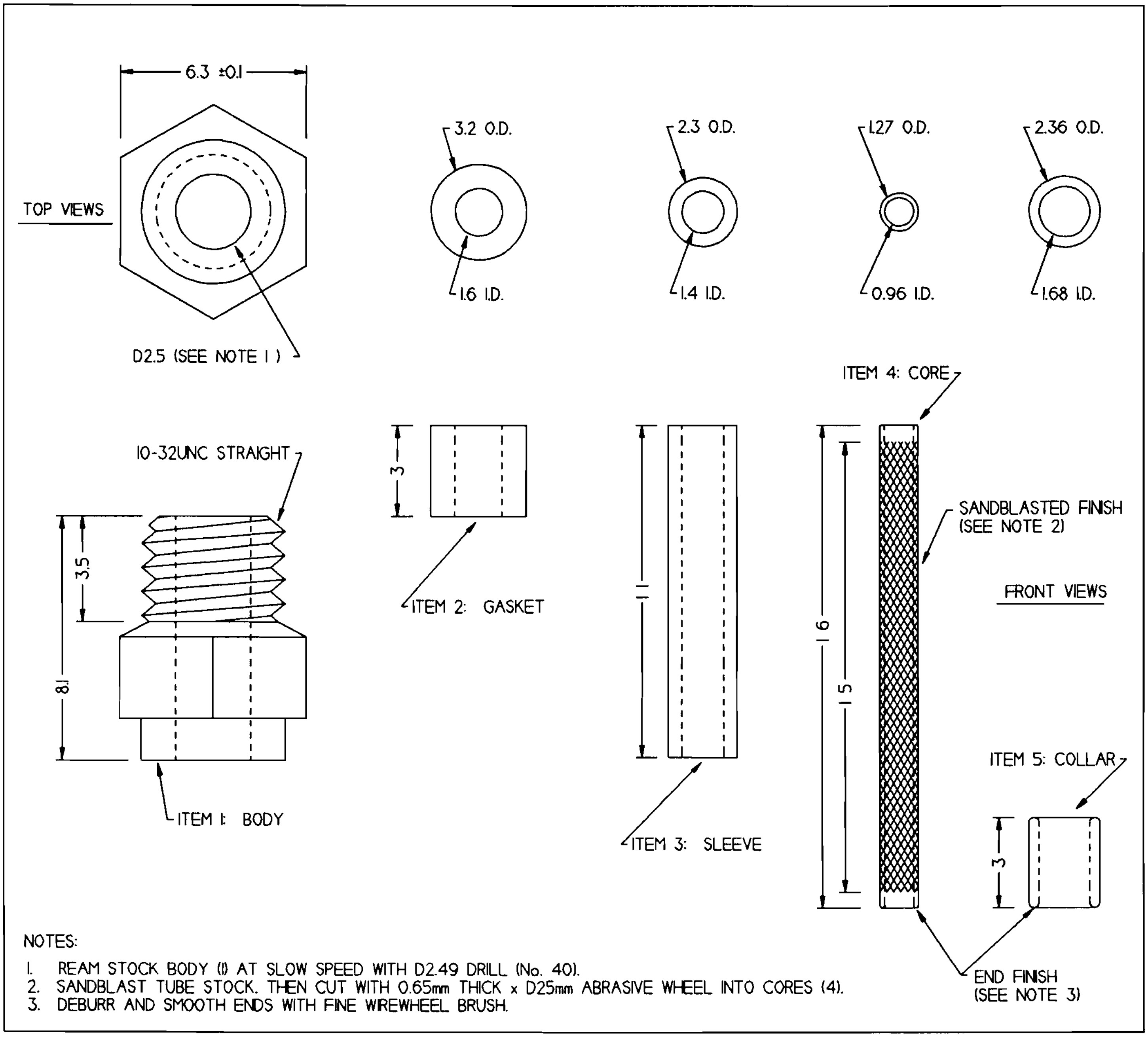


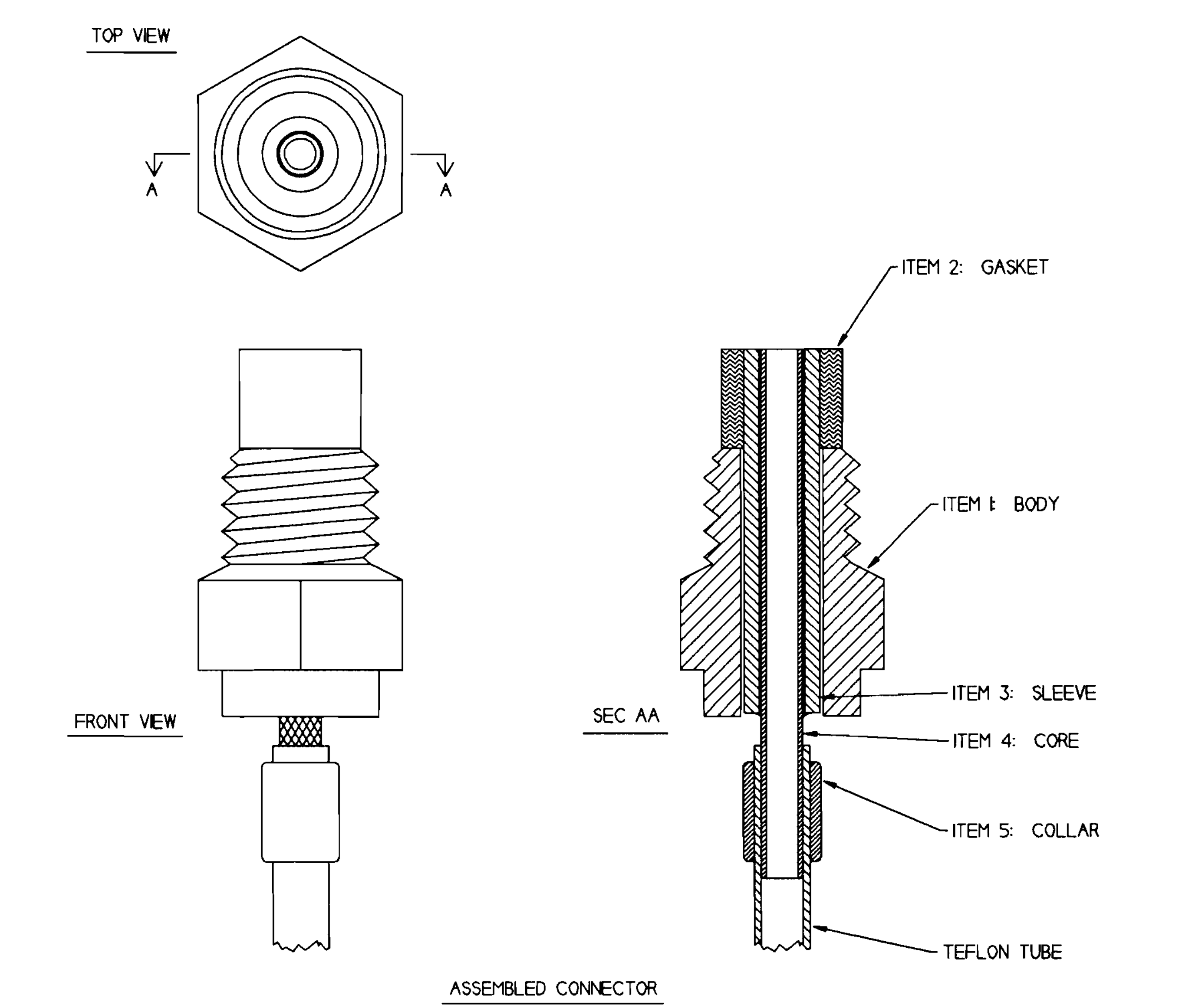
Figure 20: Assembly detail drawing showing driver manifold and taxel adapters designed to fit 20 AWG TEFLON® tubing. Scale 5X. Drawing DTRV3003.



QTY	BC PART/ID NO.	NOMENCLATURE OR DESCRIPTION	ITEM NO.
1	TDRV3126-PRT05	MANIFOLD ADAPTER - COLLAR (BRASS TUBE. SMALL PARTS CO. No. Q-TTRB-2)	5
1	TDRV3126-PRT04	MANIFOLD ADAPTER - CORE (18AWG SS THINWALL TUBE. SMALL PARTS CO. No. Q-HTX-18TW)	4
1	TDRV3126-PRT03	MANIFOLD ADAPTER - SLEEVE (16AWG PVC TUBING. SPC/VOLTREX PVI-S16)	3
1	TDRV3126-PRT02	MANIFOLD ADAPTER - GASKET (SUPERTHANE. US PLASTICS NO. 800)	2
1	TDRV3126-PRT01	MANIFOLD ADAPTER - BODY (VALUE PLASTICS INC. No. BDMK-81. REAM CENTRAL HOLE TO D2.5)	1

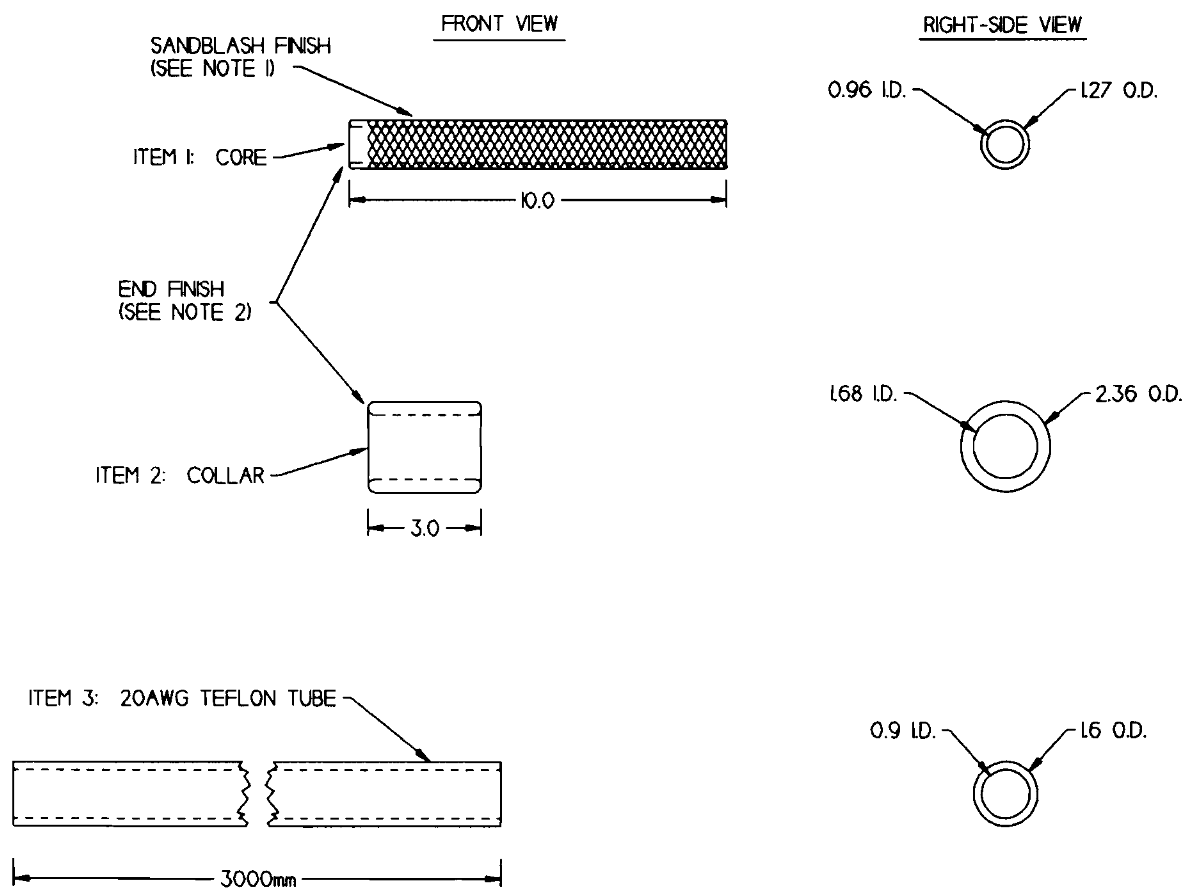
PARTS LIST (ONE TAXEL)

Figure 21: Tubing components for driver manifold adapter. Drawing TDRV3126-1.



NOTES:
1. CEMENT SLEEVE (3) TO GASKET (2) WITH CYANOACRYLATE (CA) ADHESIVE (PRY INTERFACE WITH SCRIBE TO ENCOURAGE WICKING).
2. ATTACH CORE (4) TO SLEEVE (3) WITH CA ADHESIVE.
3. ROTATABLE SLIP-FIT REQUIRED BETWEEN BODY (1) AND SLEEVE (3).
4. TAXEL TUBING: 20AWG THINWALL TEFLON TUBING (ZEUS CO.) x 3m LONG.
5. COLLAR INSTALLATION PROCEDURE:
   - SLIDE COLLAR DOWN TEFLON TUBE
   - SLIP TUBE 4mm ONTO CORE
   - USING TOOL. PUSH COLLAR OVER TUBE-COVERED CORE.
     APPROXIMATELY 0.5mm OF THE CORE SHOULD PROTRUDE INTO THE TUBE BEYOND COLLAR TO ACT AS A STRAIN RELIEF.
6. FINGER-TIGHTEN ADAPTER INTO MANIFOLD DURING INSTALLATION.

Figure 22: Assembly drawing of tubing adapter to display driver manifold. Drawing TDRV3126-2.



NOTES:
1. SANDBLAST TUBE STOCK, THEN CUT WITH 0.65mm THICK x D25mm ABRASIVE WHEEL INTO CORES (1).
2. DEBURR AND SMOOTH ENDS WITH FINE WIREWHEEL BRUSH.

1	TDRV3127-PRT03	TUBING, 20 AWG, 3m LONG, THIN-WALLED TEFLON (ZEUS IEA-20-TW-0)		3
1	TDRV3127-PRT02	TAXEL ADAPTER - COLLAR (BRASS TUBE, SMALL PARTS CO. Q-TTRB-2)		2
1	TDRV3127-PRT01	TAXEL ADAPTER - CORE (18AWG SS THINWALL TUBE, SMALL PARTS CO. Q-HTX-18TW)		1
QTY	BC PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
PARTS LIST (ONE TAXEL)				

Figure 23: Tubing adapter components for attachment to taxel body. Drawing TDRV3127-1.

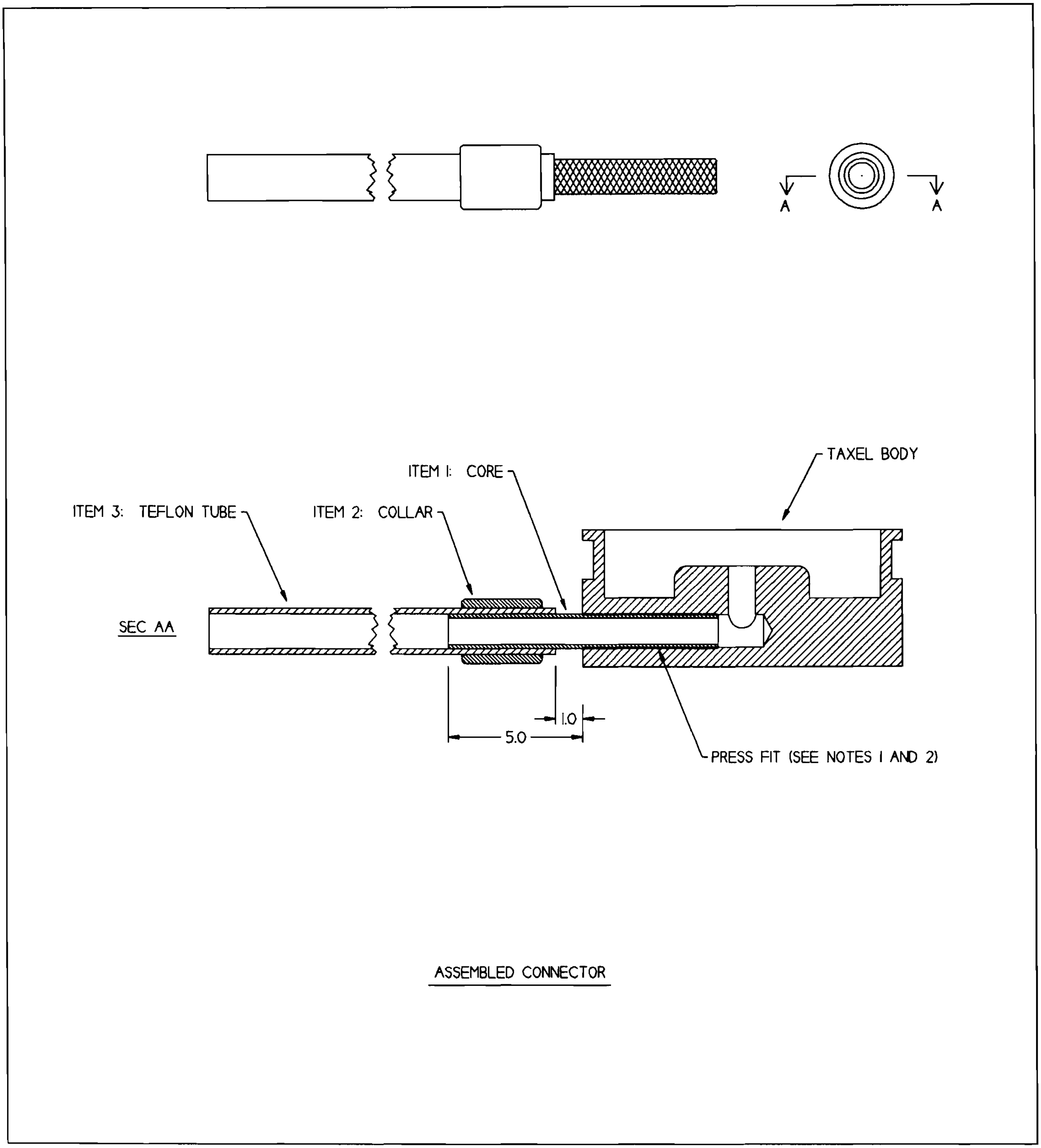


Figure 24: Assembly drawing of tubing adapter to taxel. Drawing TDRV3127-2.

2.7. Tactile Display Panels

The concept of a removable discrete taxel permits a large degree of flexibility in terms of the allowed taxel distributions over the display suit. However, this adaptablilty to various applications must be traded off against the time required to fully configure a suit with 512 taxels, the suit donning/doffing time, and the maintenance of personal hygiene across multiple users. A compromise between these issues was struck by grouping the taxels into standard panels, or display modules, that could readily be attached or removed from a personal substrate or undergarment of elastic fabric. In this manner, some customization of taxel placement could be obtained depending on the particular taxel number and distribution within each display panel and placement of panels over the undergarment. Correspondingly, the donning/doffing time would be vastly improved as only a relatively small number of standard panels would need to be installed/removed each time, and the issue of personal hygiene would be addressed by the ability to launder the undergarment without restriction.

For convenience, the 512 taxels of the WAM TDS were grouped into eight standard display panels, each panel containing 64 taxels arranged on a 6x11 grid and spaced on 15 mm centers. The layout of a standard WAM tactile display panel is illustrated in **Figure 25**. The panel material was SPANDEX® elastic/nylon fabric, with taxels initially installed on 16 mm centers to allow for a 5-7% dimensional shrinkage after snapring installation. **Figure 26** shows the front of the panel, and illustrates the appearance of the snaprings as they hold the taxels in place on the panel surface. **Figure 27** is a photograph of the back of the panel, and shows the panel back cover and cover zipper. An interior view of the panel is shown in **Figure 28** and illustrates the tube routing pattern and method of anchoring of the cable sheath at the snap-covered ends. A close-up of panel interior is presented in **Figure 29** and shows a taxel just prior to installation. The installation process requires only a standard snapring tool, and takes approximately a minute. A completed tactile display panel is shown in **Figure 30** and is ready for installation into the TDS. This latter step would entail attachment of the manifold connectors to a display valve module and zipping-in the panel onto a SPANDEX® undergarment or suit.

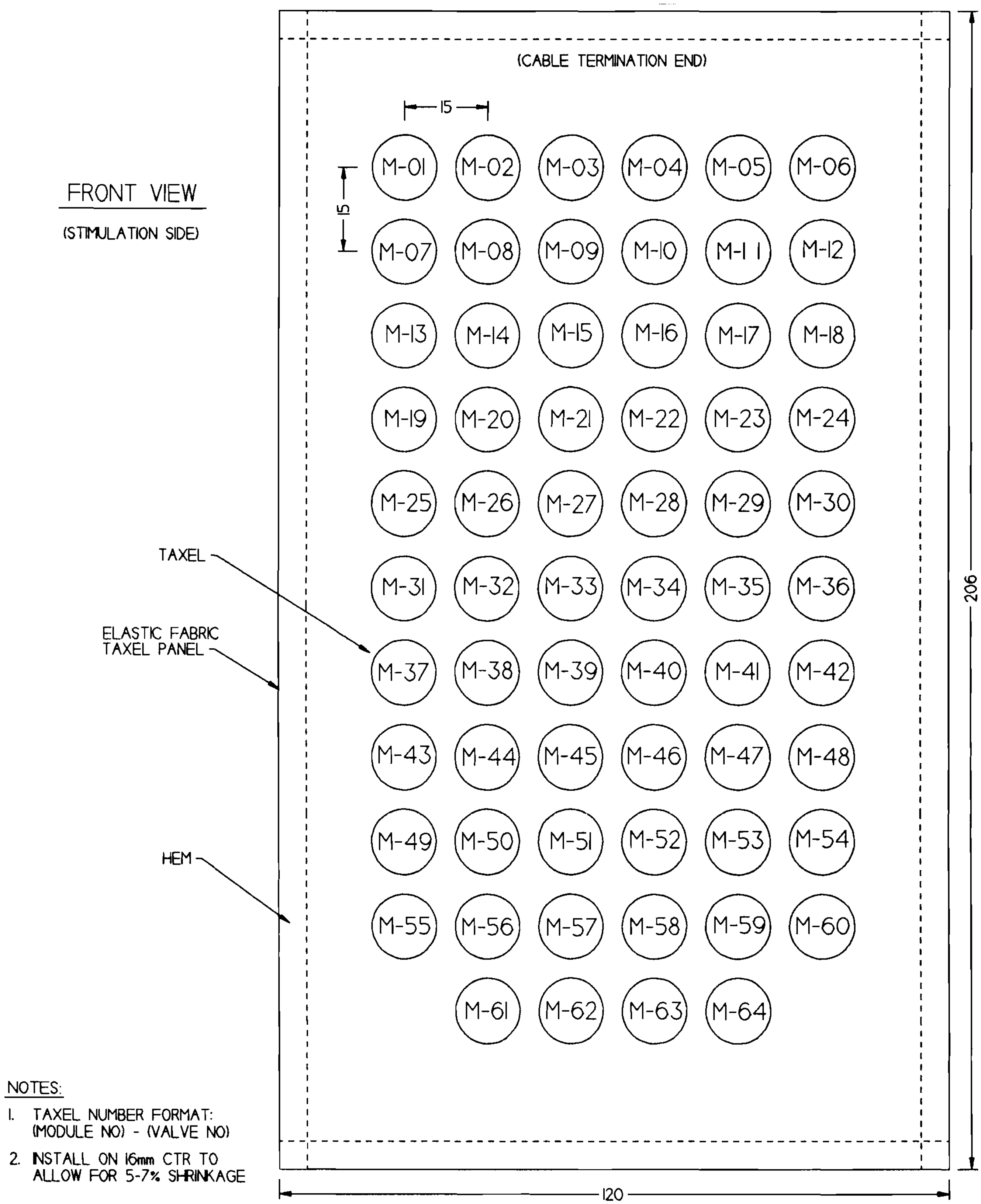


Figure 25: Layout of standard WAM tactile display panel. The panel material was SPANDEX® elastic/nylon fabric with taxels installed on 15 mm centers. Not shown are the zipper tabs placed on the left and right edges, or snaps at the top and bottom edges for closing the end of the panel and anchoring the cable sheath. Drawing TDRV3132-1.

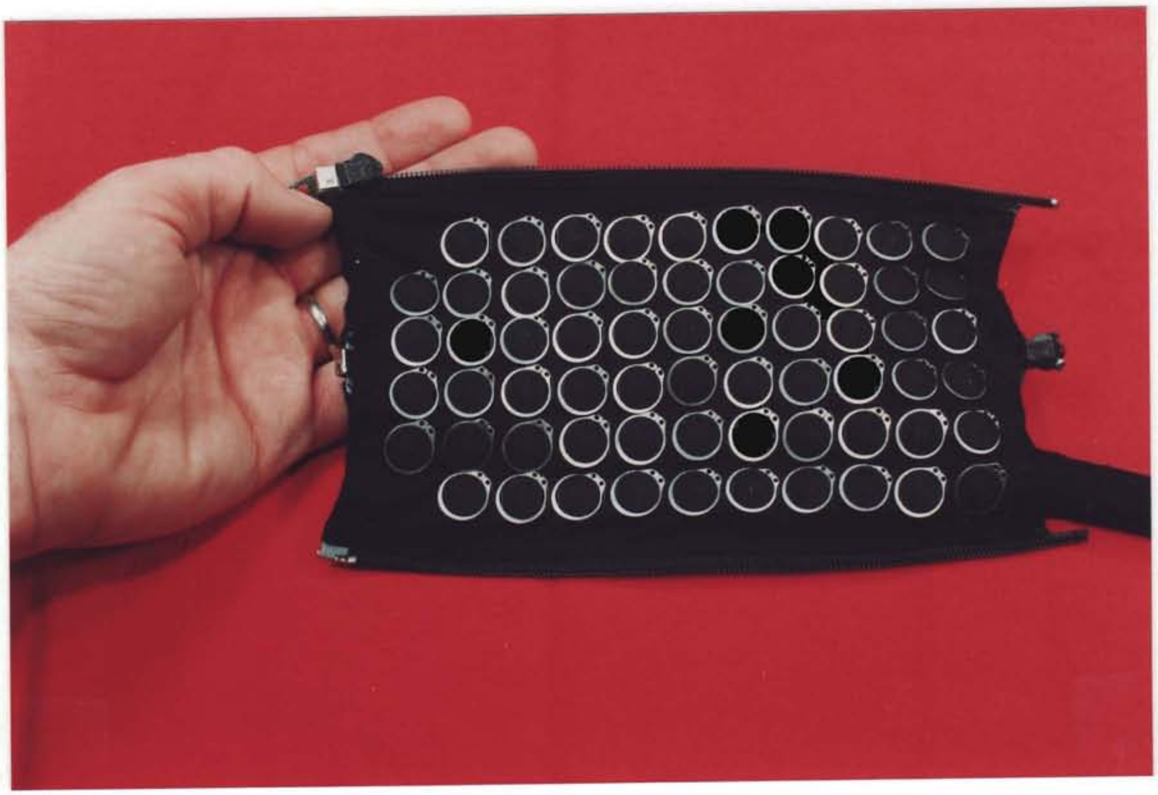


Figure 26: Front view (stimulation side) of standard WAM tactile display panel illustrating how taxels are pushed through panel fabric and clamped to the surface by means of snaprings. Zipper strips on top and bottom edge are used to attach the display panel to the SPANDEX® undergarment. Photo WAM-020196B-21.

Figure 27: Rear view (inactive side) of standard WAM tactile display panel showing rear cover panel. Access to taxels and tubing is made through the center zipper. Photo WAM-020196B-22.

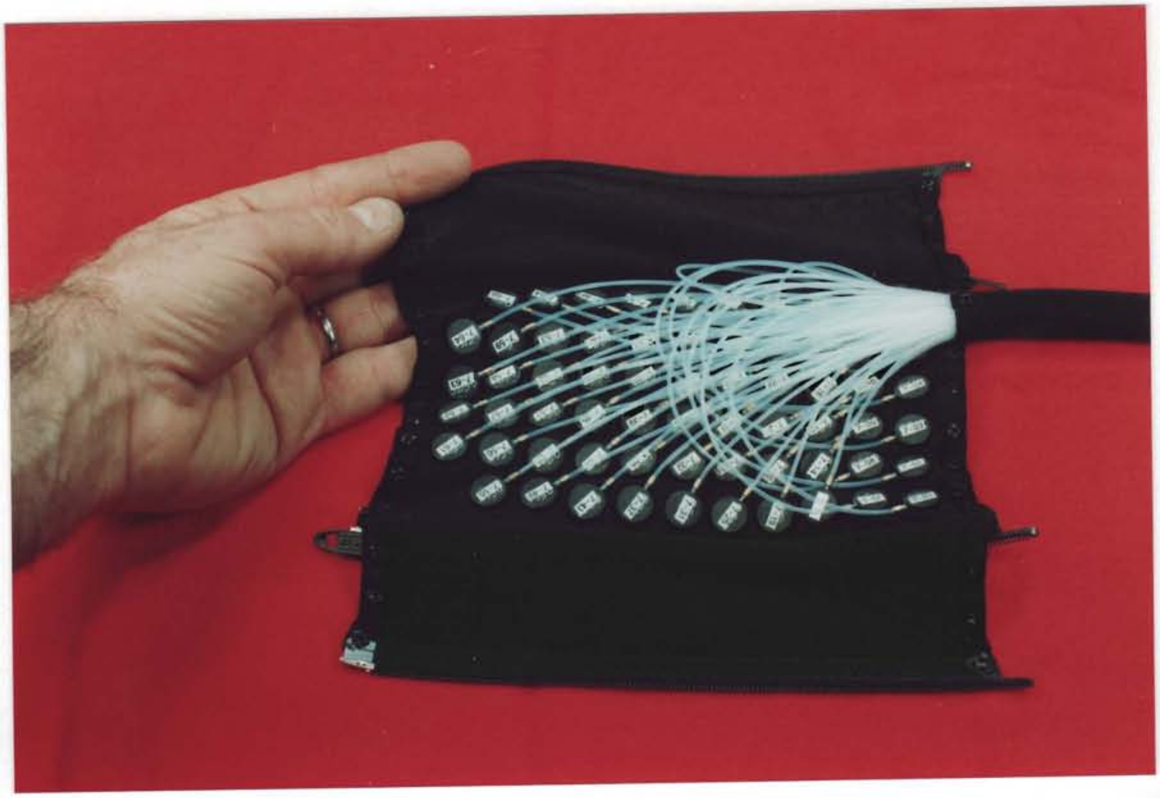


Figure 28: Interior view of standard WAM tactile display panel showing placement of taxels and tubing routing. Longitudinally-zippered cable sheath (at right) is anchored to panel by means of snaps at end of panel. Photo WAM-020196B-23.

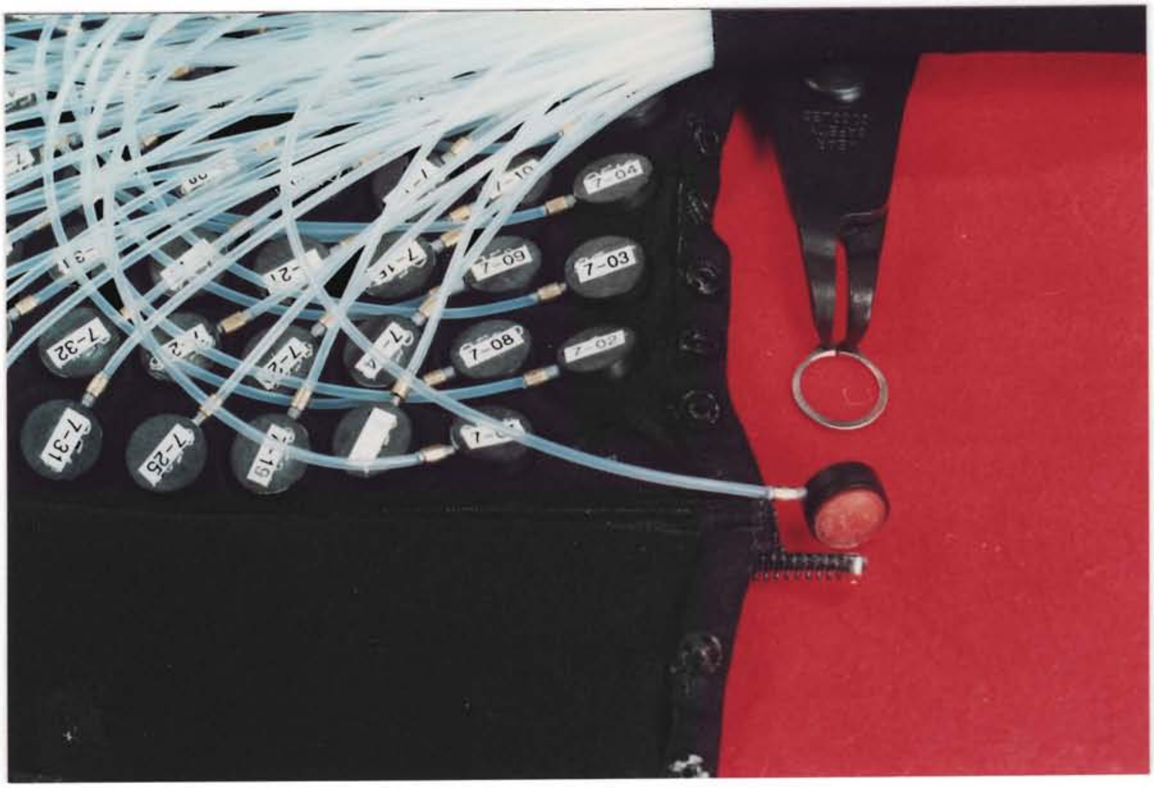


Figure 29: Close-up of display panel interior showing a taxel just prior to installation. Note presence of wear disk (milky film) over the taxel membrane (brown). A standard snapring tool is used to install snapring once taxel is properly positioned. Photo WAM201096B-24.

Figure 30: Completed tactile display panel assembly. Panel installation into the TDS would entail connection of the manifold connectors (top) to a display valve module and zipping-in the panel (bottom) onto a SPANDEX® undergarment or suit. Photo WAM-020196A-28.

3. DISPLAY DRIVER DEVELOPMENT

One of the tasks of this Phase II project was to develop a new version of a high-density tactile display driver and associated control electronics. The resulting driver package is shown in **Figure 31** to **Figure 33**, with the corresponding mechanical drawings appearing in Appendix A. The principal features of these advanced valve modules are:

- Each module was capable of driving up to 64 taxels, thereby requiring only 8 modules to drive the 512 taxels on the display suit.

- The Pulse-Width Modulation (PWM) circuitry controlling the valve duty cycle was miniaturized and mounted directly within the valve module.

- The manifold system could accommodate up to 72 valves, thereby making up to 8 available for conveniently overcoming the problem of valve failure during service. (During the course of development, it was determined that such failure was not as frequent a problem as originally anticipated, so only 4 spare valves were included with each valve module.)

- A vacuum manifold was coupled directly to each valve exhaust port so as to lower the taxel height in the unexcited state and to speed taxel deflation, thereby reducing the taxel response time.

The most significant improvement of the tactile display system over previous versions was the incorporation of the PWM valve control circuitry within the enclosure containing the valve manifolds. After production and testing of a high-density wirewrapped PWM circuit utilizing DIP components, an SMT-PCB version was designed and fabricated by an external PCB service. A photograph of the PCB PWM board is shown in **Figure 34**, and the full electrical schematics presented in APPENDIX B. An advantage of this approach was the elimination of an intermediate PWM control unit and 16 associated electrical cables present on earlier versions of the TDS, as now a single 68-lead SCSI cable could be used to directly connect the D/A output cards associated with the tactile data processors to the tactile display driver modules. (Theoretically, the Tactile Display Processors are not required to control the taxels, as any 0-5 V analog control signal applied to the inputs of the PWM control cards would suffice.)

Figure 35 and **Figure 36** illustrate how the eight valve modules were mounted in a support structure and the associated pneumatic plumbing attached and routed. Pressure testing at 650 kPa (95 psi) after attachment of all taxels revealed no noticeable pressure leakage, but a very significant leakage to the exhaust (vacuum) side was noted. A relatively large capacity vacuum pump rated at 1.6 L/s (3.3 cfm) could only produce a vacuum level of -14 kPa (-2 psi) with no taxels active, and it was estimated that a pumping capacity of approximately 20 L/s (41 cfm) would be required to achieve and maintain the desired vacuum level under moderate taxel activation. Such a pump would not only be expensive, but noisy and require a separate power line or, in the case of a jet vacuum pump, a air supply capable of delivering very high air flow rates. Due to the relatively modest increase in taxel performance provided by vacuum assistance (i.e., 5-15% improvement in response time), utilizing such a pump was judged not to be cost effective. Therefore, the vacuum pump was omitted from the delivered TDS, and the PWM frequency dropped slightly from 5 Hz to 4.5 Hz to compensate for the longer taxel response time. However, one retained benefit of the vacuum manifold was silencing of the valve exhaust noise level to non-disturbing levels.

Figure 37 shows the appearance of the tactile display driver assembly positioned within the system rackmount enclosure. Each 64-taxel display panel module was connected to a corresponding valve display module via pneumatic TEFLON® tubing. The tubing cable was protected in a zippered cloth sheath with strain reliefs on both ends of the sheath.

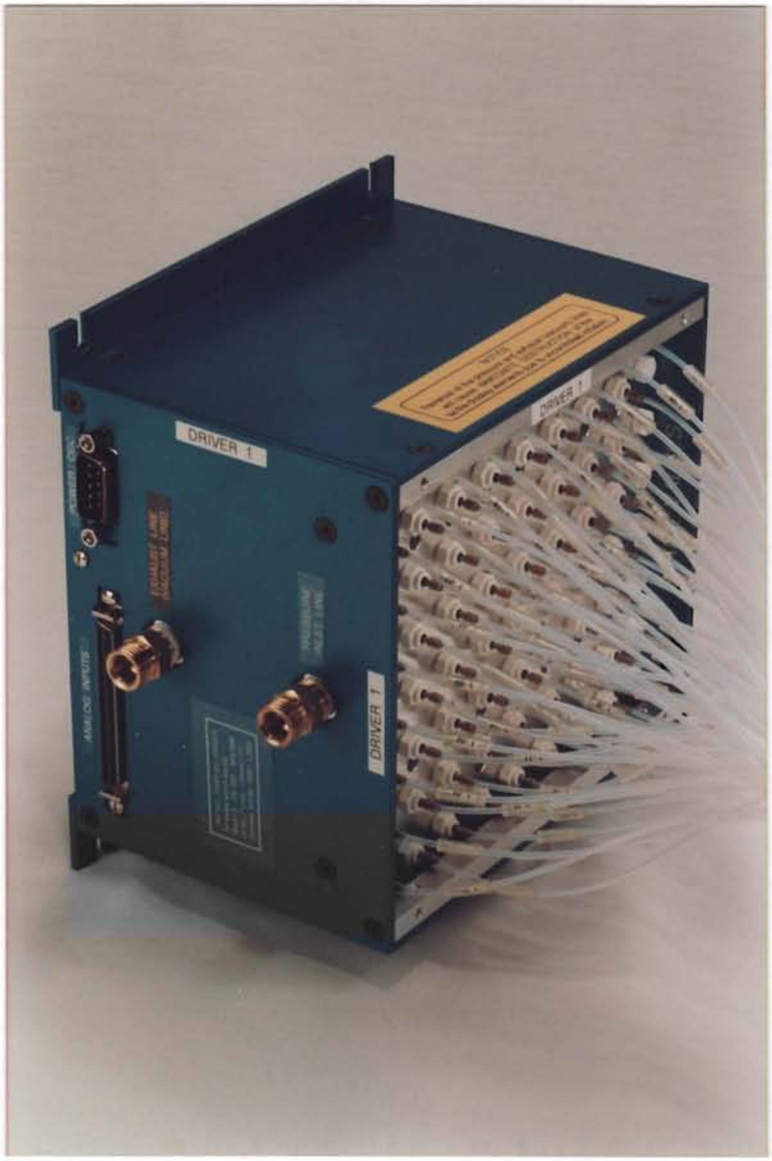


Figure 31: One of eight valve modules used in the Tactile Display System, each capable of driving 64 taxels. Front view shows pneumatic tubing connected to exhaust ports on pressure manifold (left), pressure inlet and vent ports (center), analog input connector (lower-left), and power/PWM waveform input connector (upper-right). Photo WAM-020696A-05.

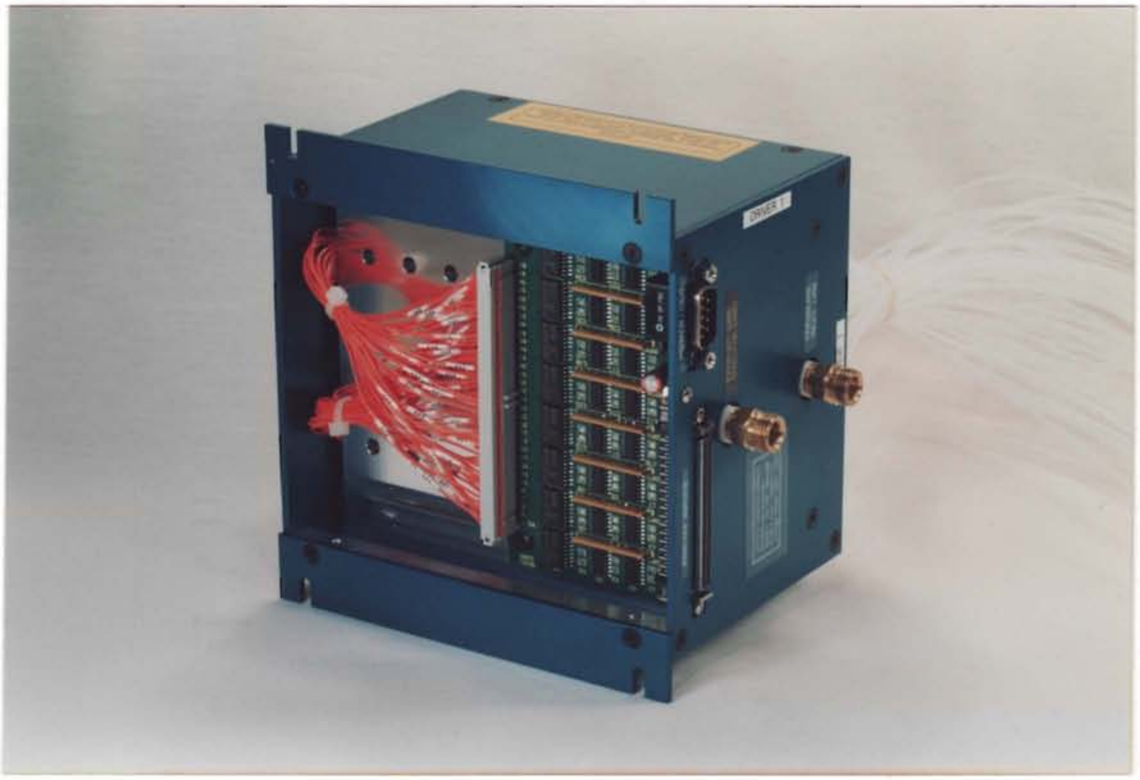


Figure 32: Rear view of valve module showing PCB-version of PWM valve control board, valve leads (orange), and mounting flanges. Photo WAM-020696A-10.

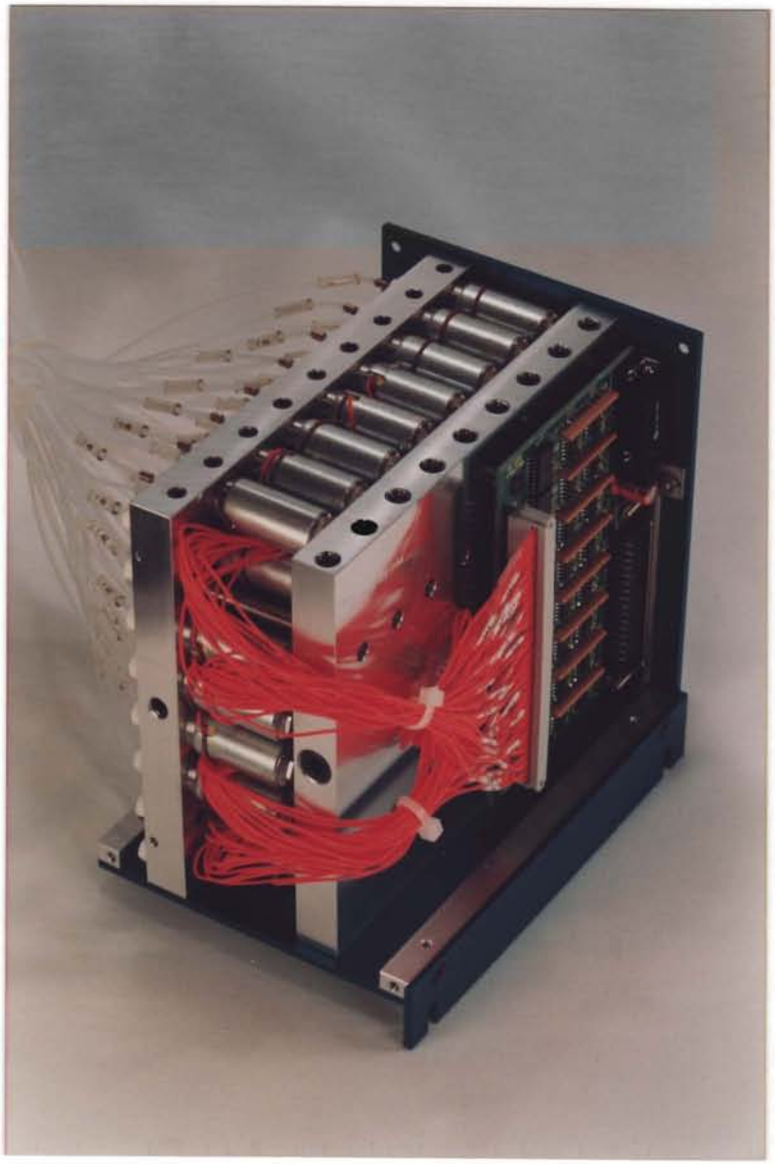


Figure 33: Tactile display valve module with covers removed showing the internal arrangement of pressure and venting manifolds, valves (the four closest the viewer are spares), valve leads, and PWM control board. Photo WAM-020696A-24.

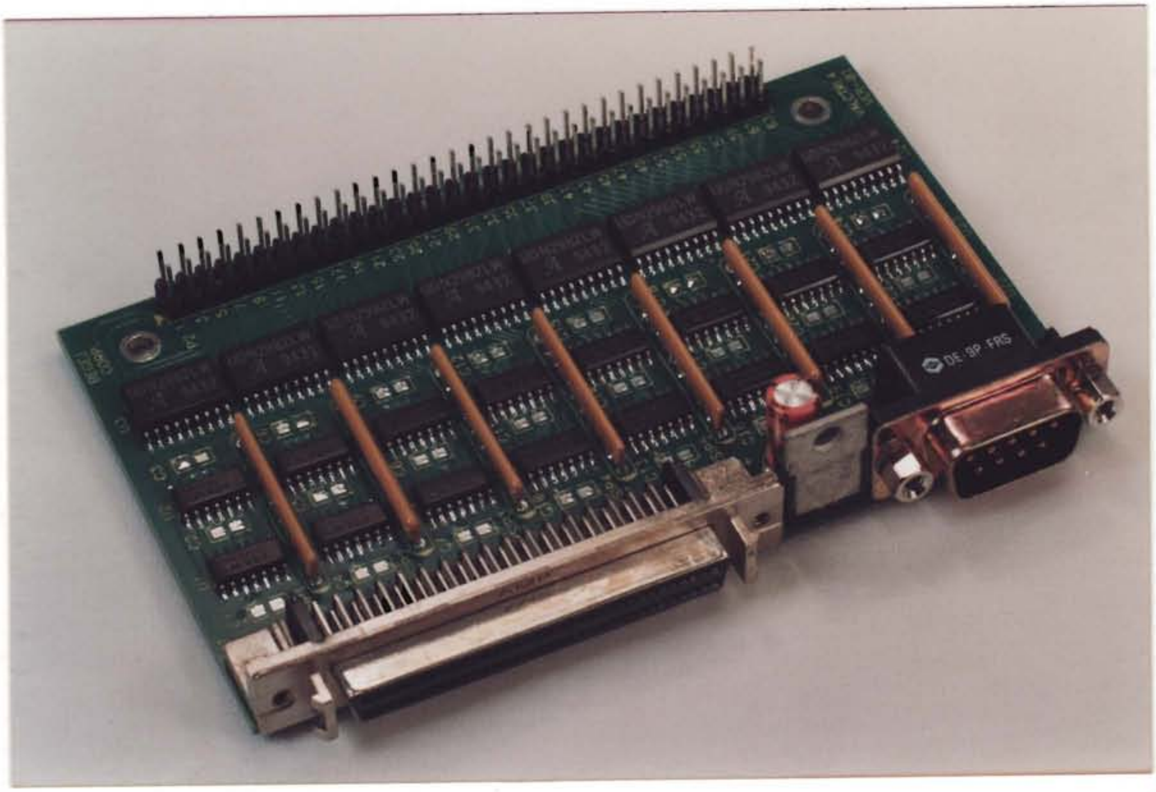


Figure 34: PCB-version of the PWM valve control circuit. The PWM ramp waveform and power (+24V) are supplied through the DB-9 connector at right, while the analog control signals for each or the 64 valves (taxels) enter through the 68-pin SCSI connector at left. Photo WAM-020696A-12.

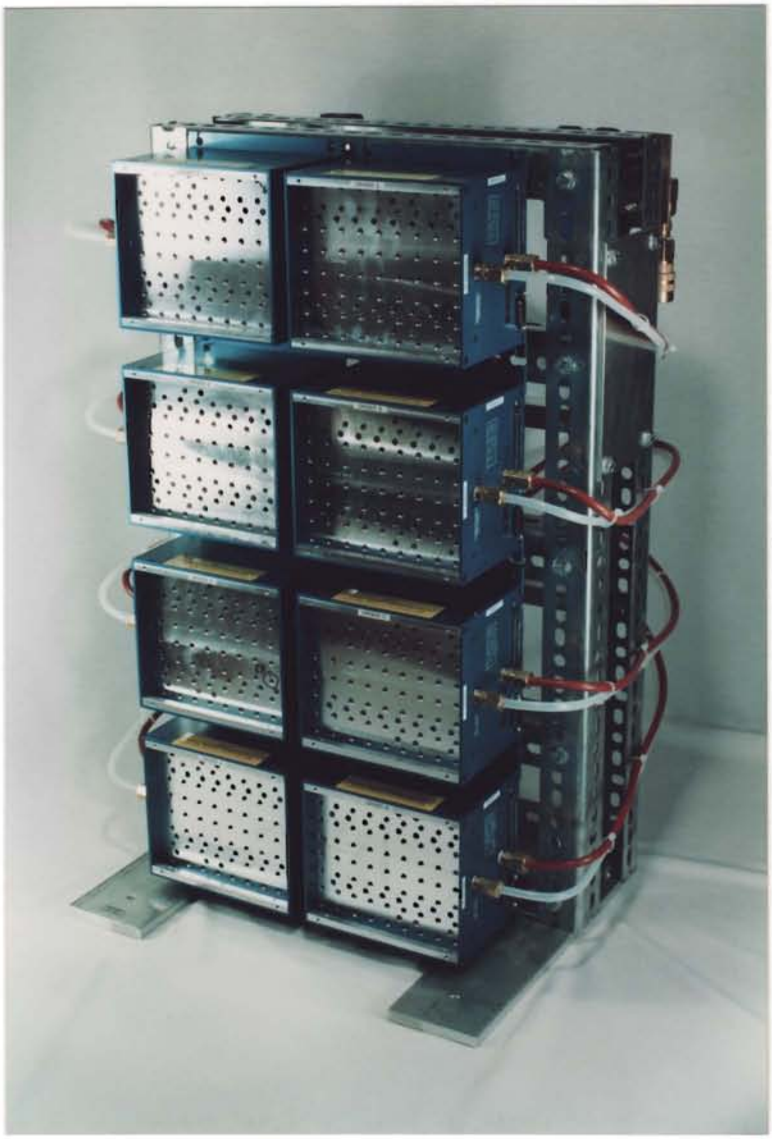


Figure 35: Front view of support structure for 8 TDS valve modules showing ports in pressure manifolds to which taxel tubing would be attached. Photo WAM-020196A-04.

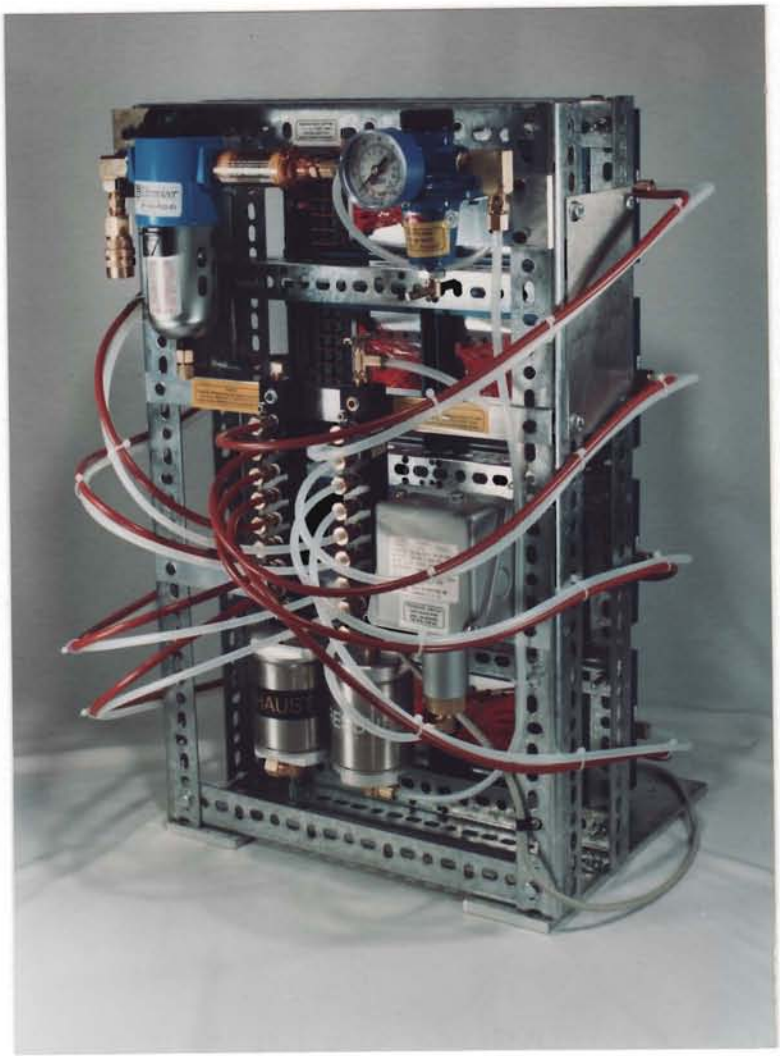


Figure 36: Rear view of the TDS driver module support structure. The quick-disconnect (top-left) is the inlet for dry, oil-free which is fed into a backup bulk de-watering unit (blue), dryer cartridge (amber), system pressure regulator, and the pressure accumulator cylinder (lower-right). The latter is attached to a distribution manifold with connections (white tubing) to each of the pressure manifolds in the valve modules. Each corresponding vent manifold in the valve modules is connected (brown tubing) to a vacuum, or exhaust, distribution manifold and vacuum accumulator cylinder. Photo WAM-020196A-01.

4. ELECTRICAL COMPONENTS of the TACTILE DISPLAY SYSTEM

4.1. Introduction

In addition to the previously-discussed driver valves modules and their associated PWM control cards, the Tactile Display System has four additional electrical and/or computing sections. These are illustrated in **Figure 38**, and are listed below:

- AC Power Center
- Display Driver Controller
- Driver Power Supply
- Tactile Data Processor

A discussion of the function and construction details are provided in the following sections.

4.2. AC Power Control Center

The purpose of the AC Power Center is to provide a single turnkey power control point for the entire TDS. Photographs of the AC Power Center are shown in **Figure 39**, and a block diagram indicating its control functions presented in **Figure 40**. Additionally, an electrical schematic is presented in **Figure 41**.

The AC Power Center distributes 120 VAC to the various TDS subsystems such as the Display Driver Controller, Driver Power Supply, Tactile Data Processors and associated peripherals. It differs from standard distribution centers in two ways. First, the output is latched so as to insure uniform TDS startup and shutdown during normal operation or in the event of any significant AC line interruption. Secondly, the AC Power Center has a 120 VAC sensor that is interfaced with the Display Driver Controller interlock circuit, and will immediately disable the display driver power supply relay should any line power interruption occur. Both features were deemed necessary to prevent any possibility of suit activation during periods when the various control circuits and software were in a transient state associated with startup, shutdown, or line glitches. Additionally, the outlets of the Power Center are type EAC-305, and are intended to minimize the possibility of inadvertently connecting any TDS component to any other power source other than the AC Power Center.

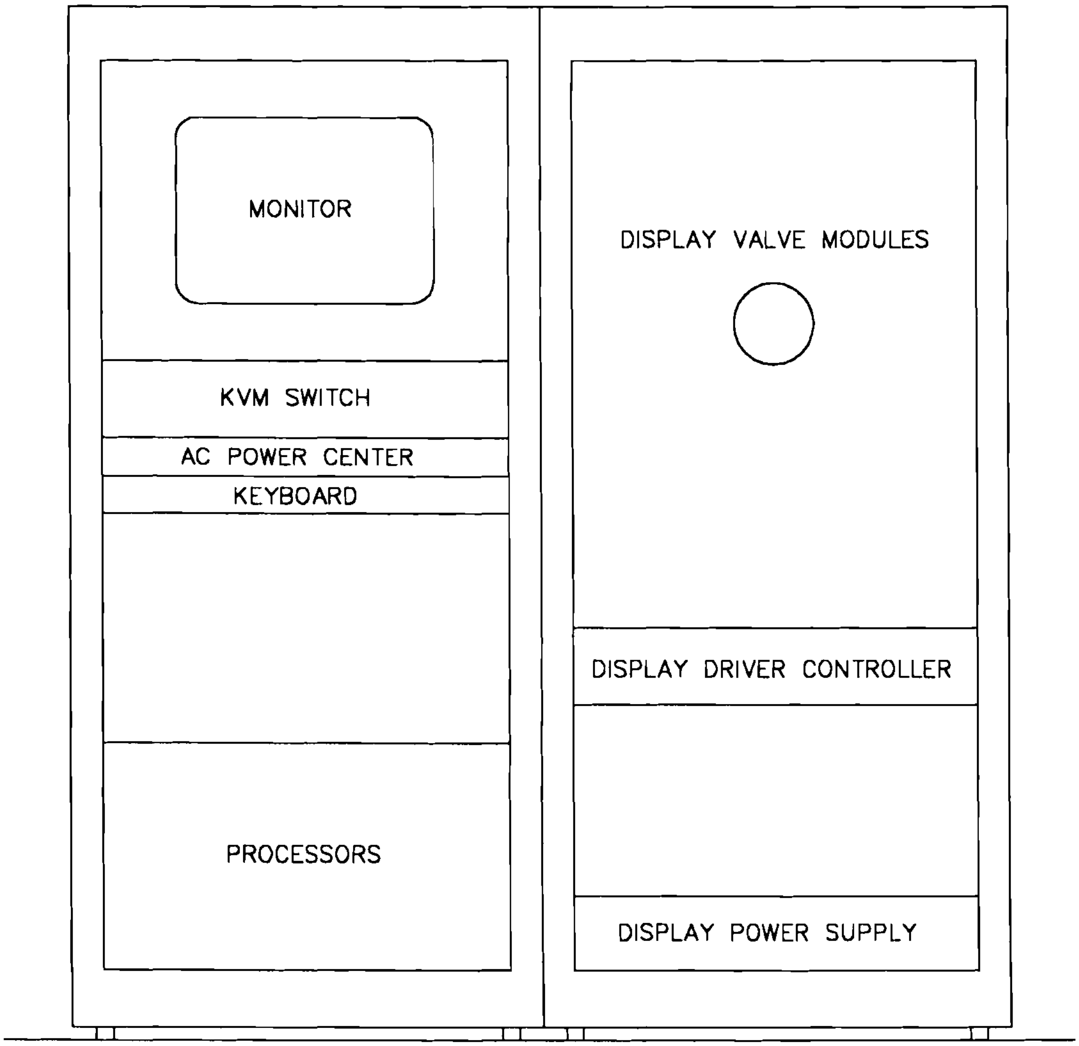


Figure 38: Block/physical diagram of the main electrical and computing components of the Tactile Display System. Drawing TDSDIAG1-1.

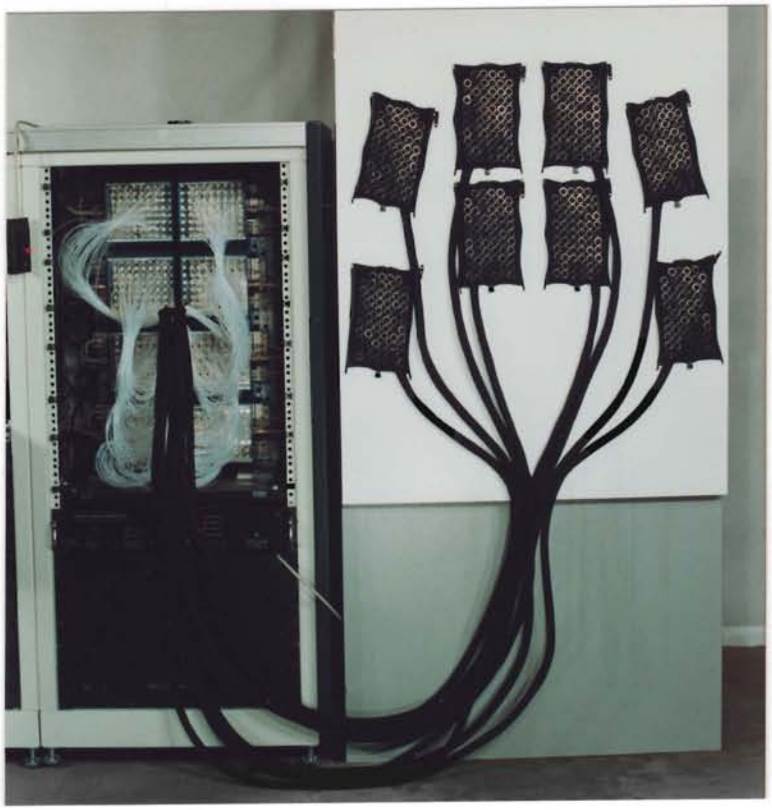


Figure 37: Attachment of the TDS panels to the driver array mounted within the system rack enclosure. Each 64-taxel display panel array is connected to a corresponding valve module via pneumatic TEFLON® tubing. The tubing cable is protected in a zippered cloth sheath with strain relief's on both ends of the sheath. Photo WAM-170696A-22.

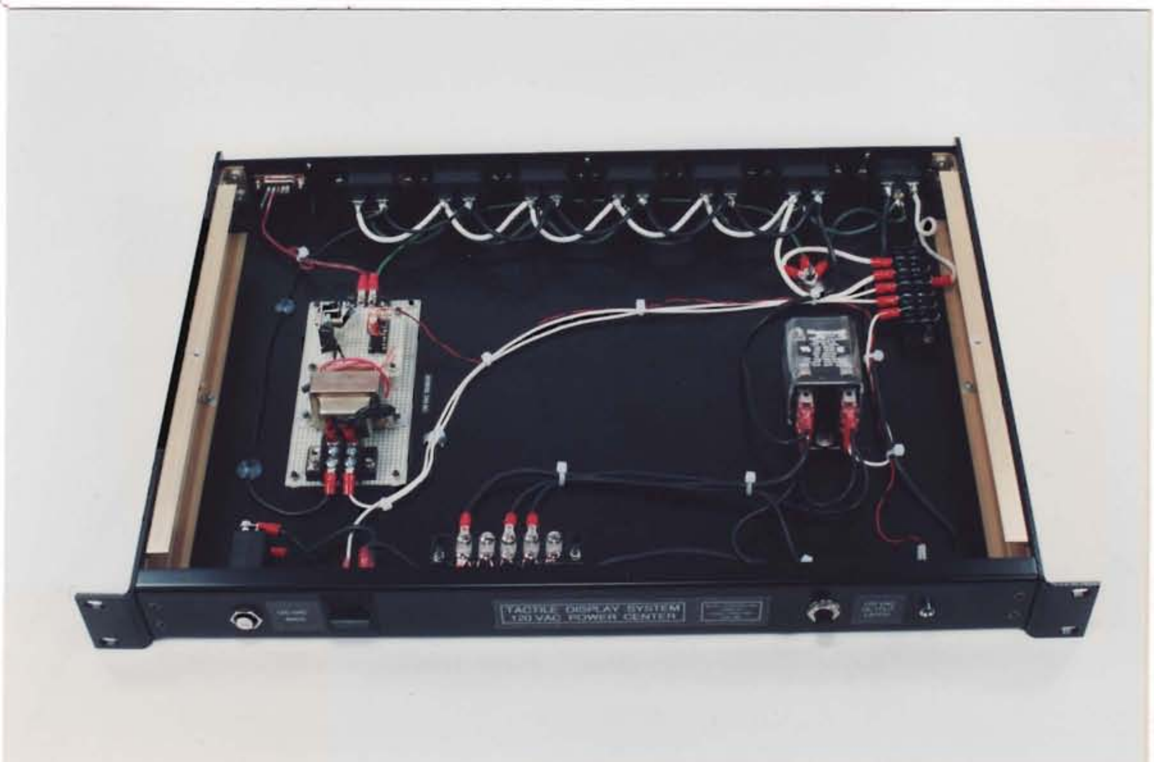


Figure 39: AC Power Center for the Tactile Display System. Top photo (WAM-010596-09) shows assembled center with main TDS power switch on the left and latch relay button on the right. Bottom photo (WAM-010596-07) shows 120 VAC sensor circuit on left and latch relay on right.

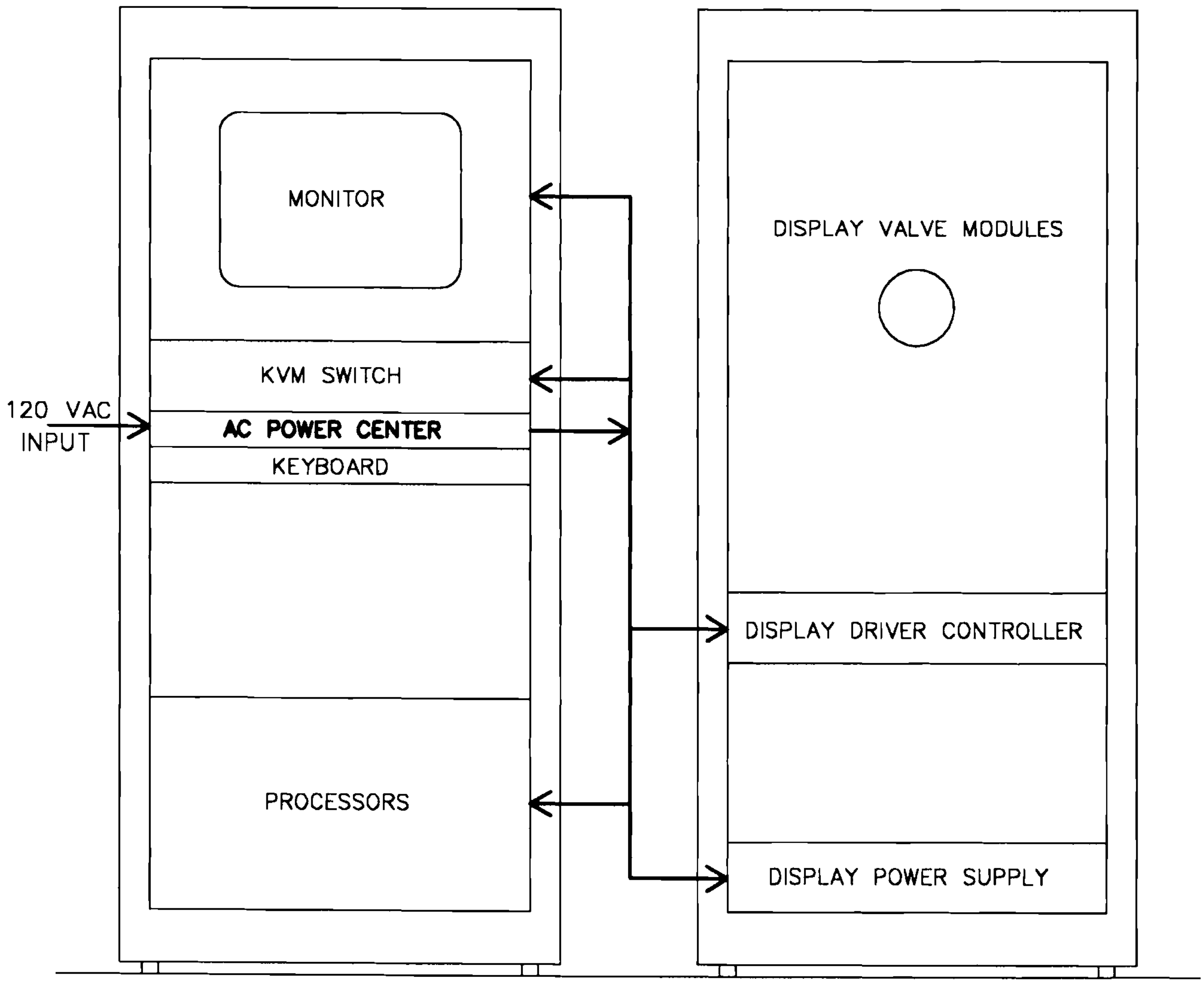


Figure 40: Block/physical diagram indicating the TDS modules or subsystems controlled by the AC Power Center. Drawing TDSDIAG1-2.

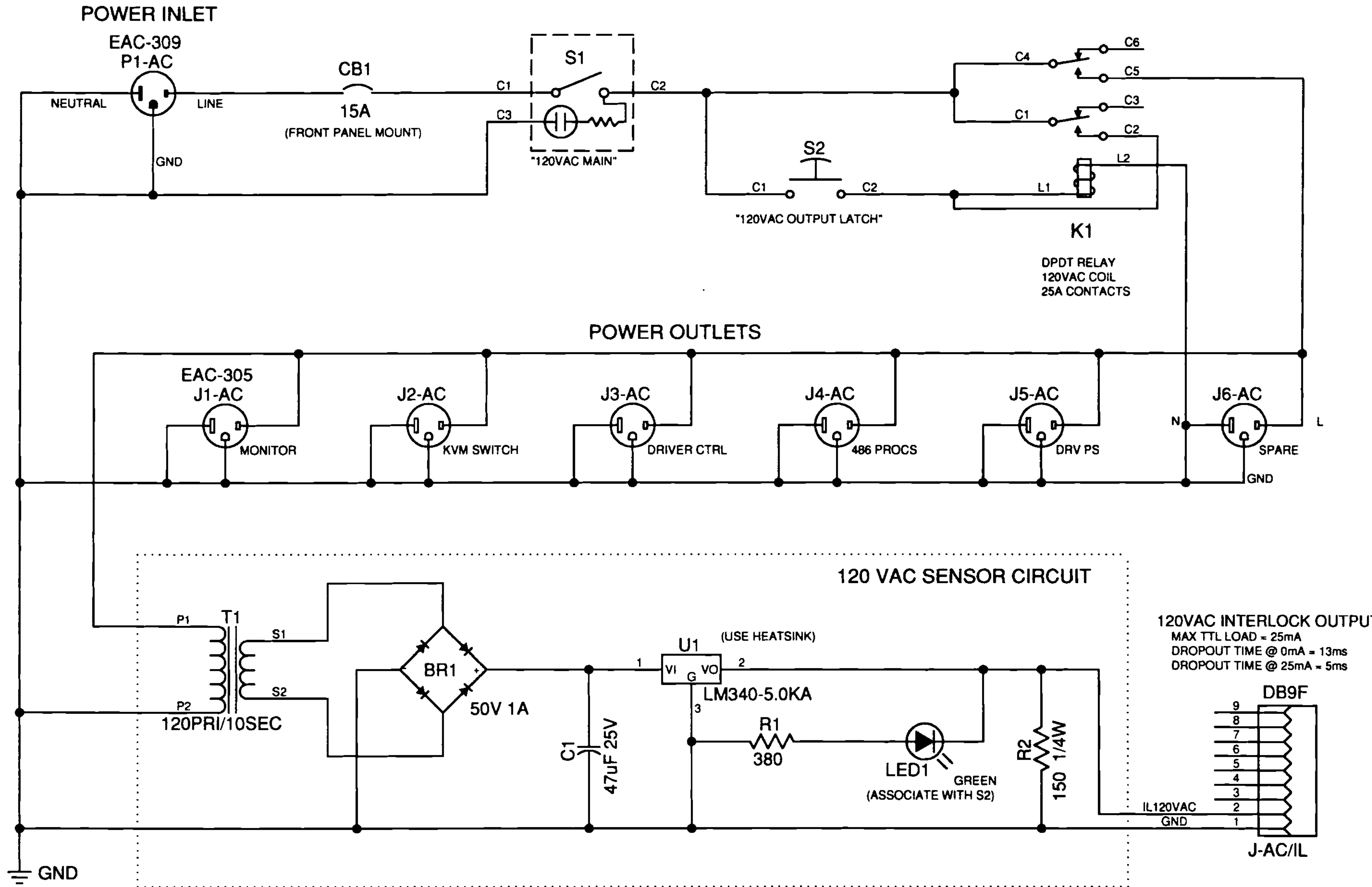


Figure 41: Electrical schematic of the AC Power Center. Dwg ACPWRCTL.

4.3. Display Driver Controller

A system-level block/physical diagram of the Display Driver Controller (DDC) is presented in **Figure 42**. The DDC performs three functions within the TDS:

- Monitors various system safety and equipment protection interlocks,
- Controls the main power (24 VDC) supplied to the display valve modules, and
- Supplies the PWM ramp waveform to the display valve modules.

Photographs of the DDC hardware are shown in **Figure 43** and **Figure 44**, and a block function and connector diagram is shown in **Figure 45**. The complete electrical schematics for the DDC appear in Appendix C.

As illustrated in **Figure 43**, the front panel of the DDC contains an ON/OFF switch and various indicator lamps. The "PWM WAVEFORM OUTPUT STATUS" lamp indicates whether the PWM ramp output waveform is being generated, in which case the green lamp will flash at 4.5 Hz. Additionally, the red "UNCALIBRATED" LED indicates whether the waveform is within satisfactory limits: if not, the red lamp will flash briefly for mildly uncalibrated states or be ON continuously if the waveform is far from specifications. Any activity of the red lamp indicates recalibration is required.

Another bank of red LED's on the front panel are the "SYSTEM INTERLOCK FAULT" indicators, and alight whenever a fault condition exists on one of the interlock lines:

- MANUAL: Controlled by a manual switch accessible to the operator at all times to allow for display disablement during suit adjustment or testing.
- EXCESSIVE PRESSURE: A pressure switch monitors the air line to the display valve manifolds for pressure that significantly exceed the rating of the valves (690 kPa, or 100 psi).
- INSUFFICIENT VACUUM: A vacuum switch monitors the exhaust line from the display valve manifolds for vacuum levels that significantly fail to meet a set minimum value (approximately -50 kPa, or -7 psi).

(Note: this switch was omitted from the delivered version of the TDS, and the fault indicator overridden.)

- AC POWER: Connected to a sensor in the AC Power Center module that monitors for loss of primary AC power.
- PROCESSOR No. 1 to 4: Connected to each or four Tactile Data Processors to insure that the software on each unit is running properly prior to TDS activation.

The final indicator on the front panel is the green "DISPLAY SYSTEM ENABLED" LED at the far right, and signals that 24 VDC power is being supplied to the display valve modules and that the TDS is ready for operation. This activation occurs only when all interlock fault lights are extinguished.

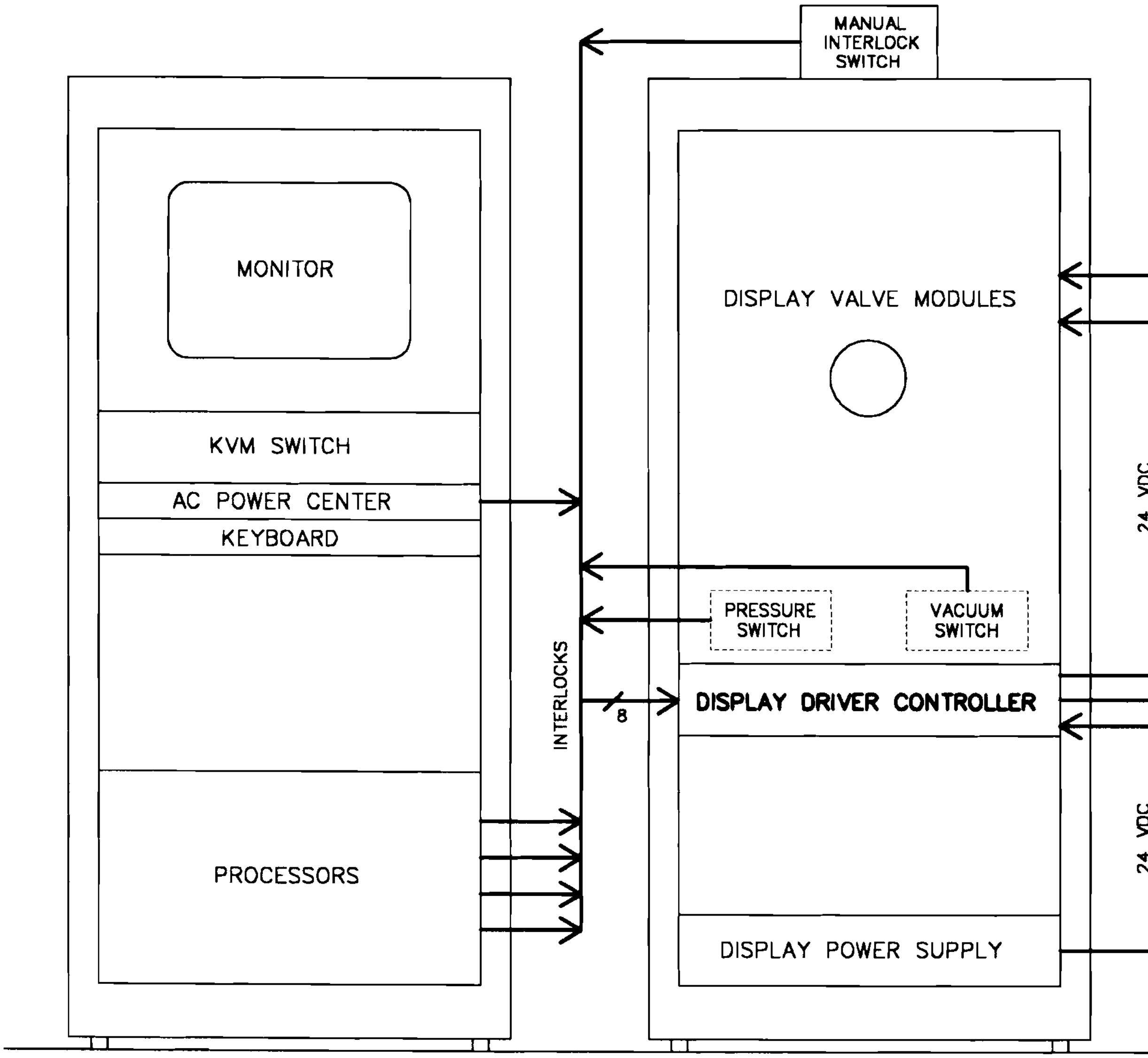


Figure 42: Block/physical diagram illustrating functions performed by the Display Driver Controller. Drawing TDVDIAG1-3.

Figure 43: Display Driver Controller (DDC) for the TDS. Top photo shows front panel with associated PWM waveform, interlock status, and TDS status indicator lights. Bottom photo shows rear panel and connectors for interlocks (left), display power supply (center), and display output (right). Photos WAM-010596-24 and WAM-010596-25, respectively.

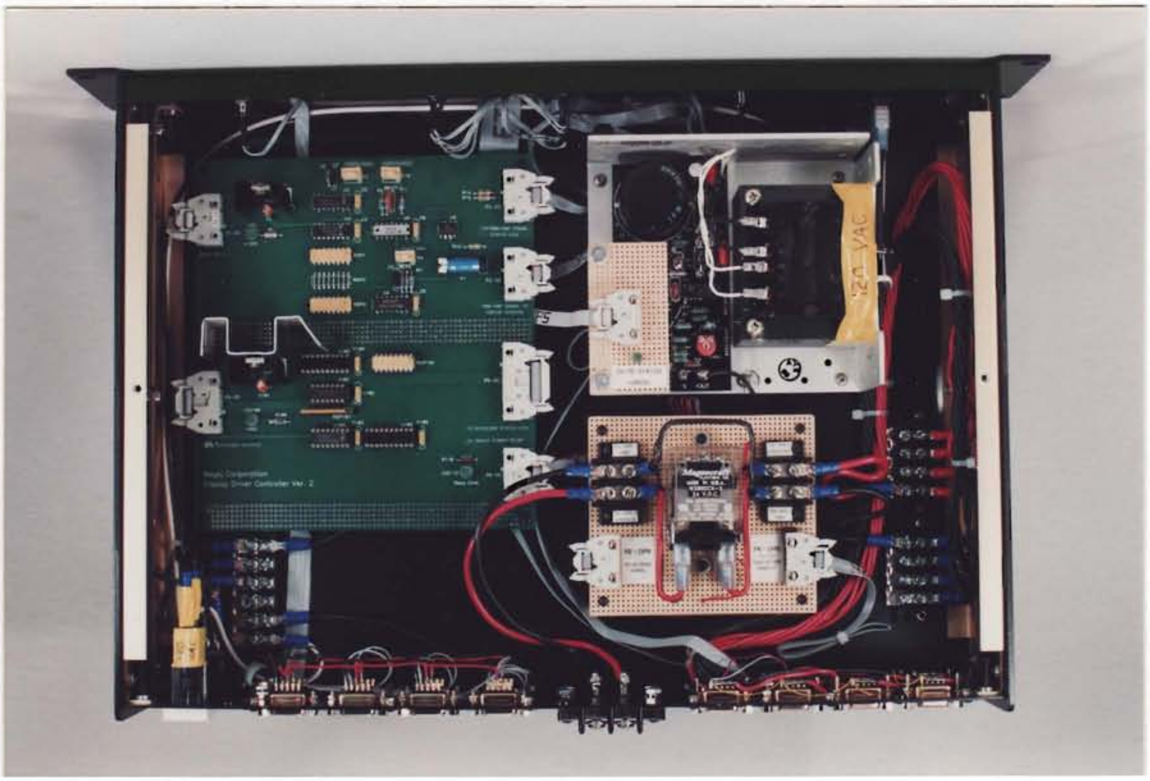


Figure 44: Interior view of Display Driver Controller (DDC) for the TDS. Shown is the front panel (top), driver controller PC board (left) which houses the PWM ramp waveform generator and interlock logic circuits, DDC local power supply (top right), driver power relay (center), and back-panel connectors (bottom). Photo WAM-010596-18.

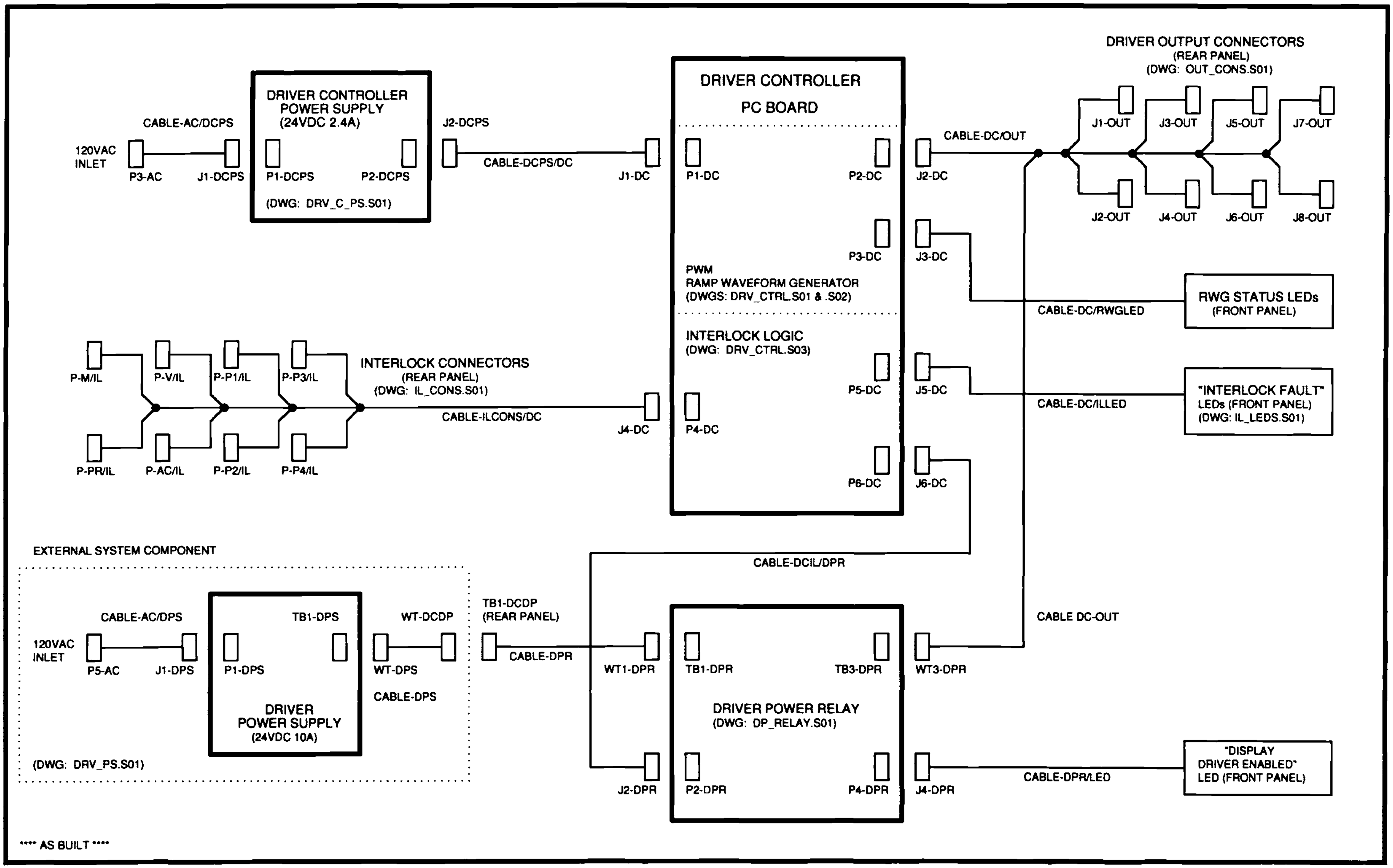


Figure 45: Block and connector diagram concerning the Display Driver Controller (DDC). Drawing CON-LIST.

4.4. Display Power Supply

The function of the Display Power Supply (DPS) module was to provide primary power at 24 VDC to the display valves. This power was routed through the Display Driver Controller module to insure proper TDS operation, as illustrated in **Figure 42**. Originally, the DPS was housed within the Display Driver Controller module, but was removed for the delivered system and installed as a separate module to permit more convenient upgrading. Photographs and an electrical schematic of the DDC are shown in **Figure 46** and **Figure 47**, respectively.

The DPS rating was 10 A continuous at 24 VDC (or 16.5 A peak for $t < 100$ ms) and, as illustrated in **Figure 48**, was considered adequate to reliably energize approximately 175 valves simultaneously. This power supply size was considered adequate for the TDS, as it was not expected that more than 50-75 taxels would be active at any one time during normal use. It was, furthermore, considered undesirable to utilize a power supply capable of actuating ALL taxels simultaneously (this would require a rating of at least 55 A peak for $t < 100$ ms), as a failure of the Display Driver Controller (e.g., PWM ramp waveform generator) or software programming error may result in ALL 512 taxels to be simultaneously activated and possibly cause severe damage to the TDS or injury to the operator. By limiting the size of the DDC power supply in the manner described, such catastrophes cannot occur as the system then lacks the inherent power to activate all taxels simultaneously.

Should more than 175 taxels require actuation, ample space was provided in the TDS rack for substitution of a larger Display Power Supply (see **Figure 42**). However, it is strongly advised that the peak current be limited to approximately 40 A to minimize the damage of an accidental event involving the simultaneous actuation of all taxels.

Figure 46: Display Power Supply (DPS) module used to supply power to the TDS valves. Shown are front (top), back (center) and interior views (bottom). Photos WAM-010596-14, -13 and -11, respectively.

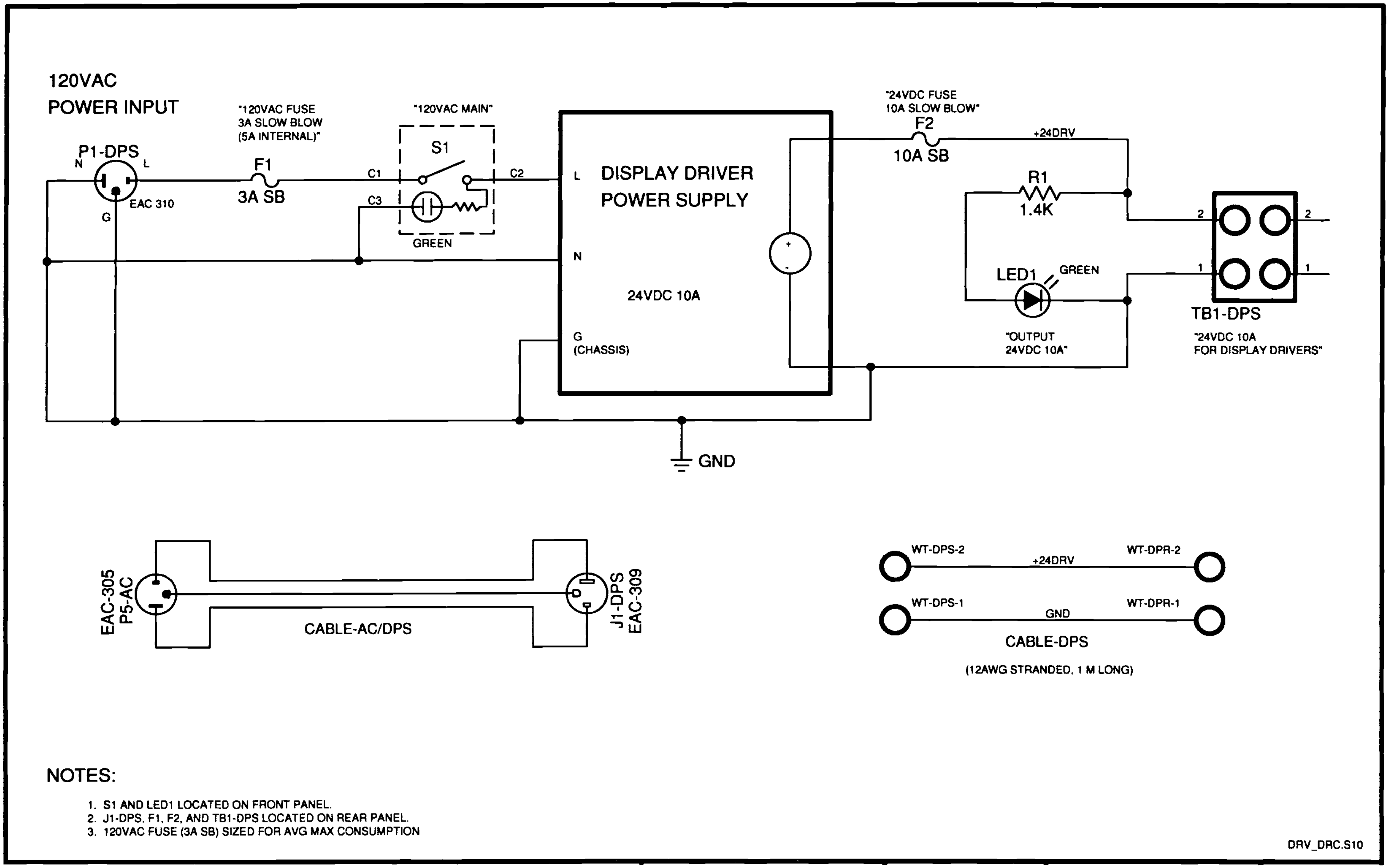


Figure 47: Electrical schematic of Display Power Supply using a SOLA model 86-310-24 switcher rated at 10 A at 24 V (16.5 A peak for t < 100 ms). Drawing DRV-PS.

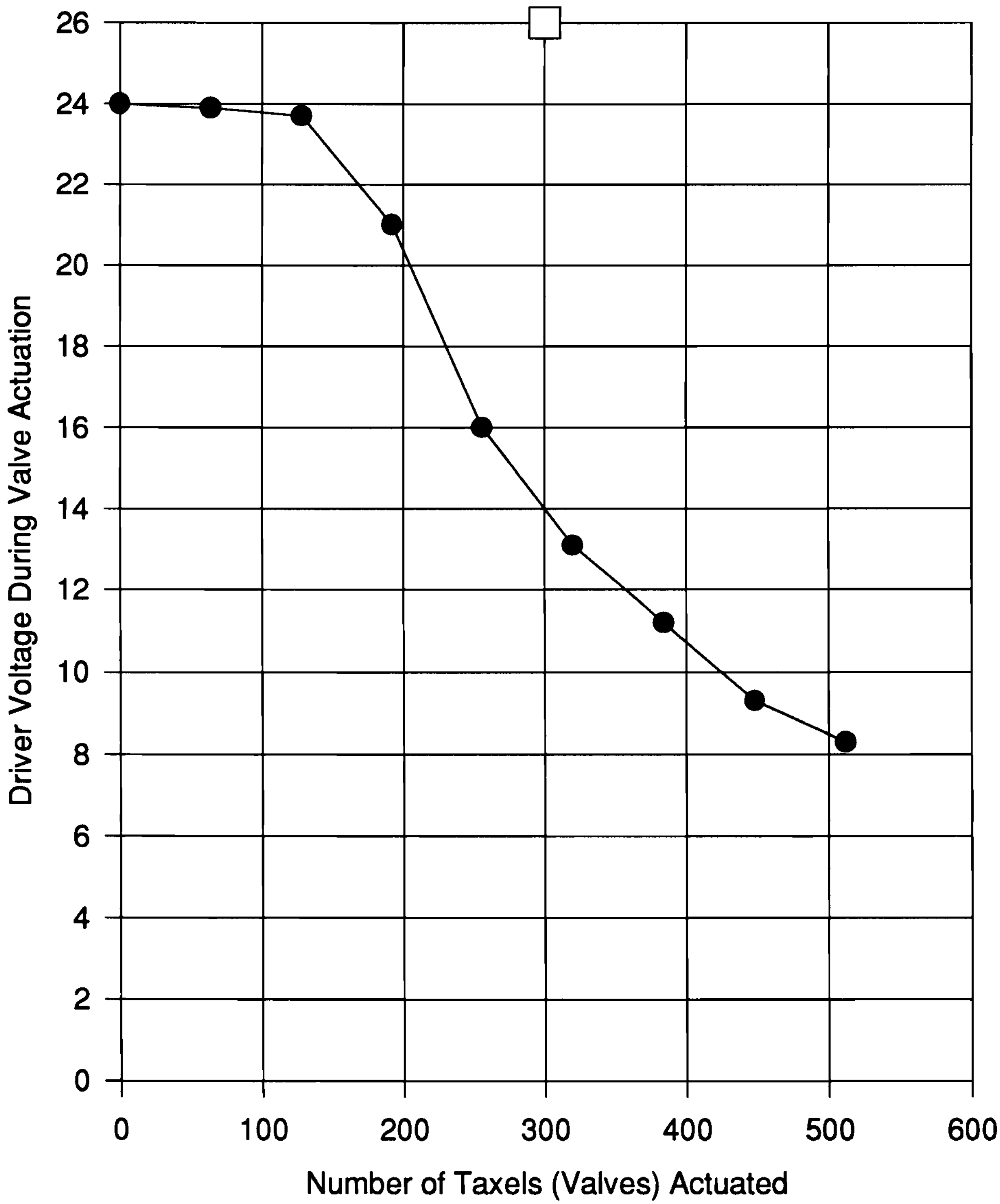


Figure 48: Graph showing output voltage of Driver Power Supply (SOLA model 86-310-24) as a function of the number of taxels (valves) activated. It was concluded that approximately 175 taxels could be simultaneously activated with this power supply, assuming 21.6 V (10% droop) as the cutoff for reliable valve actuation. Graph DRV-PS-2.

5. TACTILE DATA PROCESSORS

5.1. Introduction

Tactile Data Processors (TDP) were included with the Tactile Display System and were intended to serve two primary purposes:

1. Provide a method of conveniently generating multiple test signals for evaluating taxels, display panels, and the tactile display suit during the course of development

2. Provide an interface to an external source of real or virtual tactile sensor signals and be capable of acquiring, conditioning and calibrating such signals.

The following sections will discuss the both the hardware and software aspect of the TDP with regard to the TDS.

5.2. Hardware

The basic appearance of the Tactile Data Processor subsystem is illustrated in **Figure 1** where is it seen to occupy the entire left-hand cabinet of the Tactile Display System. The organization of the TDP at the highest level is revealed in the block/physical diagram shown in **Figure 49**. The processor enclosure contains an industrial computer chassis with a split, 4-segment backplane into which four TDP subsystems have been placed. All four subsystems have been interfaced to a single Keyboard - Video - Mouse (KVM) switch (BLACK BOX ServSwitch Model 721) to permit control of all processors through a single keyboard and monitor. The KVM switch permits all four subsystems to boot-up from the floppy drives without any user intervention. During operation of the TDS, the four processor subsystems run independently in parallel. (However, all taxels are actuated in phase, as they are driven by a single global PWM ramp waveform signal.)

Each of the four processor subsystems contain the following hardware:

- One 486DX2-66 processor card (AXIOM SSC-486VGA) with 1 MB RAM, integral disc controllers and VGA display

- One 3.5" floppy drive (Processor No. 1 has a 40 MB HD containing various utilities and a DOS-based C-code development system)

- Two A/D cards (INDUSTRIAL COMPUTER DESIGNS No. A/D 64-PC) with 64 analog, single-ended inputs (0-5 VDC) per card.

- Two D/A cards (IDC No. D/A 64-PC) with 64 analog outputs (0-5 VDC) per card. and 24 DIO channels. The first DIO channel on board 1 is used as an interlock to prevent premature or unwanted operation of the TDS before all hardware and software systems have stabilized and are operating normally.

A photograph of the processor chassis is shown in **Figure 50**, and a block/physical diagram depicting the flow and connections of the tactile data is shown in **Figure 51**. A detailed component and connector list is presented in **Table 2**. Each processor subsystem accommodates 128 tactile sensor signals. Data input is accepted by the two 64-channel A/D cards, processed by the CPU card, and outputted on the two 64-channel D/A cards. To simplify cable connections to the display driver modules (valve manifolds) and Display Driver Controller, the D/A cards have been modified by the addition of a SCSI-68 and DB9 connector on the rear mounting strip. A photograph of the modified D/A board is shown in **Figure 52**, and the electrical schematic describing the modification presented in **Figure 53**.

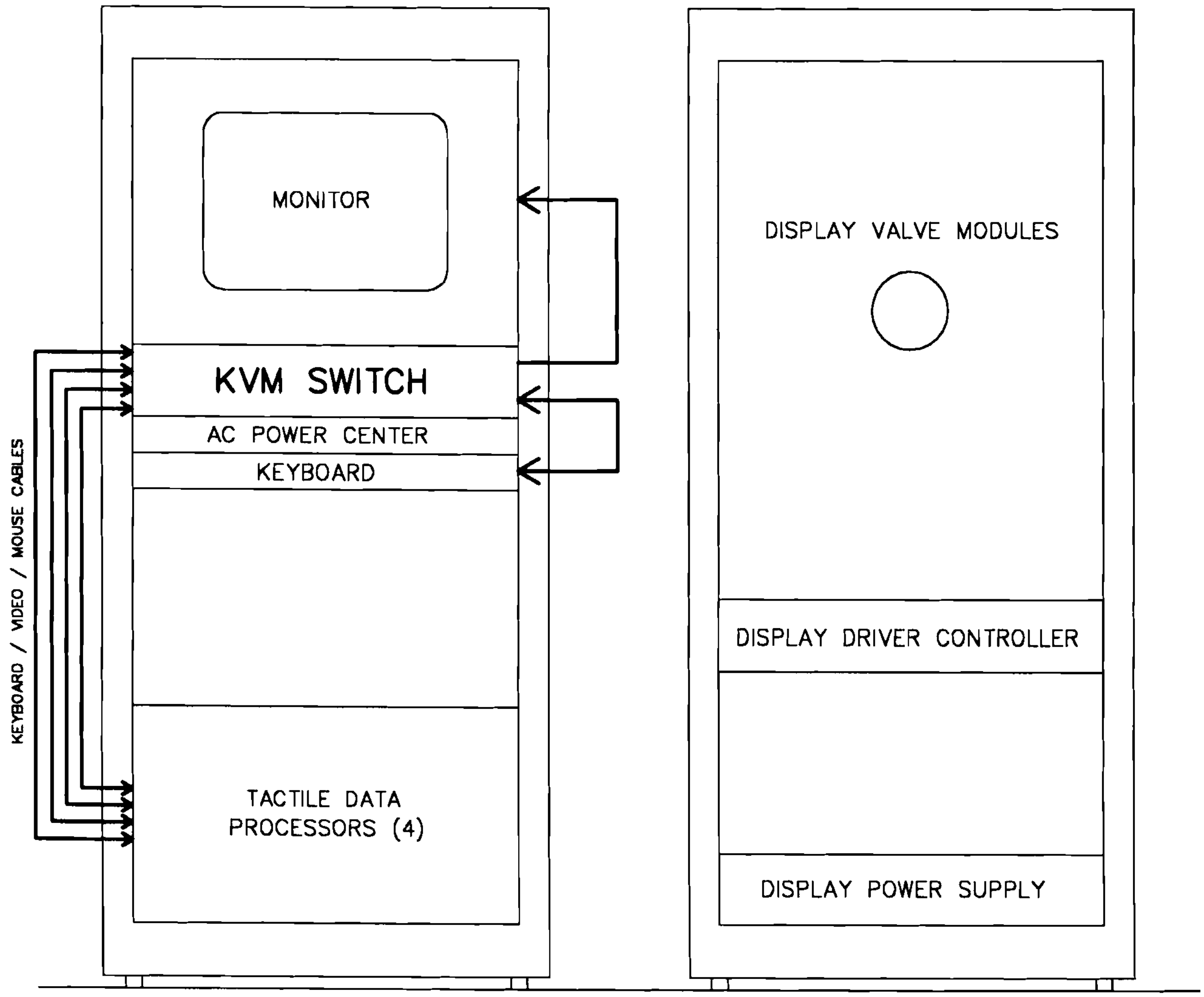


Figure 49: Block/physical diagram of the Tactile Data Processor. Four 486DX2-66 processor subsystems are interfaced to a Keyboard - Video - Mouse (KVM) switch which allows independent bootup and control with a single keyboard and display. Drawing TDSDIAG1-4.

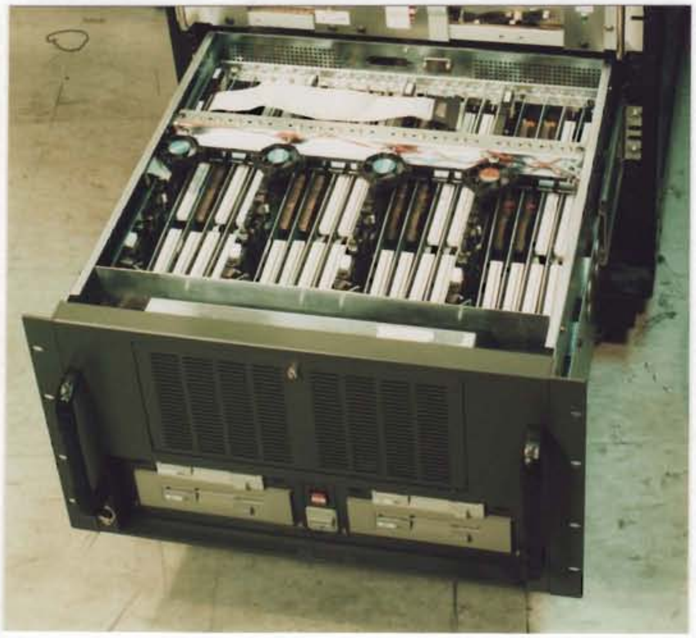


Figure 50: Computer chassis showing internal arrangement of four processor subsystems. Photo WAM-270795A-14.

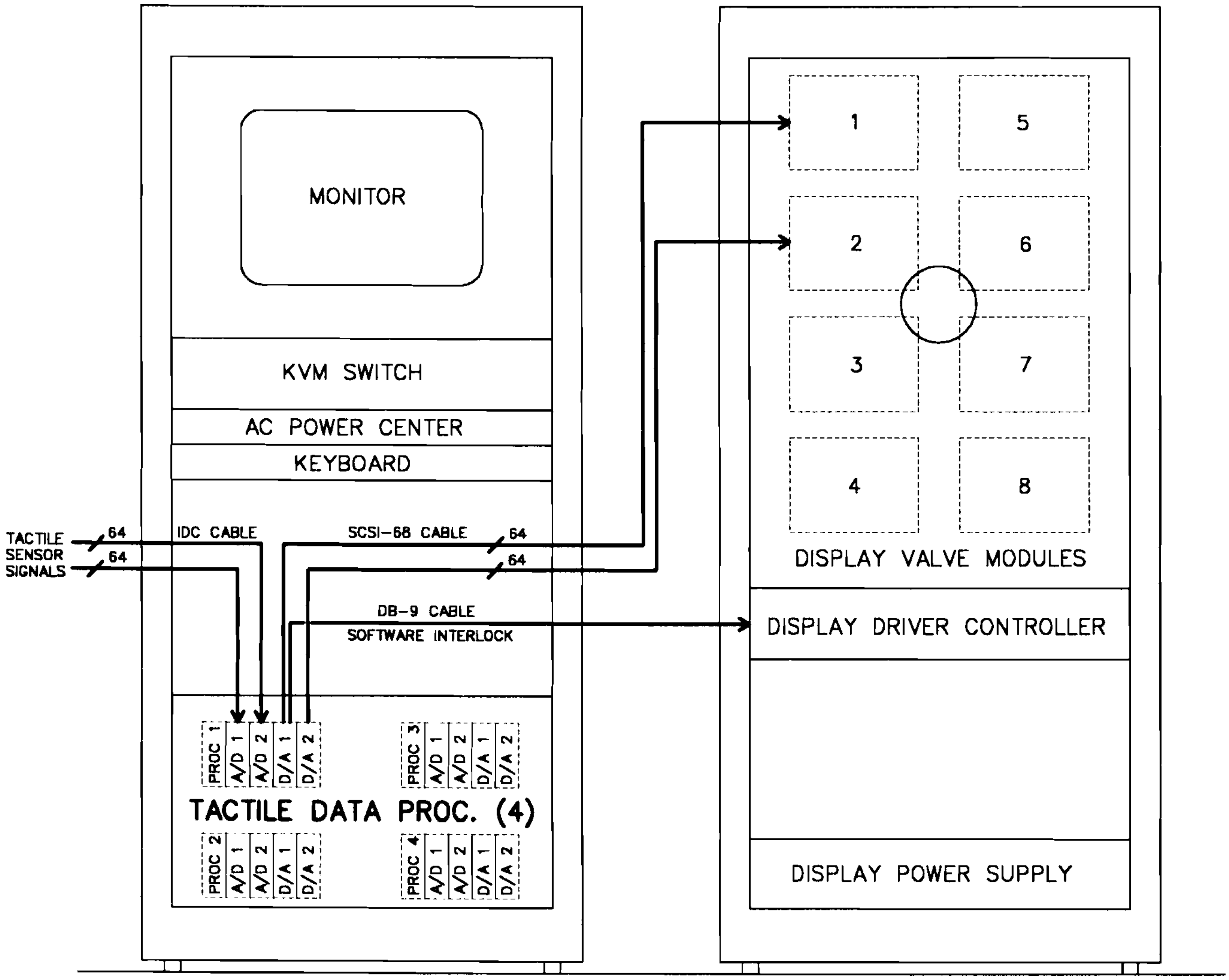


Figure 51: Block/physical diagram illustrating the flow and connections of the tactile data from processor subsystems number 1. The connections for processor subsystems 2, 3, and 4 are similar. Drawing TDSDIAG1-5.

Table 2: Component and connector list for processor subsystem number 1. Notation for processors 2, 3 and 4 are the same except for processor index number.

PROC. SUBSYSTEM No. 1		CONNECTORS		
BOARD NAME	**FUNCTION**	**NAME (STYLE)**	**FUNCTION**	**TERMINATION**
PROC. No. 1	Intel 486DX2-66 Processor with integral video, mouse, and KB	(DB-15F)	Video output (VGA)	KVM switch connectors labeled "CPU 1"
		(DB-9M)	Mouse	KVM switch connector labeled "CPU 1"
		(DIN-6F)	Keyboard	KVM switch connector labeled "CPU 1"
PROC. 1 T.S. INPUT BOARD 1	Tactile sensor input board number 1 for processor 1. Contains 64 A/D channels.	J1 and J2 (IDC2x32 M internal)	Accept up to 64 analog tactile sensor inputs (single-ended 0-5V) per connector	Tactile sensor signal conditioner, or synthetic data source
PROC. 1 T.S. INPUT BOARD 2	Tactile sensor input board number 2 for processor 1. Contains 64 A/D channels.	J1 and J2 (IDC2x32 M internal)	Accept up to 64 analog tactile sensor inputs (single-ended 0-5V) per connector	Tactile sensor signal conditioner, or synthetic data source
PROC. 1 T.D. OUTPUT BOARD 1	Tactile display output board number 1 for processor 1. Contains 64 D/A channels.	J4 (SCSI-68F)	Output up to 64 analog tactile display signals (0-5V) per connector	Connector J4 (SCSI-68F) ("Analog Inputs") on tactile display **Driver No. 1**
		J5 (DB-9F)	Processor status signal (TTL)	Interlock input connector P-P1\IL on DISPLAY DRIVER CONTROLLER
PROC. 1 T.D. OUTPUT BOARD 2	Tactile display output board number 2 for processor 1. Contains 64 D/A channels.	J4 (SCSI-68F)	Output up to 64 analog tactile display signals (0-5V) per connector	Connector J4 (SCSI-68F) ("Analog Inputs") on tactile display **Driver No. 2**
		J5 (DB-9F)	Processor status signal (TTL)	Not used: only signal from output board no. 1 used.

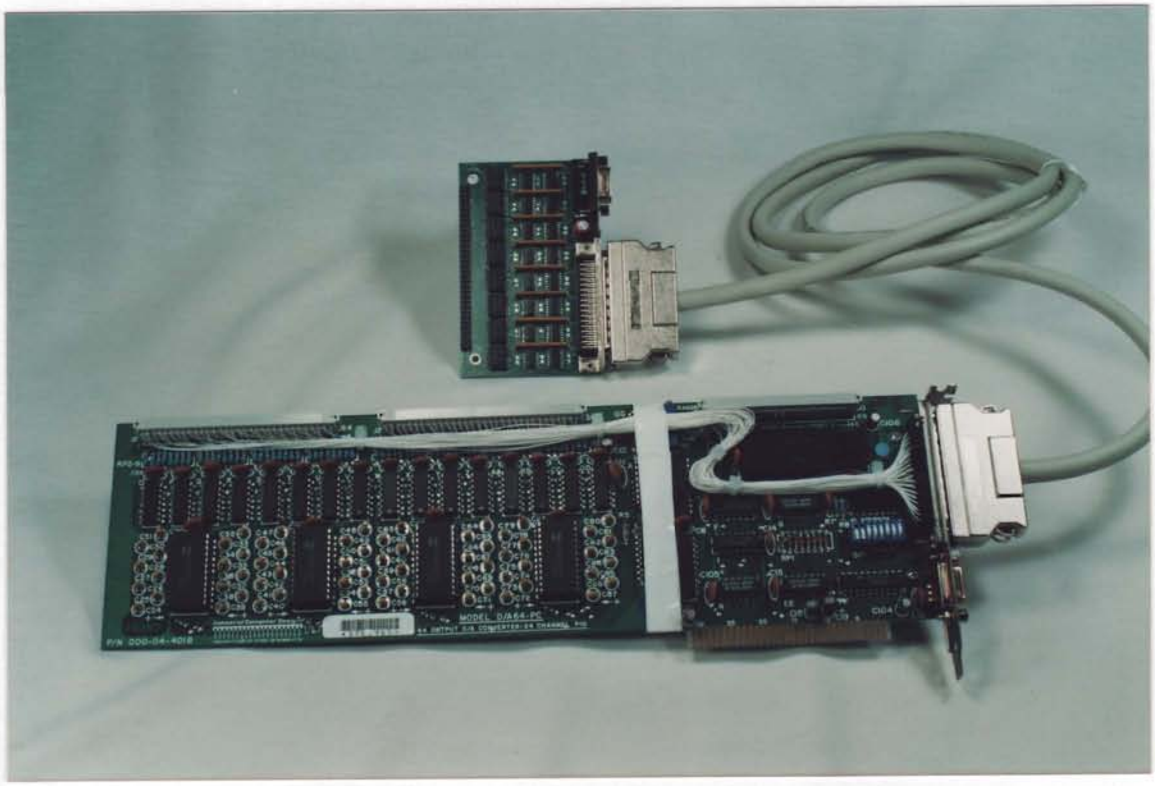


Figure 52: The stock 64-channel D/A card was modified by the addition of SCSI-68 and DB-9 connectors at the back plate to simplify the connection from the card to the display driver modules and interlock inputs of the Display Driver Controller. Photo GC-170596A-20.

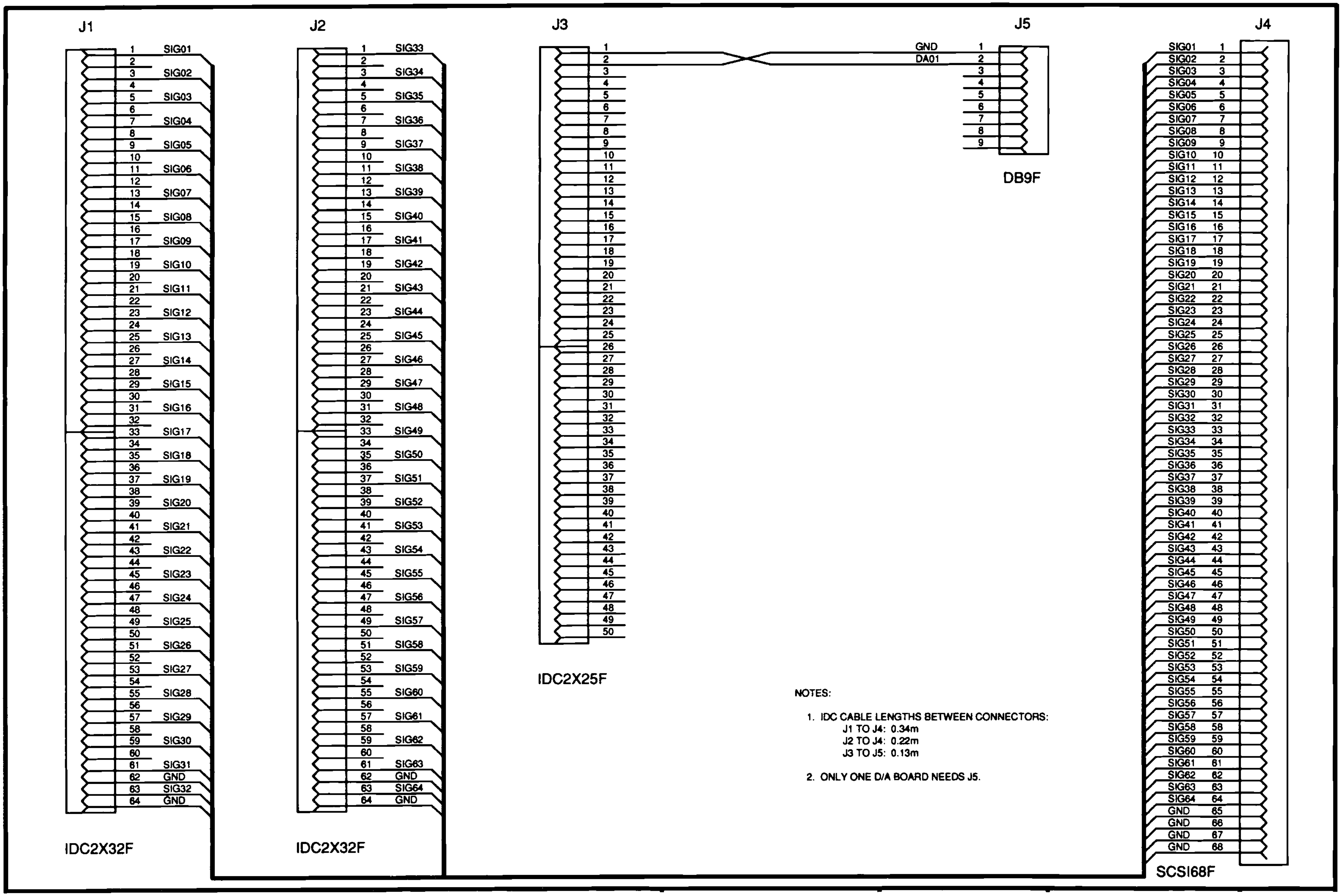


Figure 53: Electrical schematic indicating cabling modifications to standard 64-channel D/A card. Drawing DACONNS6.

5.3. Software

Software development was excluded from the program tasks due to the custom nature of the applications at the customers facility. However, a collection of general purpose routines (written in C using the Microsoft C compiler, ver. 7 for DOS) developed by the contractor over the years for the purpose of testing and evaluating various tactile sensors and displays was also utilized in this program and delivered "as is." These routines allow for the exercise of all taxels under computer control, and allow interfacing the tactile display with external tactile sensor signals. A brief introduction to the use of these routines is presented in Appendix D.

The instructions for interfacing the A/D and D/A cards to the user's code is described in detail in the respective manuals for each card. However, the instructions in C-code are summarized below :

A/D card:

Set base address for card 1:	#define AD1_BASE	0x300
Set base address for card 2:	#define AD2_BASE	0x308

Conversion (data acquisition) is initiated by writing to the MUX control latch for a specific channel (0-63) on each card:

MUX control latch address for card 1:	AD1_BASE + 4
MUX control latch address for card 2:	AD2_BASE + 4

After conversion, data is retrieved from the data latch register:

Data latch address for card 1:	AD1_BASE + 5
Data latch address for card 2:	AD2_BASE + 5

To read a INVALUE (0-255) from input channel 0-63 (taxel 1-64) for card 1, use the following C-code:

```
outp (AD1_BASE + 4, ChannelNumber); /* Start conversion process */
/* Wait approximately 100 us for conversion to be completed */
INVALUE = inp (AD1_BASE + 5);
```

Similarly, to read a VALUE (0-255) from input channel 0-63 (taxel 65-128) for card 2, use the following C-code:

```
outp (AD2_BASE + 4, ChannelNumber); /* Start conversion process */
/* Wait for conversion to be completed */
INVALUE = inp (AD2_BASE + 5);
```

For high-speed compiled code, the manual recommends polling the converter DONE BIT to determine if conversion is completed:

```
A = inp ( AD1_BASE + 4)  /* Card 1, taxels 1-64)  */
A = inp ( AD2_BASE + 4)  /* Card 2, taxels 65-128)  */
```

where

A = 0 indicates conversion is not complete
A = 1 indicates conversion is done.

This approach, however, could not be satisfactorily implemented without having the system hang, so the alternative of a simple FOR delay loop was used instead.

D/A card:

Set base address for card 1:	#define DA1_BASE	0x310
Set base address for card 2:	#define DA2_BASE	0x318

Output data latch address for card 1 is	DA1_BASE + 4
Output data latch address for card 2 is	DA2_BASE + 4
MUX control latch (channel number) for card 1 is	DA1_BASE + 5
MUX control latch (channel number) for card 2 is	DA2_BASE + 5

Then, to write a OUTVALUE (0-255) to output channel 0-64 (taxel 1-64) for card 1, use the following C-code:

```
outp ( DA1_BASE + 4, OUTVALUE );
outp ( DA1_BASE + 5, ChannelNumber ) ;
```

or, to write a OUTVALUE (0-255) to output channel 0-64 (taxel 65-128) for card 2, use the following C-code:

```
outp ( DA2_BASE + 4, OUTVALUE );
outp ( DA2_BASE + 5, ChannelNumber );
```

For rapid sequential data output, sufficient time must be allowed between successive write operations for the output to settle sufficiently, i.e., approximately 0.5 to 1 ms.

D/A Card: Interlock Output

To disable the processor fault indicator on the Tactile Display Controller, the interlock signal DA01 must be driven high (TTL 5 VDC). The 24 bit DIO capability of D/A board number 1 (only) for each processor is used for this purpose:

Set up DIO ports to be input or output by writing to port control register:

```
outp ( DA1_BASE + 3, 0x8B ); /* Port A = output, Port B and C = input */
```

To disable the Tactile Driver Controller:

```
outp ( DA1_BASE, 0 ); /* Set all bits in Port A to be zero */
```

To enable the Tactile Driver Controller:

```
outp ( DA1_BASE, 1 ); /* Set first bit in Port A to be one */
```

Note:

It is STRONGLY recommended that the inlet pressure regulator be turned down to less than 70 kPa (10 psi) during any software development activities to avoid damage or destruction of the taxels should something go unexpectedly awry.

6. RESULTS and CONCLUSIONS

Taxel reliability:

Each taxel was individually tested at several stages of the taxel fabrication and TDS assembly process:

- After fabrication of each connectorized taxel unit
- After installation of each taxel into a display panel and driver module
- After installation of all panels onto the display suit
- After donning/doffing the suit 5 times

No taxel was found to fail after passing the initial fabrication exam, and the TDS was shipped with zero defective taxels.

The TDS was configured to run continuously with a real or synthetic tactile sensor signals applied to the A/D inputs. Each processor cycle time was measured to be approximately 50 ms, i.e., inputs were measured, conditioned, and outputted to the display driver for 128 taxels (2 driver modules) in 50 ms. As each of the four processor subsystems were running in parallel, the cycle time for the entire suit of 512 taxels was also 50 ms.

Stimulation Intensity:

During the course of evaluating the taxel reliability, the intensity of taxel stimulation was also noted. Most taxels were readily discernible at 10-15% of their maximum inflation value (i.e., 0.3 to 0.5 mm inflation height), and all were discernible at 30% maximum inflation. Several observations were noteworthy, however:

- The stimulation intensity was not uniform, as the inflation level of some taxels were visibly less than their neighbors despite receiving the same control command. From past experience, this phenomenon was primarily attributed variations of valve mounting within the display manifolds (i.e., the degree to which the exhaust port of the valve lined up with the inlet port of the taxel). It has also been observed that this effect seems to lessen with time and taxel use, perhaps as the silicone membranes loosen up and become more flexible.

- Some taxels may lose contact with the skin during certain body movements that create highly concave regions under a display panel, e.g., the chest and stomach area when the operator wraps their arms around a very small object or assumes an extremely bent posture at the stomach. This was somewhat mitigated by wearing various straps or harnesses that acted to keep the disengaging portions of the display panels inside the concave area formed during such extreme movements.

In conclusion, the Tactile Display Suit seemed to perform as planned and - given the design lifetime of the individual taxels - is expected to give reasonably trouble-free performance in a typical R&D environment.

7. DIRECTIONS for FUTURE STUDY

The following topics were considered important areas of future study:

- Design and fabricate taxels of different size and shape for more optimal placement and tactile stimulation, e.g., larger or smaller diameter, or oval shaped.

- Increase the ranging radius of the suit by increasing the tubing length. This could be accomplished by increasing the operating pressure (thereby requiring a new source of high-pressure miniature valves) or by increasing the internal diameter of the tubing (which would increase the cable thickness, weight, and decrease maneuverability).

- Eliminate all spare valves on the display valve manifolds to minimize cost and system size.

- Replace the vacuum manifold on the display driver modules with a simpler, less expensive vent or silencer system.

- Develop a simpler connector for TEFLON® tubing, or find a replacement tubing material that can be terminated with adhesives.

8. REFERENCES

[BEGEJ 1984] Begej, S., "An optical tactile sensor array," Proceedings of the SPIE Conf. Intelligent Robotics and Computer Vision, pp. 271-280, November, 1984.

[BEGEJ 1985] Begej, S., A Tactile Sensing System and Optical Tactile Sensor Array for Robotic Applications, Technical Report 85-06, MS Thesis, Computer and Information Science Department, Univ. Massachusetts, Amherst, May, 1985.

[BEGEJ 1986] Begej, S., Fingertip-Shaped Touch Sensor for Teleoperator and Robotic Applications, Final Report, Begej Corporation, Littleton, CO, NASA SBIR Phase I Contract No. NAS7-968, September, 1986.

[BEGEJ 1988a] Begej, S., "Fingertip-Shaped Optical Tactile Sensor for Robotic Applications," Proc. IEEE Int. Conf. Robotics and Automation, Philadelphia, PA, pp. 1752-1757, 25 April, 1988.

[BEGEJ 1988b] Begej, S., Tactile Telepresence System for Dexterous Telerobotics, Final Report, Begej Corporation, Littleton, CO, NASA JPL SBIR Phase I Contract NAS7-1015, 29 August, 1988.

[BEGEJ 1988c] Begej, S., "Planar and Fingertip-Shaped Tactile Sensors for Robotic Applications," IEEE J. Robotics and Automation, vol. 4, no. 5, Oct., 1988.

[BEGEJ 1988d] Begej, S., Tactile Sensor Subsystem Utilizing a Fingertip-Shaped Sensor with Shear Force-Sensing Capability, Final Report, Begej Corporation, Littleton, CO, NSF Phase I SBIR Grant ISI 87-60319, 21 December, 1988.

[BEGEJ 1990] Begej, S., Glove Controller with Force and Tactile Feedback for Dexterous Robotic Hands, Final Report for Phase I SBIR contract NAS9-18308, NASA Johnson Space Center, September, 1990.

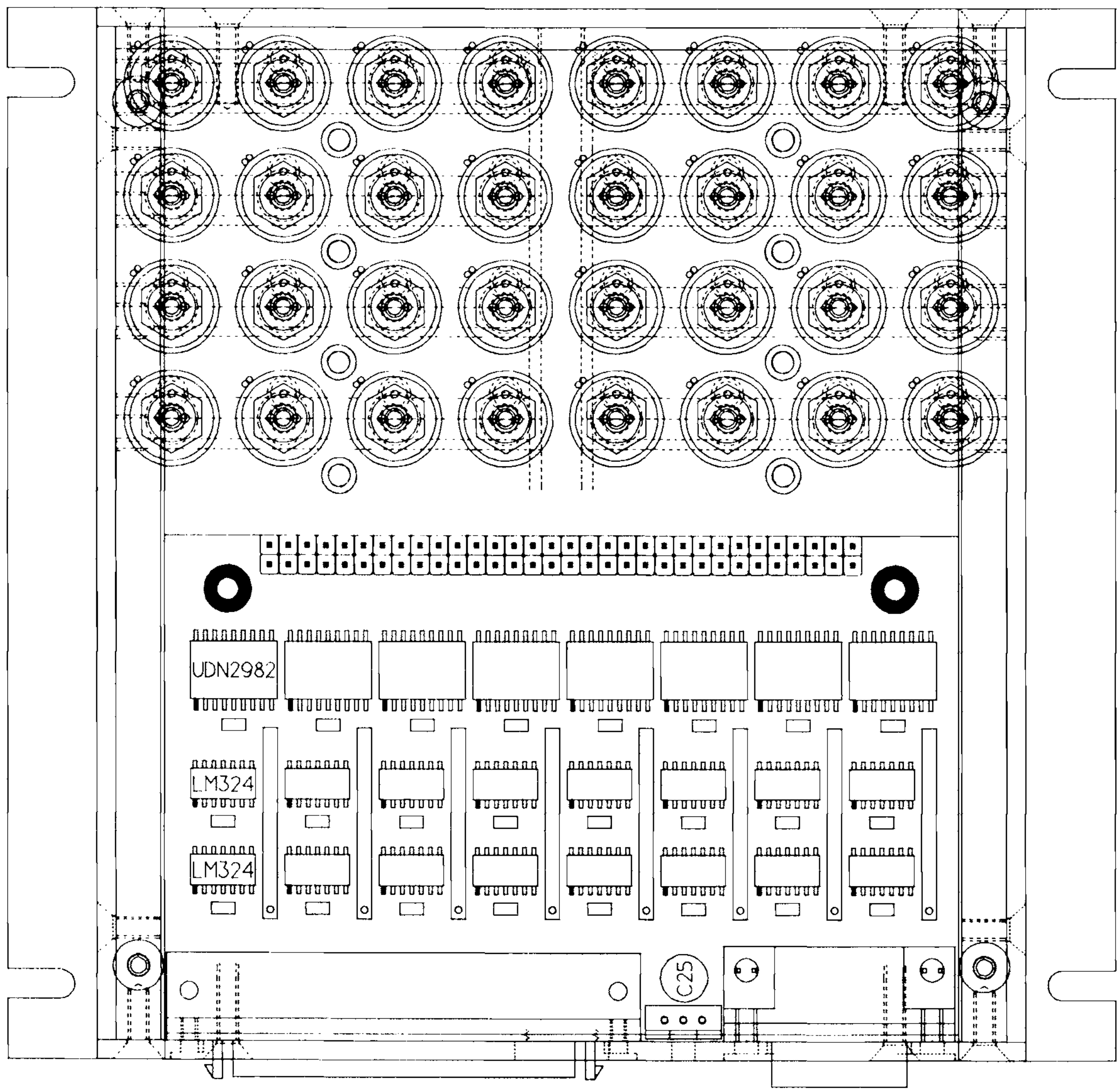
[BEGEJ 1992] Begej, S., Telepresent Master/Slave Tools with Force and Tactile Feedback, Final Report for Phase I SBIR contract F4162-90-C-1002 for the H.G. Armstrong Aerospace Medical Research Laboratory, Human Systems Division, US Air Force, Wright Patterson Air Force Base, January 1992.

[BEGEJ 1995] Begej, S., Glove Controller with Force and Tactile Feedback for Dexterous Robotic Hands. Final Report for Phase II SBIR contract NAS9-18558, NASA Johnson Space Center, Begej Corporation Report Number GC-170595FR, 31 May, 1995.

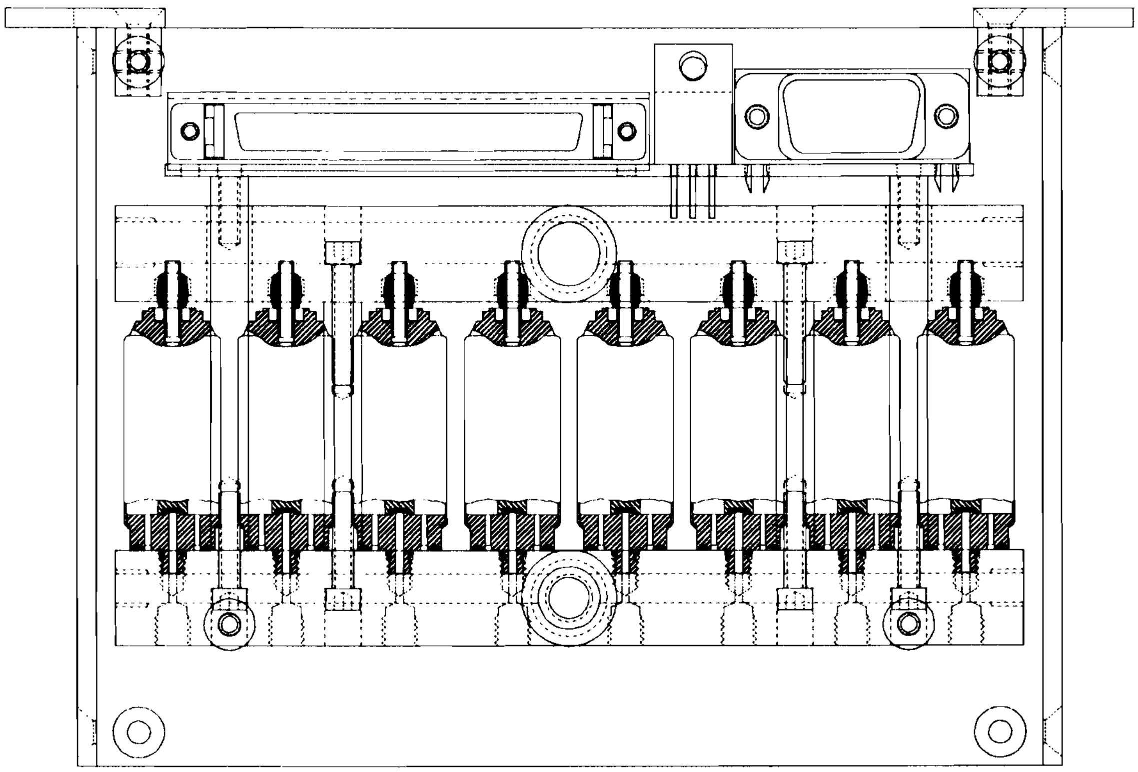
APPENDIX A

MECHANICAL DRAWINGS of the TACTILE DISPLAY DRIVERS (VALVE MANIFOLDS)

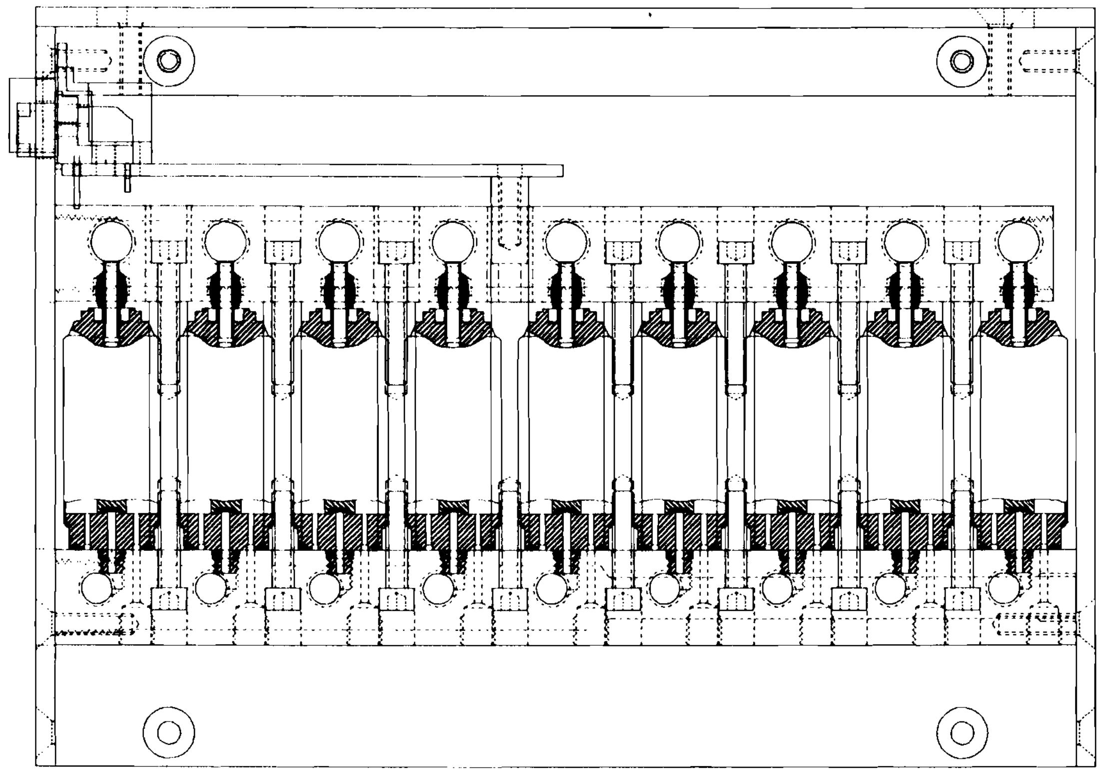
The following drawings detail all mechanical components of the tactile display driver modules. All CAD drawings were made with Generic CADD, version 6 (DOS).



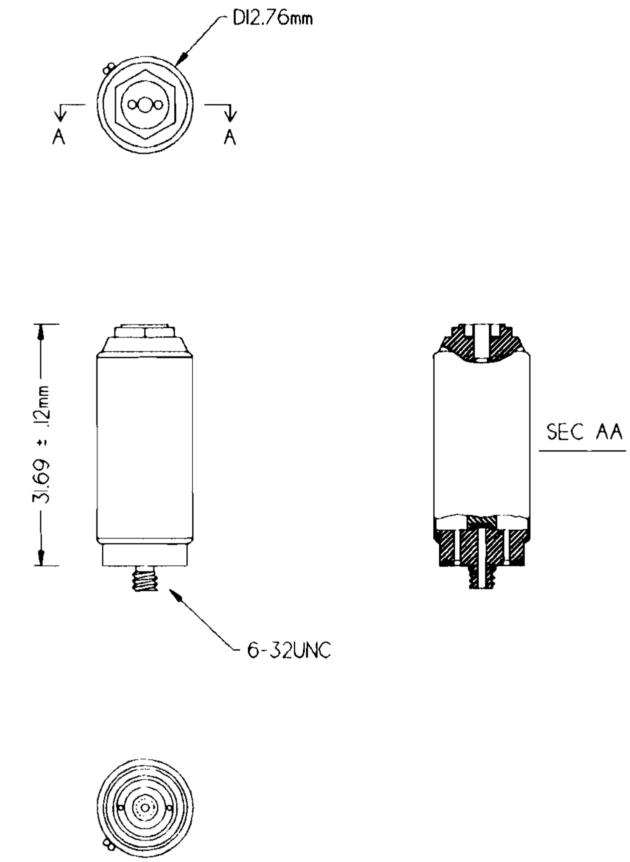
Assembly drawing of tactile display driver.
Top view, full scale, drawing number TDRV3004.



Assembly drawing of tactile display driver.
Front view, full scale, drawing number TDRV3004.



Assembly drawing of tactile display driver.
Right-side view, full scale, drawing number TDRV3004.



NOTES:
1. REMOVE LABEL FROM VALVE BODY PRIOR TO INSTALLATION.
2. SOLDER ONE LEAD TO BODY (GROUND CONNECTION).
3. INSTALL IN MANIFOLD WITH FINGER-TORQUE ONLY.

72	TDRV3105-PRT01	VALVE, MANIFOLD-MOUNT, ANGAR 407M304024100N		1
QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
PARTS LIST (ONE MODULE)				

DISTRIBUTION STATEMENT: CONFIDENTIAL AND PROPRIETARY INFORMATION. NOT FOR PUBLIC RELEASE. RESTRICTED DISTRIBUTION.

METRIC

THIRD ANGLE PROJECTION

TOL: X ±0.1 mm
X.X ±0.05mm
X.XX ±0.02mm

CONTRACT NO.
NAS9-18901
PH-2 WAM TACT. DISP.

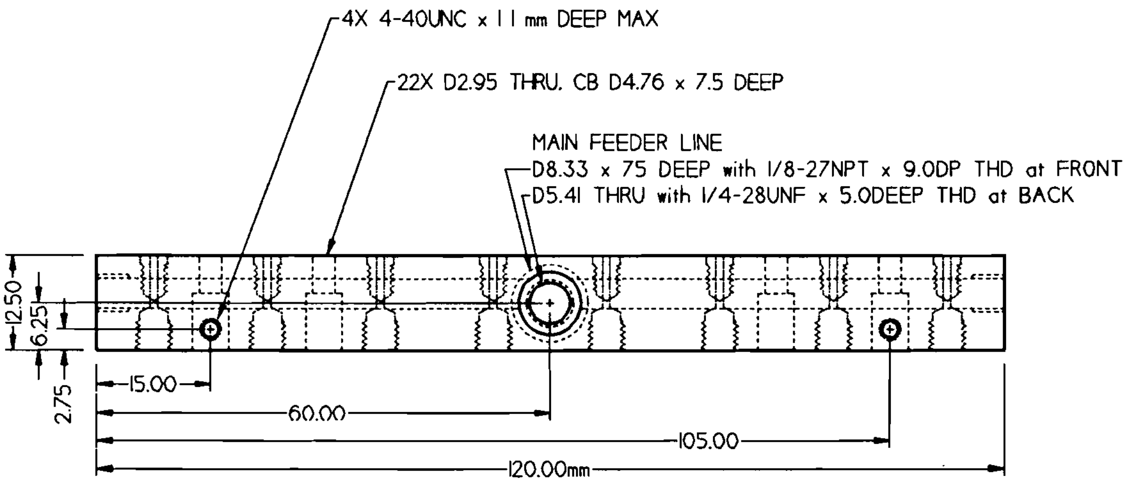
APPROVALS	DATE
FINAL:	

BEGEJ CORPORATION

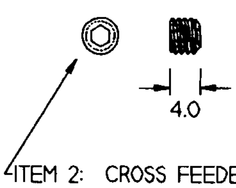
5 CLARET ASH ROAD
LITTLETON, CO 80127
TEL/FAX: (303) 932-2186

TITLE PNEUMATIC VALVE, ANGAR 407M304024100N

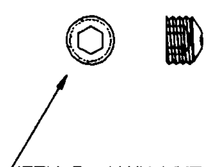
SIZE:		DWG. NO. TDRV3105	REV. 17 NOV 94
SCALE: FULL		LAYER: 105	SHEET: 1 OF 1



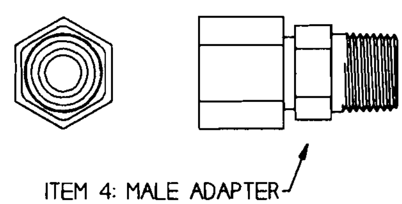
FRONT VIEW ITEM 1



ITEM 2: CROSS FEEDER PLUG



ITEM 3: MAIN LINE PLUG



ITEM 4: MALE ADAPTER

1	TDRV3100-PRT04	MALE ADAPTER 1/8"NPT X 1/4"TUBE		4
1	TDRV3100-PRT03	MAIN LINE PLUG. SOCKET SET SCREW 1/4-28UNF x 3/16"		3
18	TDRV3100-PRT02	CROSS-FEEDER PLUGS. SOCKET SET SCREW 10-32UNF x 4mm (TRM STD 3/16" UNIT)		2
1	TDRV3100-PRT01	PRESSURE MANIFOLD. 72 VALVES. 64 TAXELS (8 SPARE VALVES)	ALUMINUM. 6061-T6 OR EQUIV.	1
QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
PARTS LIST (ONE MODULE)				

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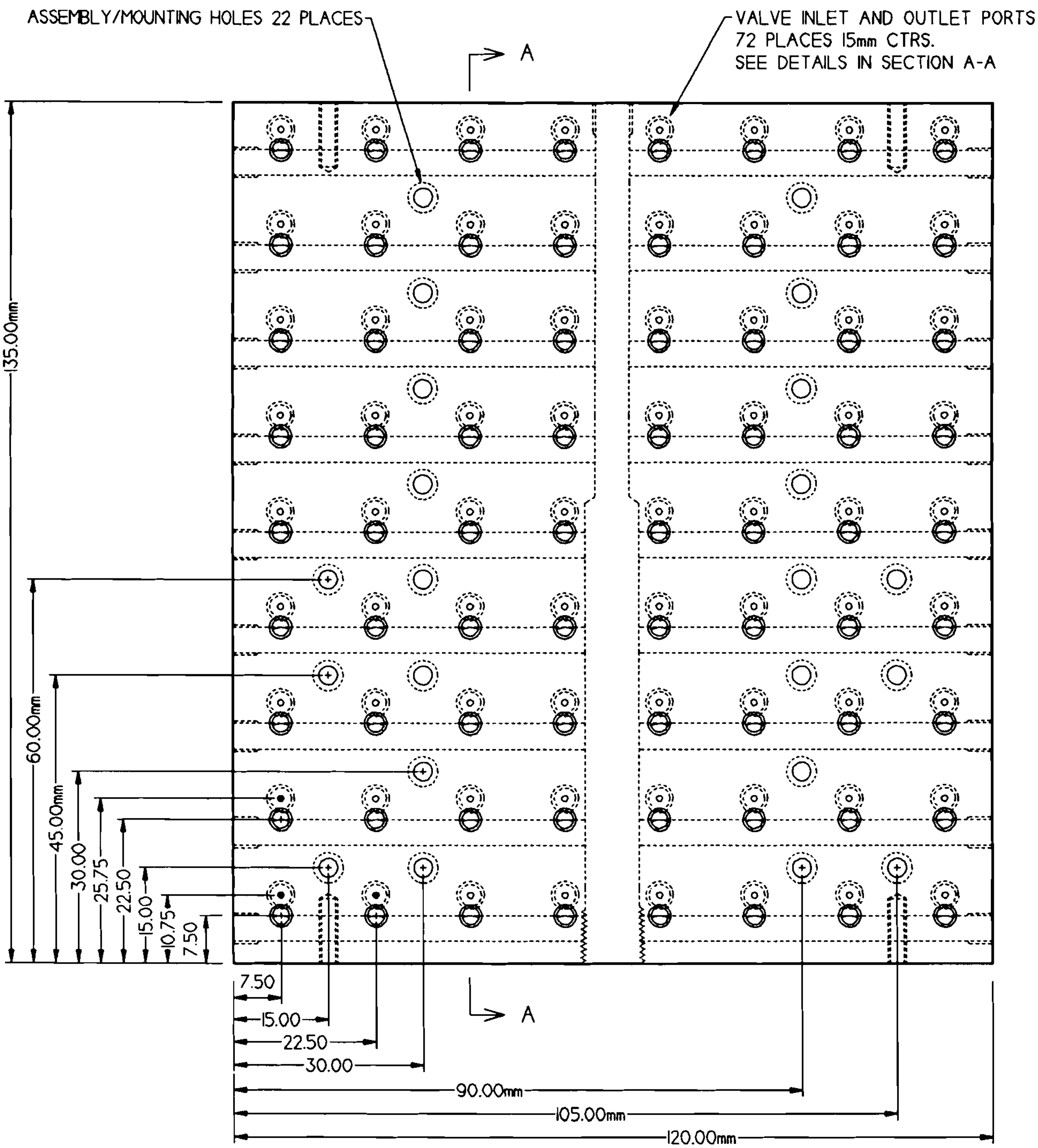
METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TAC DISP		BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON. CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE PRESSURE MANIFOLD (72 VALVES. 64 TAXELS)		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:	DWG. NO. TDRV3100	REV. 16 NOV 94
	FINAL:		SCALE:	LAYER: 100	SHEET: 1 OF 4



TOP VIEW ITEM I

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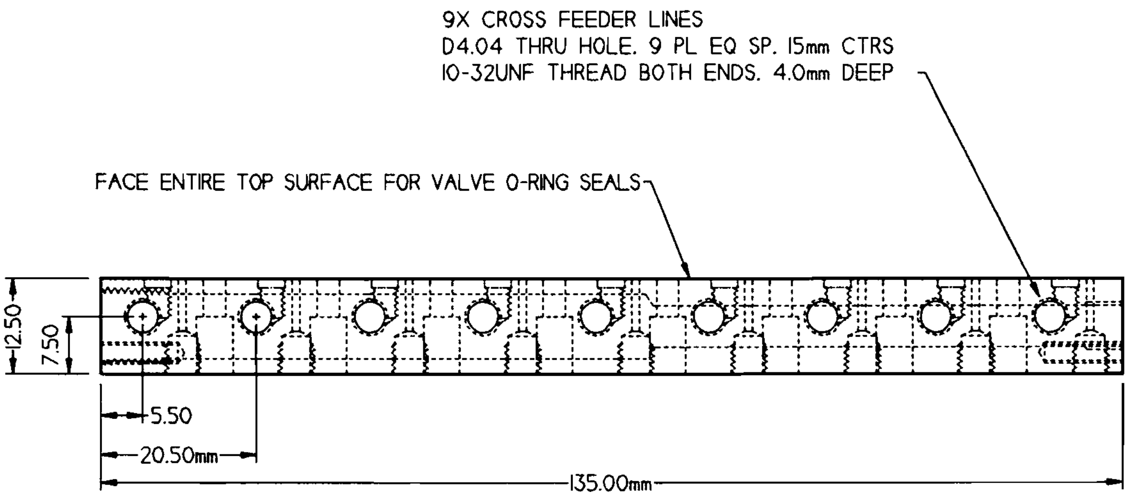
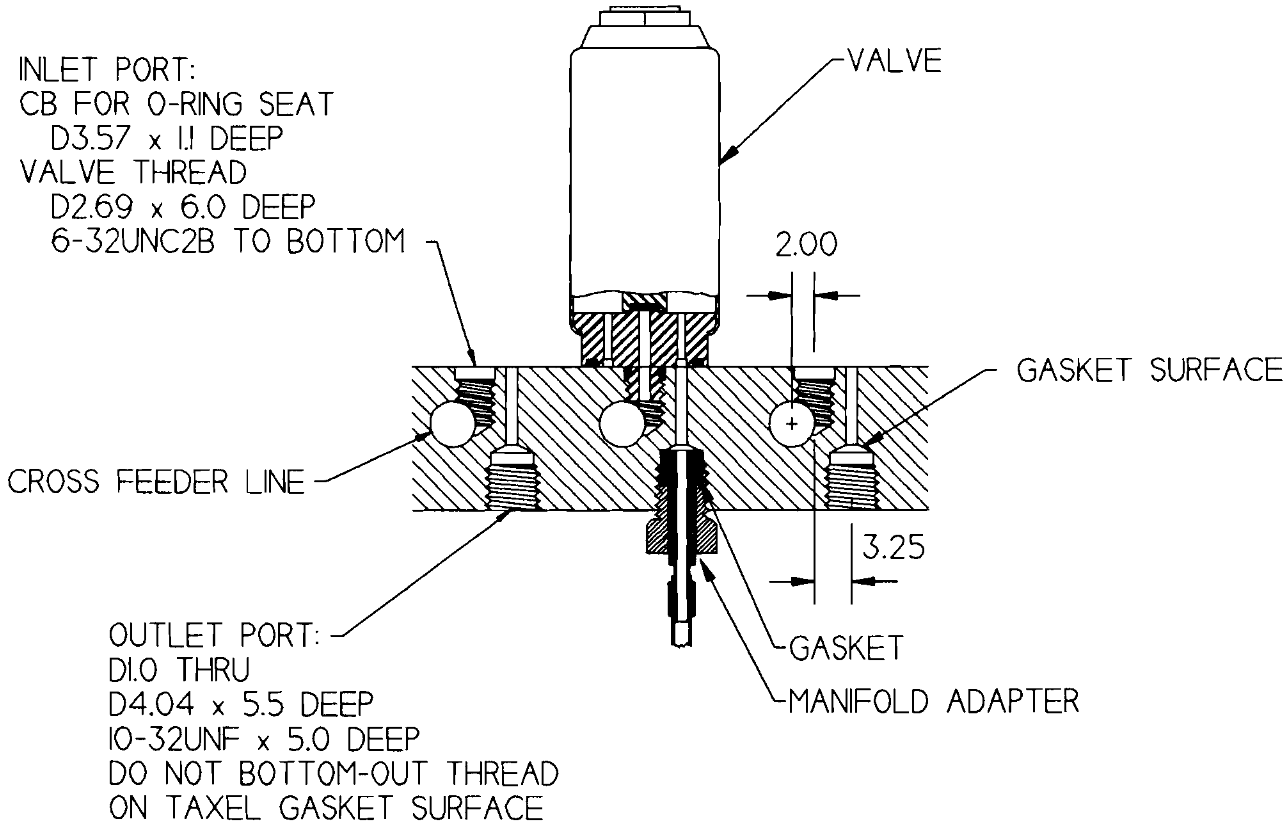
METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TAC DISP		BEGEJ CORPORATION			5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE PRESSURE MANIFOLD (72 VALVES, 64 TAXELS)			
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:		DWG. NO. TDRV3100	REV. 16 NOV 94
	FINAL:		SCALE:		LAYER: 100	SHEET: 2 OF 4



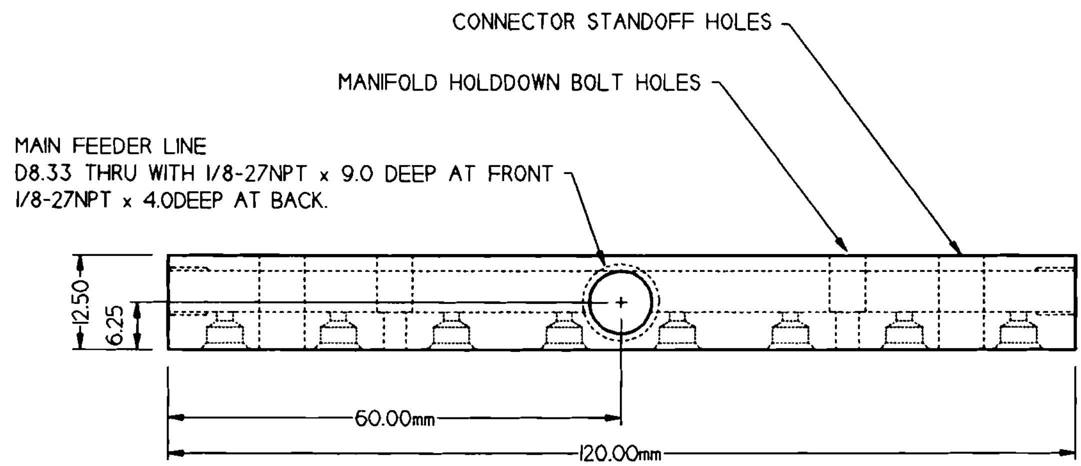
RIGHT-SIDE VIEW ITEM 1

METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TAC DISP		BEGEJ CORPORATION			5 CLARET ASH ROAD LITTLETON. CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE PRESSURE MANIFOLD (72 VALVES. 64 TAXELS)			
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:		DWG. NO. TDRV3100	REV. 16 NOV 94
	FINAL:		SCALE:		LAYER: 100	SHEET: 3 OF 4

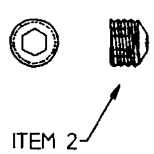


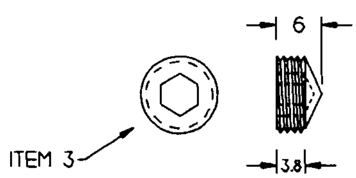
SECTION A-A

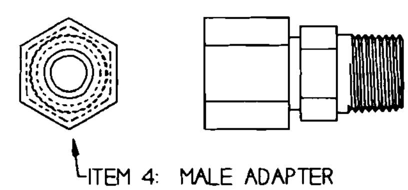
METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TAC DISP		BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE PRESSURE MANIFOLD (72 VALVES, 64 TAXELS)		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:	DWG. NO. TDRV3100	REV. 16 NOV 94
	FINAL:		SCALE:	LAYER: 100	SHEET: 4 OF 4



FRONT VIEW - ITEM 1



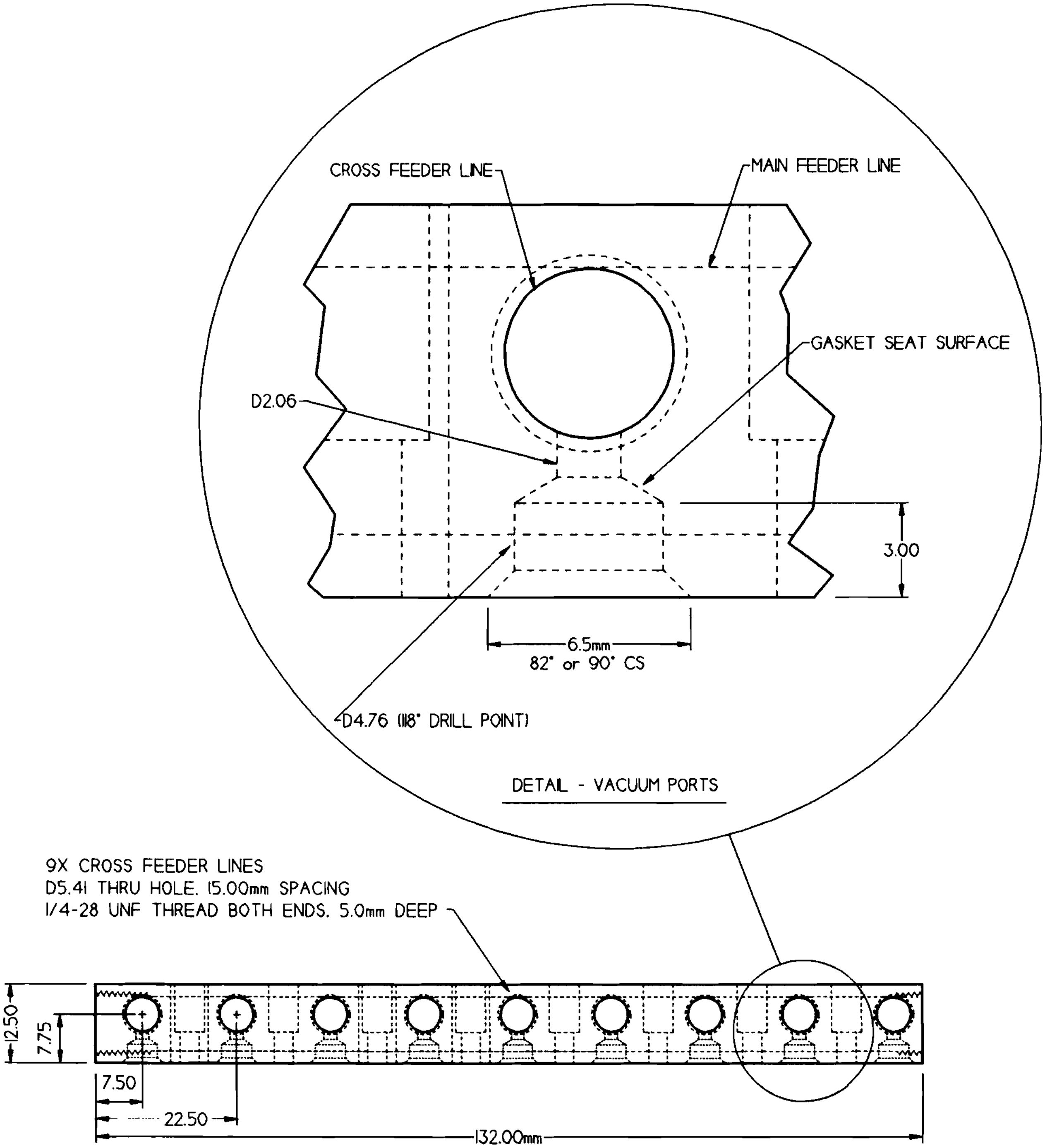




1	TDRV3101-PRT04	MALE ADAPTER: 1/8"NPT X 1/4"TUBE		4
1	TDRV3101-PRT03	MAIN LINE PLUG: SOCKET PIPE PLUG 1/8-27NPT x 6mm (MODIFY STANDARD 5/16" LONG UNIT)		3
18	TDRV3101-PRT02	CROSS FEEDER PLUG: SOCKET SET SCREW 1/4-28UNF X 3/16"		2
1	TDRV3101-PRT01	VACUUM MANIFOLD: 72 VALVES, 64 TAXELS (8 SPARE VALVES)	ALUMINUM, 6061-T6 OR EQUIV.	1
QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
PARTS LIST (ONE MODULE)				

DISTRIBUTION STATEMENT A: CONFIDENTIAL AND PROPRIETARY INFORMATION. NOT FOR PUBLIC RELEASE. RESTRICTED DISTRIBUTION.

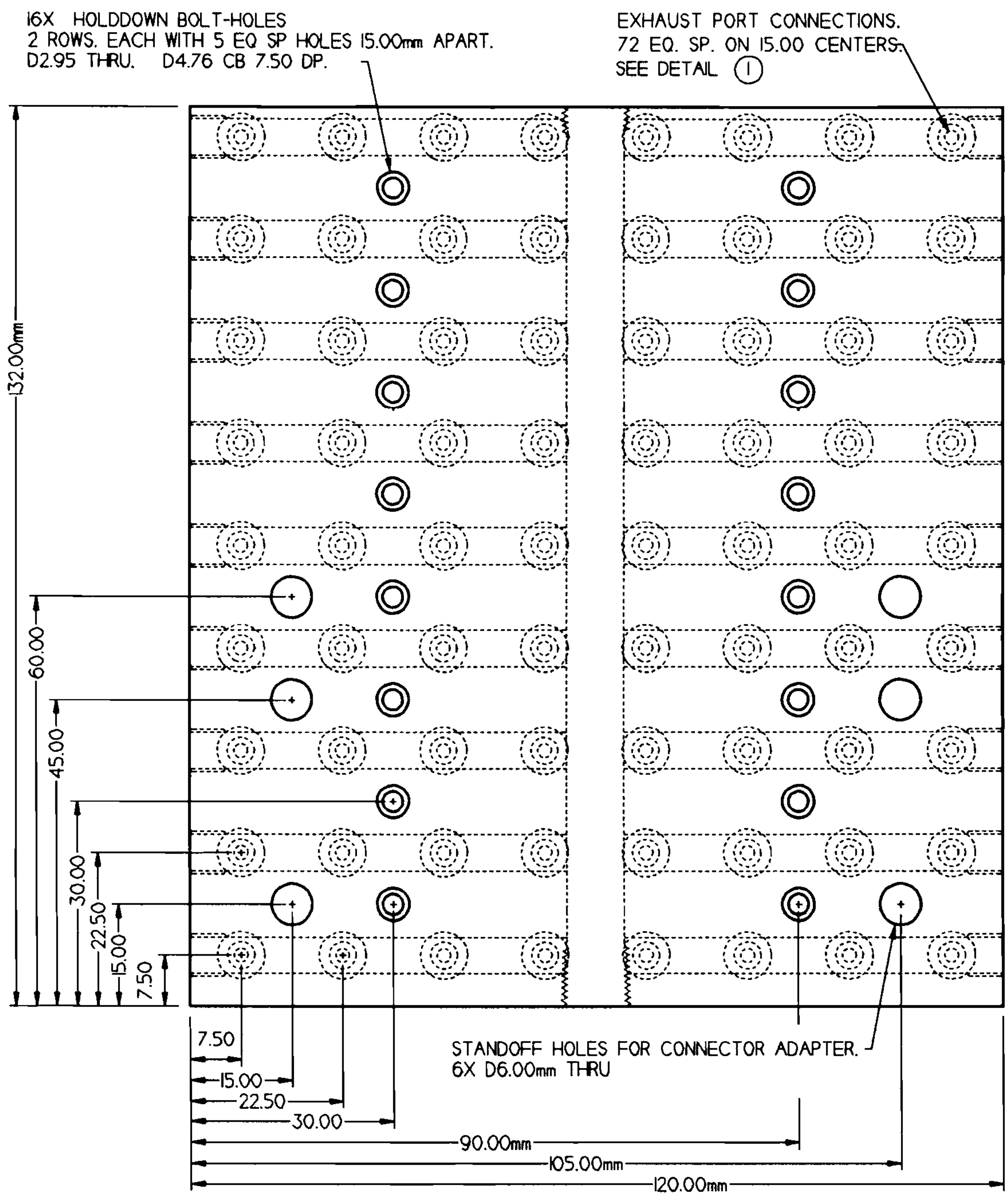
METRIC	CONTRACT NO. NAS9-18901 PH-2 WAM TAC DISP		BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186	
THIRD ANGLE PROJECTION	APPROVALS	DATE	TITLE VACUUM MANIFOLD (72 VALVES, 64 TAXELS)			
TOL: X ±0.1 mm; X.X ±0.05mm; X.XX ±0.02mm			SIZE:		DWG. NO. TDRV3101	REV. 16 NOV 94
	FINAL:		SCALE:		LAYER: 101	SHEET: 1 OF 3



RIGHT SIDE VIEW - ITEM 1

DISTRIBUTION STATEMENT A: CONFIDENTIAL AND PROPRIETARY INFORMATION. NOT FOR PUBLIC RELEASE. RESTRICTED DISTRIBUTION.

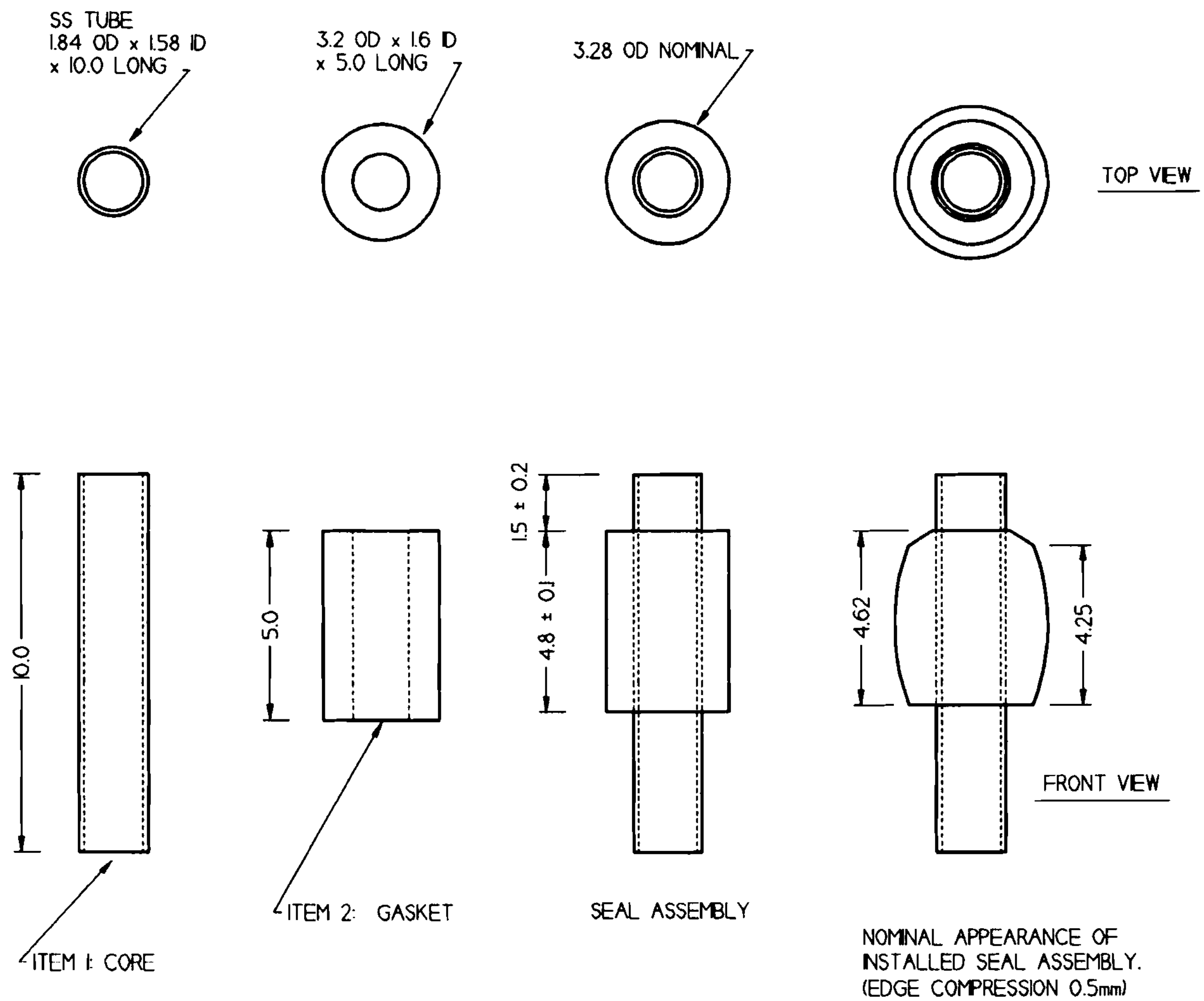
METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TAC DISP		BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE VACUUM MANIFOLD (72 VALVES. 64 TAXELS)		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:	DWG. NO. TDRV3101	REV. 16 NOV 94
	FINAL:		SCALE:	LAYER: 101	SHEET: 2 OF 3



TOP VIEW - ITEM 1

DISTRIBUTION STATEMENT A: CONFIDENTIAL AND PROPRIETARY INFORMATION. NOT FOR PUBLIC RELEASE. RESTRICTED DISTRIBUTION.

METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TAC DISP	BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS / DATE	TITLE VACUUM MANIFOLD (72 VALVES. 64 TAXELS)		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm		SIZE:	DWG. NO. TDRV3101	REV. 16 NOV 94
	FINAL:	SCALE:	LAYER: 101	SHEET: 3 OF 3

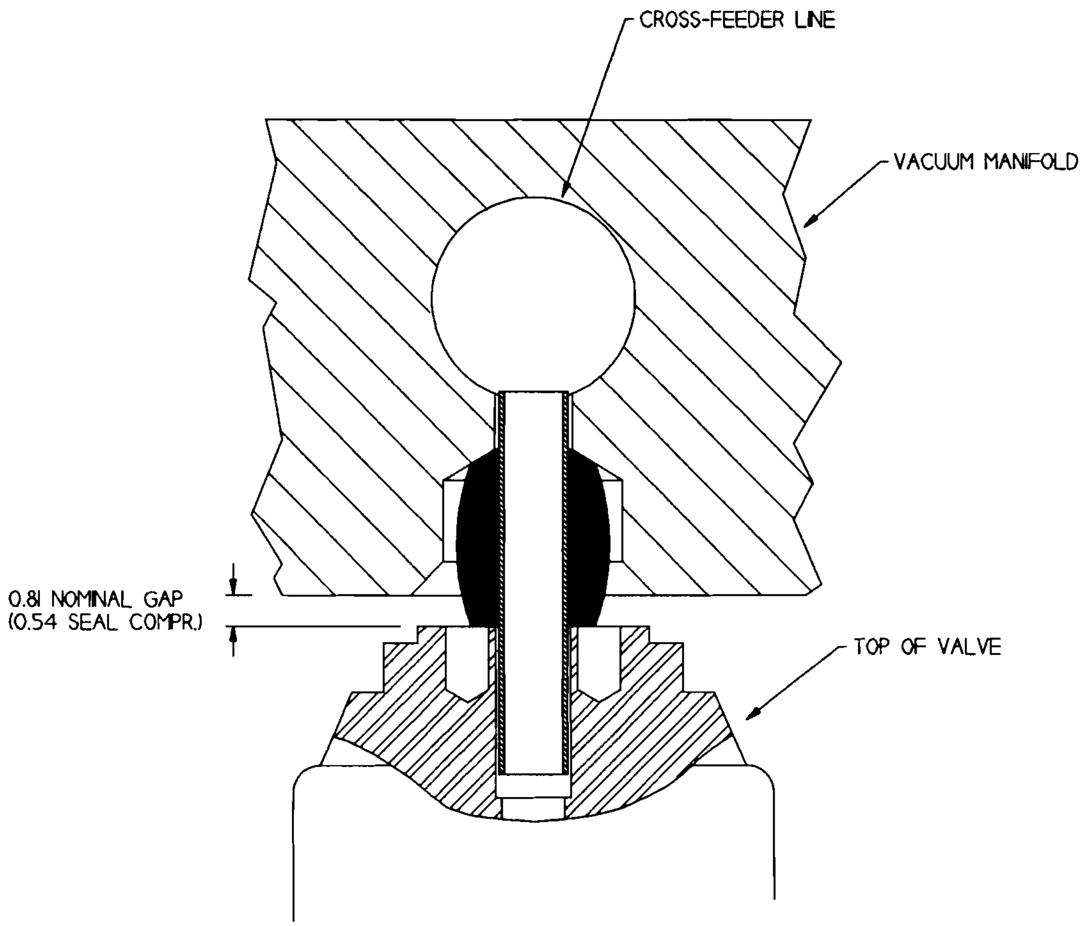


NOTES:
1. BURNISH ENDS OF CORE TUBE WITH WIRE WHEEL TO ROUND AND REMOVE BURRS.
2. MOISTEN INSIDE OF GASKET TO FACILITATE INSERTION OF CORE.

72	TDRV3106-PRT02	VACUUM SEAL - GASKET (SUPERTHANE, US PLASTICS CO. No. 800)	2
72	TDRV3106-PRT01	VACUUM SEAL - CORE (15AWG THINWALL SS TUBING, SMALL PARTS CO. Q-HTX-15TW)	1
QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	ITEM NO.
PARTS LIST (ONE MODULE)			

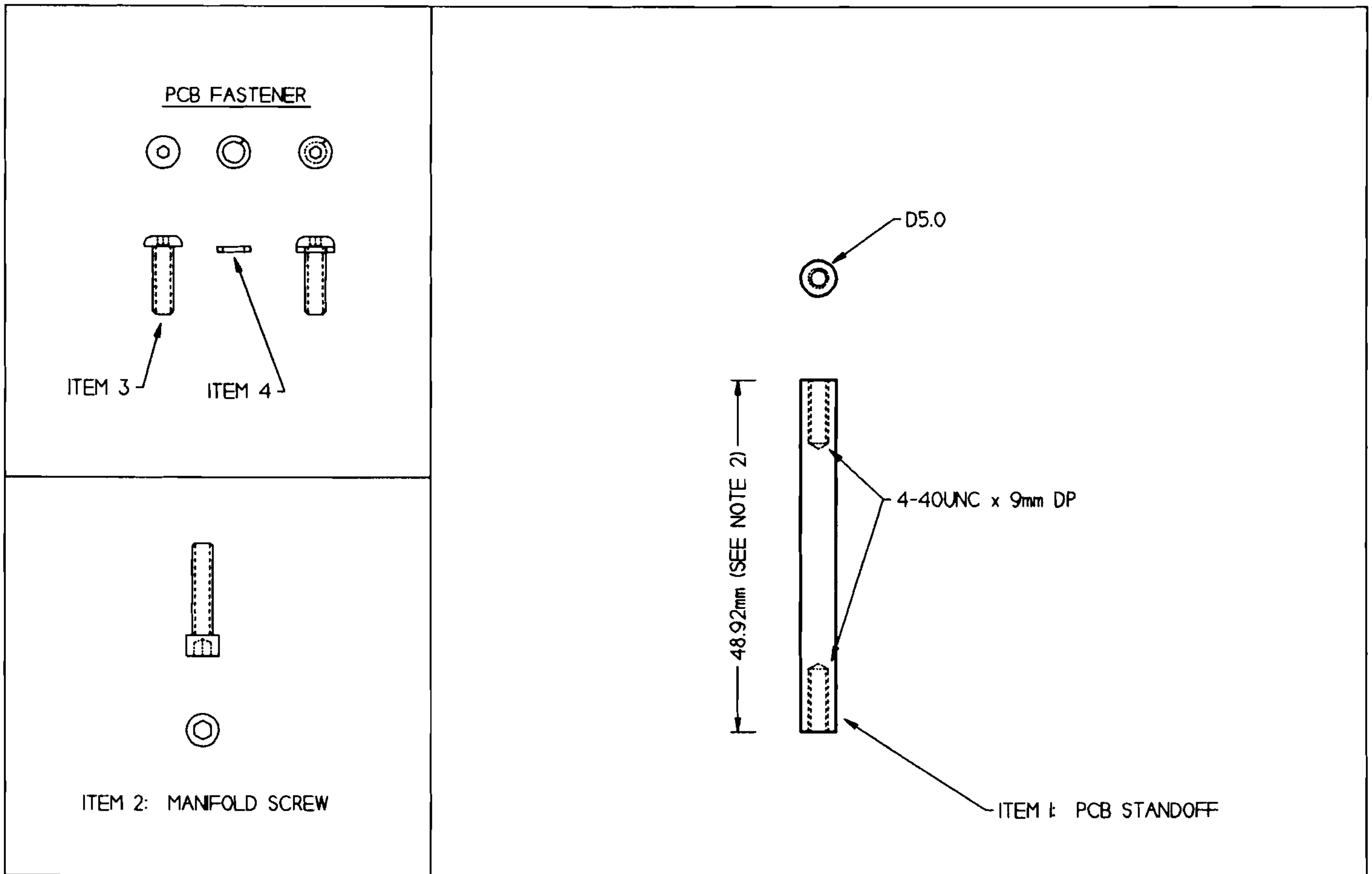
DISTRIBUTION STATEMENT: CONFIDENTIAL AND PROPRIETARY INFORMATION. NOT FOR PUBLIC RELEASE. RESTRICTED DISTRIBUTION.

METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DISP.	BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS / DATE	TITLE VACUUM SEAL		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm		SIZE:	DWG. NO. TDRV3106	REV. 20 FEB 95
	FINAL:	SCALE:	LAYER: 106	SHEET: 1 OF 2



NOTES:
1. AGITATE TOP MANIFOLD DURING ASSEMBLY TO FACILITATE SEAL SEATING.

METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DISP.		BEGEJ CORPORATION			5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE VACUUM SEAL - Assembly Detail			
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:		DWG. NO. TDRV3106	REV. 20 FEB 95
	FINAL:		SCALE:		LAYER: 106	SHEET: 2 OF 2



NOTES:

1. NO WASHERS ARE USED ON MANIFOLD SCREW.

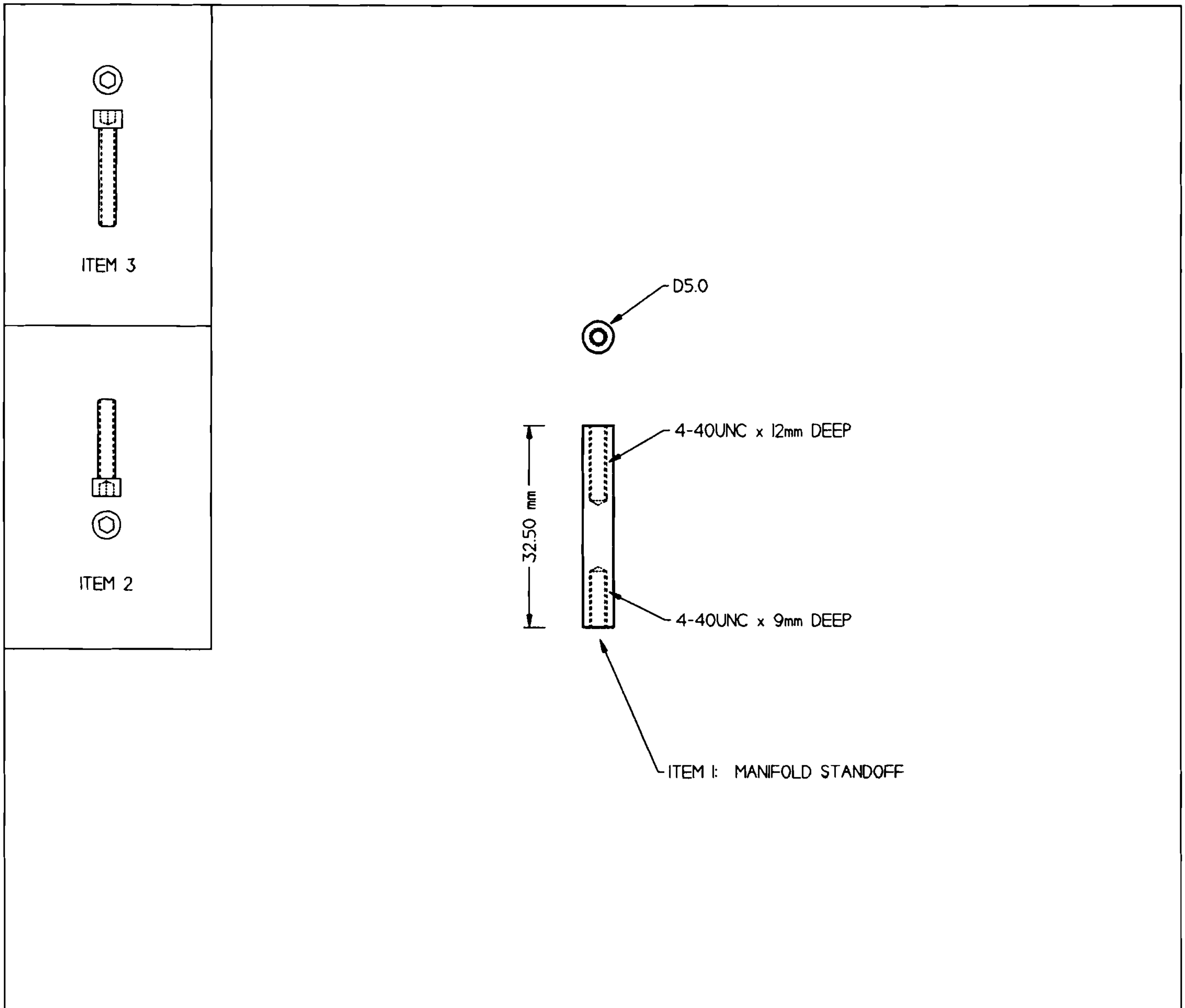
2. STANDOFF HEIGHT SELECTED TO PLACE TOP OF PWM PCB AT 79.00mm FROM BOTTOM EDGE OF ENCLOSURE. A PCB THICKNESS OF 1.58mm WOULD RESULT IN A CLEARANCE OF 3.92mm BETWEEN THE BOARD AND VACUUM MANIFOLD.

QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
2	TDRV3108-PRT04	PCB FASTENER: SPLIT LOCKWASHER 4-40UNC		4
2	TDRV3108-PRT03	PCB FASTENER: 4-40UNC x 3/8" BUTTONHEAD SOCKET SCREW		3
2	TDRV3108-PRT02	PRESSURE MANIFOLD FASTENER: 4-40UNC x 1/2" SOCKET CAP SCREW		2
2	TDRV3108-PRT01	PCB STANDOFF	STEEL	1

PARTS LIST (ONE MODULE)

DISTRIBUTION STATEMENT: CONFIDENTIAL AND PROPRIETARY INFORMATION. NOT FOR PUBLIC RELEASE. RESTRICTED DISTRIBUTION.

METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DRV.	BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS / DATE	TITLE PCB STANDOFFS (INTERNAL DRIVER VERSION)		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm		SIZE:	DWG. NO. TDRV3108	REV. 17 NOV 94
	FINAL:	SCALE:	LAYER: 108	SHEET: 1 OF 1



NOTES:
1. NO WASHERS USED ON MANIFOLD BOLTS.

QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
16	TDRV3109-PRT03	FASTENER, STANDOFF TO VACUUM MANIFOLD, 4-40UNC x 9/16" SOCKET CAP SCREW		3
16	TDRV3109-PRT02	FASTENER, STANDOFF TO PRESSURE MANIFOLD, 4-40UNC x 1/2" SOCKET CAP SCREW		2
16	TDRV3109-PRT01	MANIFOLD STANDOFF	STEEL	1

PARTS LIST (ONE MODULE)

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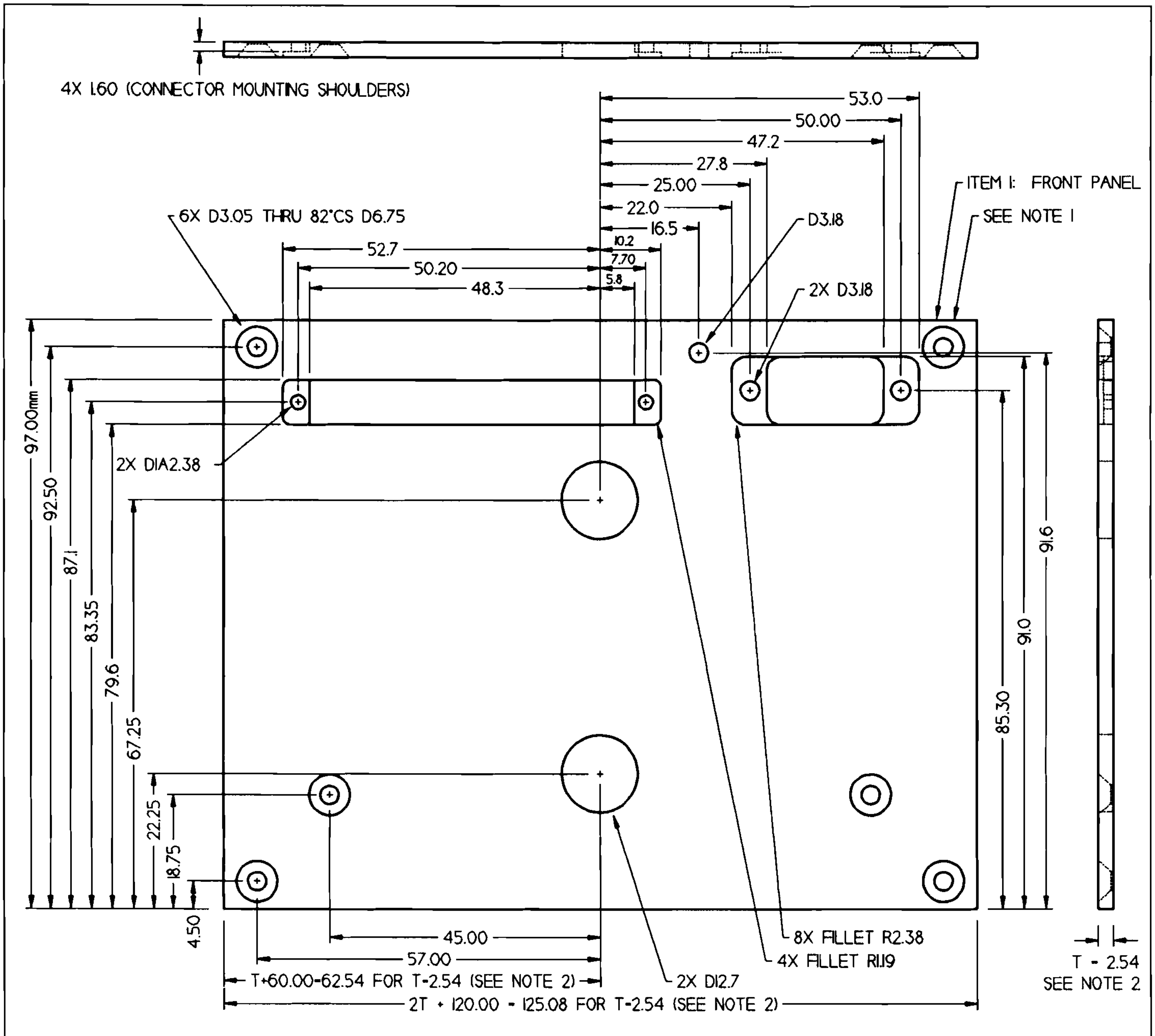
METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DISP.		BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE MANIFOLD STANDOFFS		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:	DWG. NO. TDRV3109	REV. 16 NOV 94
	FINAL:		SCALE:	LAYER: 109	SHEET: 1 OF 1



ITEM 2

ITEM 3

NOTES:

1. IMPART NON-DIRECTION FINISH WITH "SCOTCHBRITE" PAD. THEN BLUE ANODIZE.
2. ADJUST DIMENSIONS AS NECESSARY DEPENDING ON ACTUAL PLATE THICKNESS T.

QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
4	TDRV3110-PRT03	ENCLOSURE FASTENER: 4-40UNC x 1/4" FLATHEAD SOCKET SCREW		3
2	TDRV3110-PRT02	ENCLOSURE FASTENER: 4-40UNC x 3/8" FLATHEAD SOCKET SCREW		2
1	TDRV3110-PRT01	FRONT PANEL	ALUMINUM. 6061-T6 2.54mm THK	1

PARTS LIST (ONE MODULE)

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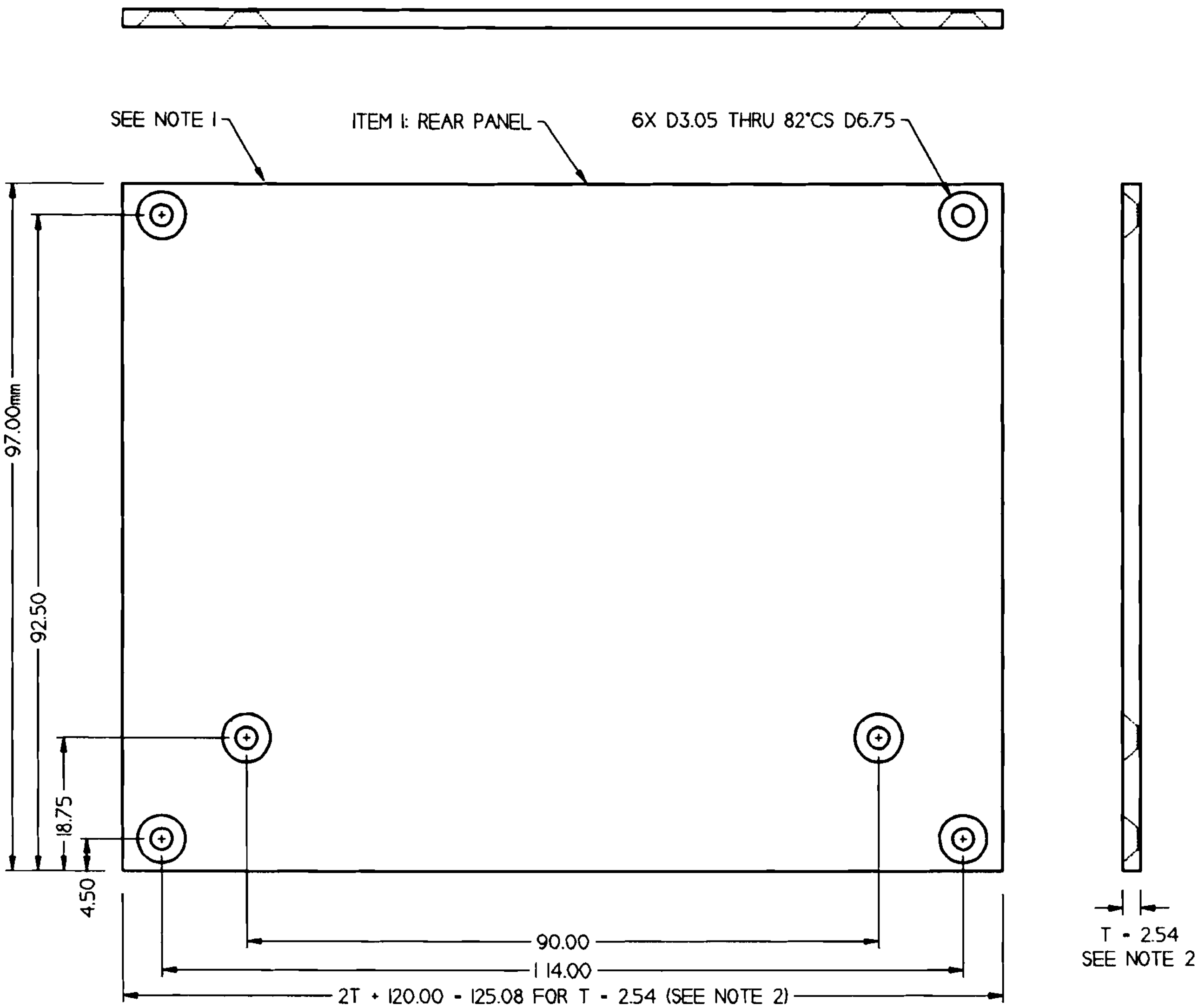
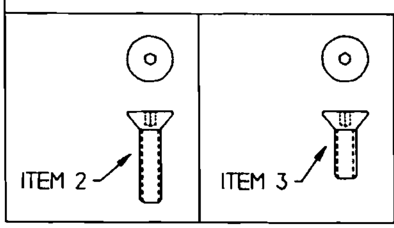
METRIC	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DISP.	BEGEJ CORPORATION	5 CLARET ASH ROAD LITTLETON. CO 80127 TEL/FAX: (303) 932-2186
THIRD ANGLE PROJECTION	APPROVALS / DATE	TITLE FRONT ENCLOSURE PANEL (INT. PCB PWM VERSION)	
TOL: X ±0.1 mm, X.X ±0.05mm, X.XX ±0.02mm		SIZE: / DWG. NO. TDRV3110	REV. 19 DEC 94
	FINAL:	SCALE: / LAYER: 110	SHEET: 1 OF 1





NOTES:

1. IMPART NON-DIRECTIONAL FINISH WITH "SCOTCHBRITE" PAD. THEN BLUE ANODIZE.
2. ADJUST DIMENSIONS AS NEEDED DEPENDING ON ACTUAL PLATE THICKNESS T.

QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
4	TDRV3111-PRT03	ENCLOSURE FASTENER: 4-40UNC x 1/4" FLATHEAD SOCKET SCREW		3
2	TDRV3111-PRT02	ENCLOSURE FASTENER: 4-40UNC x 3/8" FLATHEAD SOCKET SCREW		2
1	TDRV3111-PRT01	REAR PANEL	ALUMINUM. 6061-T6 2.54mm THK	1

PARTS LIST (ONE MODULE)

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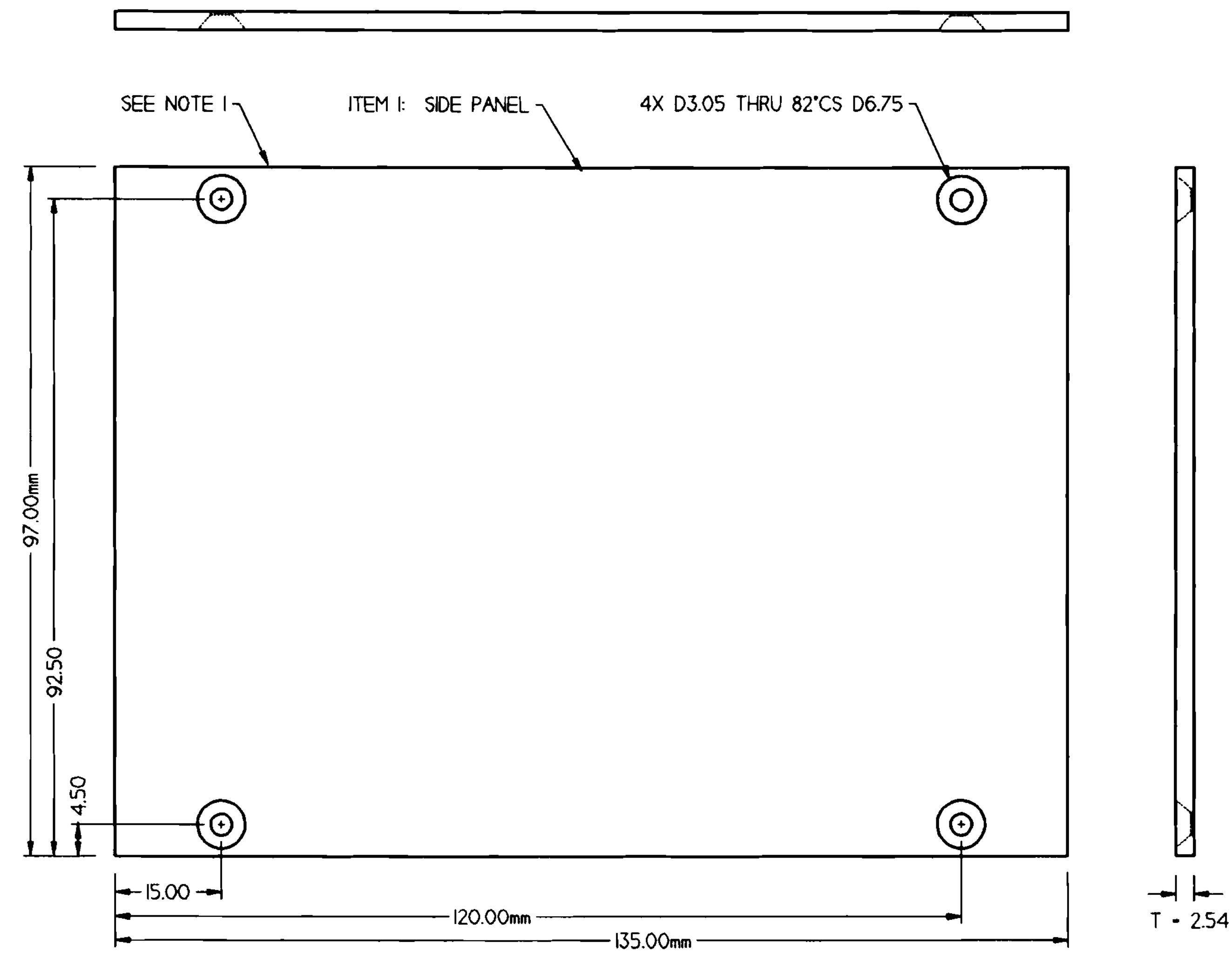
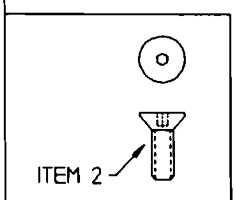
METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DRV.		BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON. CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE REAR ENCLOSURE PANEL (NO-SLOT VERSION)		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:	DWG. NO. TDRV3111	REV. 17 NOV 94
	FINAL:		SCALE:	LAYER: 111	SHEET: 1 OF 1





NOTES:

1. IMPART NON-DIRECTIONAL FINISH WITH "SCOTCHBRITE" PAD. THEN BLUE ANODIZE.

QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
8	TDRV3 1 1 2-PRT02	ENCLOSURE FASTENER: 4-40UNC x 1/4" FLATHEAD SOCKET SCREW		2
2	TDRV3 1 1 2-PRT01	SIDE PLATE	ALUMINUM, 6061-T6 2.54mm THK	1

PARTS LIST (ONE MODULE)

DISTRIBUTION STATEMENT: CONFIDENTIAL AND PROPRIETARY INFORMATION. NOT FOR PUBLIC RELEASE. RESTRICTED DISTRIBUTION.

METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DRV.	BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS / DATE	TITLE SIDE ENCLOSURE PANELS		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm		SIZE:	DWG. NO. TDRV312	REV. 17 NOV 94
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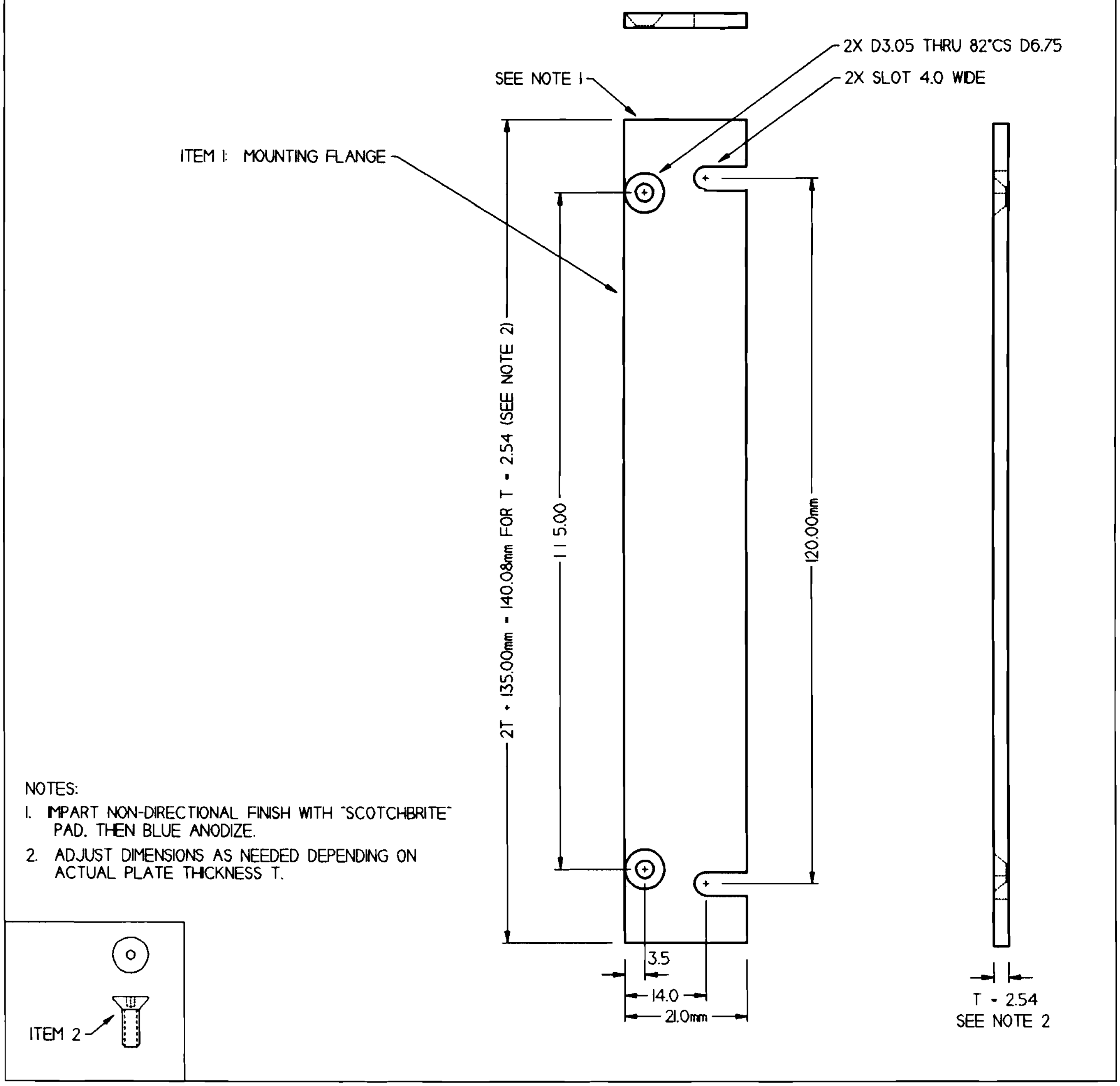

NOTES:

1. IMPART NON-DIRECTIONAL FINISH WITH "SCOTCHBRITE" PAD. THEN BLUE ANODIZE.
2. ADJUST DIMENSIONS AS NEEDED DEPENDING ON ACTUAL PLATE THICKNESS T.

QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
4	TDRV3113-PRT02	MOUNTING FLANGE FASTENER: 4-40UNC x 1/4" SOCKET FLATHEAD SCREW		2
2	TDRV3113-PRT01	MOUNTING FLANGE	ALUMINUM, 6061-T6 2.54mm THK	1

PARTS LIST (ONE MODULE)

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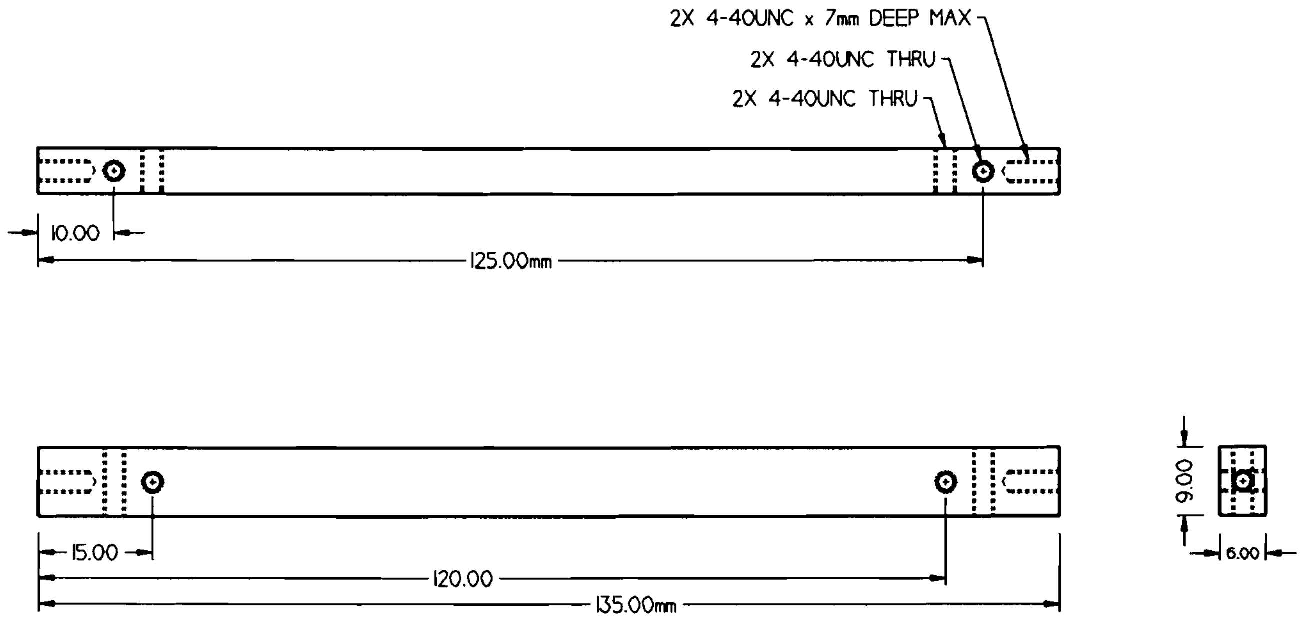
METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DRV.		BEGEJ CORPORATION	5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186	
	APPROVALS	DATE	TITLE ENCLOSURE MOUNTING FLANGES		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:	DWG. NO. TDRV3113	REV. 17 NOV 94
	FINAL:		SCALE:	LAYER: 113	SHEET: 1 OF 1



4	TDRV314-PRT01	ENCLOSURE PANEL ATTACHMENT RAIL	ALUMINUM 6061-T6	1
QTY	PART/ID NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
PARTS LIST (ONE MODULE)				

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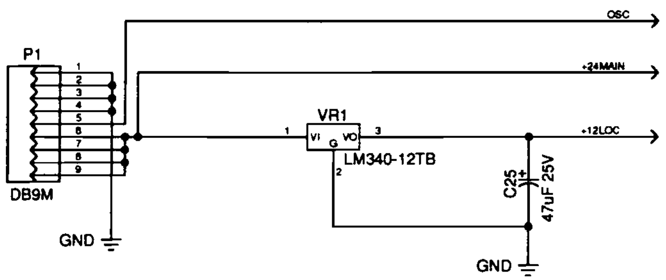
METRIC THIRD ANGLE PROJECTION	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DRV.		BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186
	APPROVALS	DATE	TITLE ENCLOSURE PANEL ATTACHMENT RAILS		
TOL: X ±0.1 mm X.X ±0.05mm X.XX ±0.02mm			SIZE:	DWG. NO. TDRV314	REV. 16 NOV 94
	FINAL:		SCALE:	LAYER: 14	SHEET: 1 OF 1

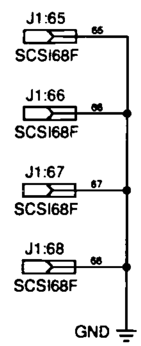
APPENDIX B

ELECTRICAL SCHEMATICS for the PWM DRIVER CONTROLLER (PCB VERSION)

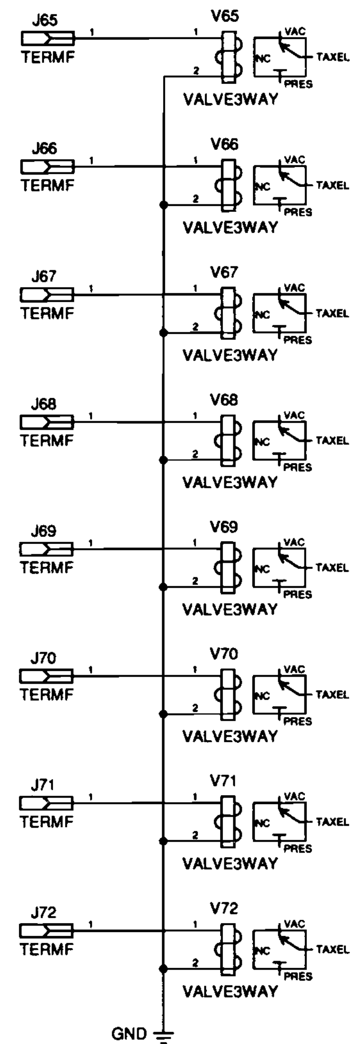
This section contains the electrical schematic diagrams, PCB layout, and valve lead routing pattern regarding the PWM valve control circuit. The electrical schematics were created with the TANGO SCHEMATIC software package from Accel Technologies, version 1.5 (DOS). The PCB design work was performed by an external design service using TANGO PCB PLUS, version 2.30A (DOS). The valve lead routing CAD drawing was made with Generic CADD, version 6 (DOS).



POWER/OSCILLATOR INTERFACE



SYSTEM GROUND PINS



SPARE VALVES

PCB NOTES:

1 PRINCIPAL OBJECTIVE IS TO REDUCE BOARD LENGTH (MAX L = 78.0mm)

2. SURFACE MOUNT DEVICES
LM324D (SOIC)
UDN2982LW (SOIC)
C1 TO C24 BYPASS CAPS

THE FOLLOWING COMPONENTS REQUIRE THRU-HOLE MOUNTING.
J100 SCSI-68 CONNECTOR
P100 DB9M CONNECTOR
VR1 LM430 12v REGULATOR. T0-220 PACKAGE
RSIP1 - RSIP8 SIP RESISTORS (NOTE 6-PIN SIPS ALTS?)
P1 - P64 2X32 HEADER STRIP

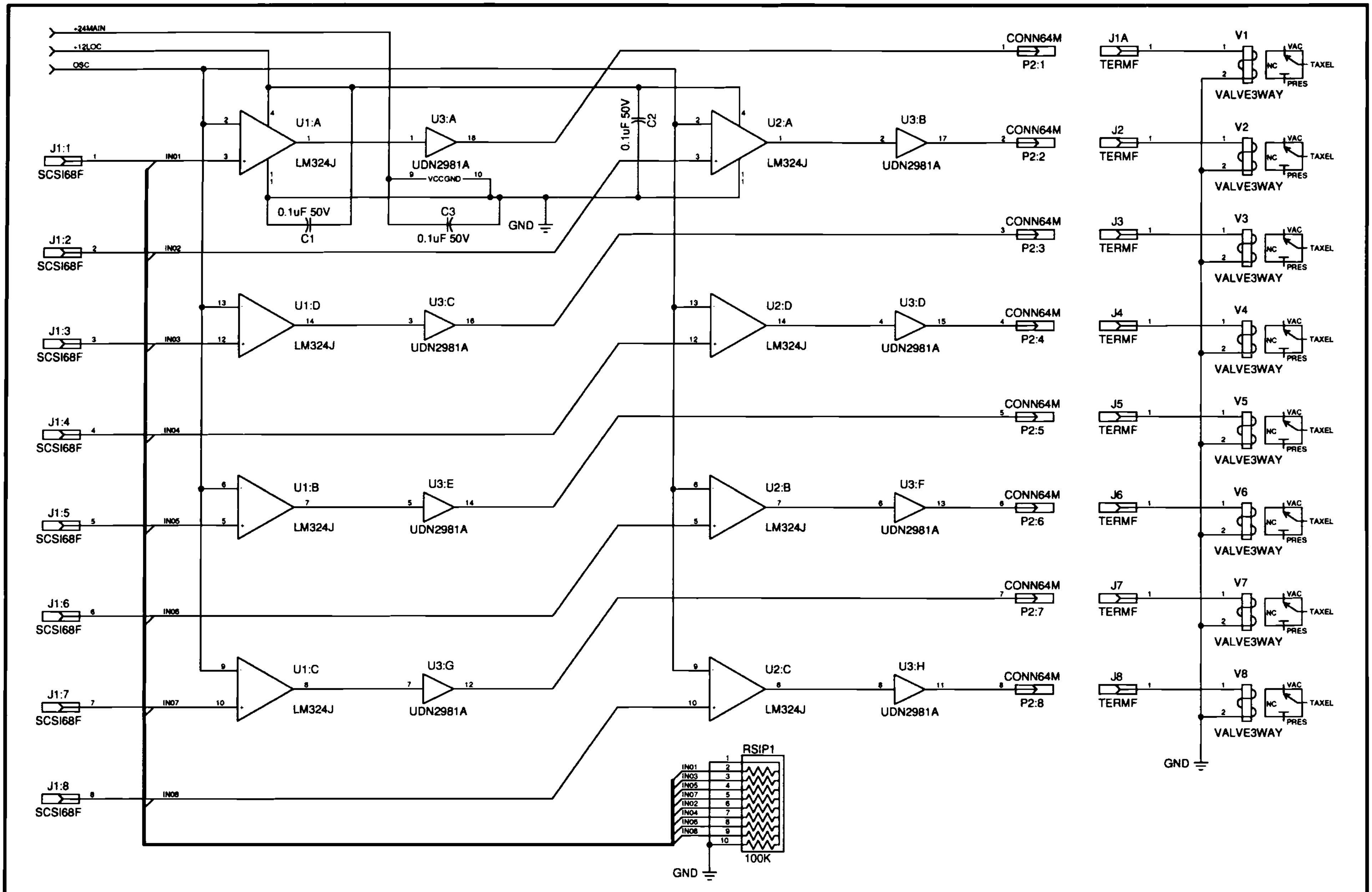
3 ALL IC's MUST BE LOCATED ON FRONT OF THE BOARD FOR COOLING PURPOSES

4 ALL OUTPUT DRIVER LINES (UDN2982) MUST BE ABLE TO CARRY A MAXIMUM CURRENT OF 120ma

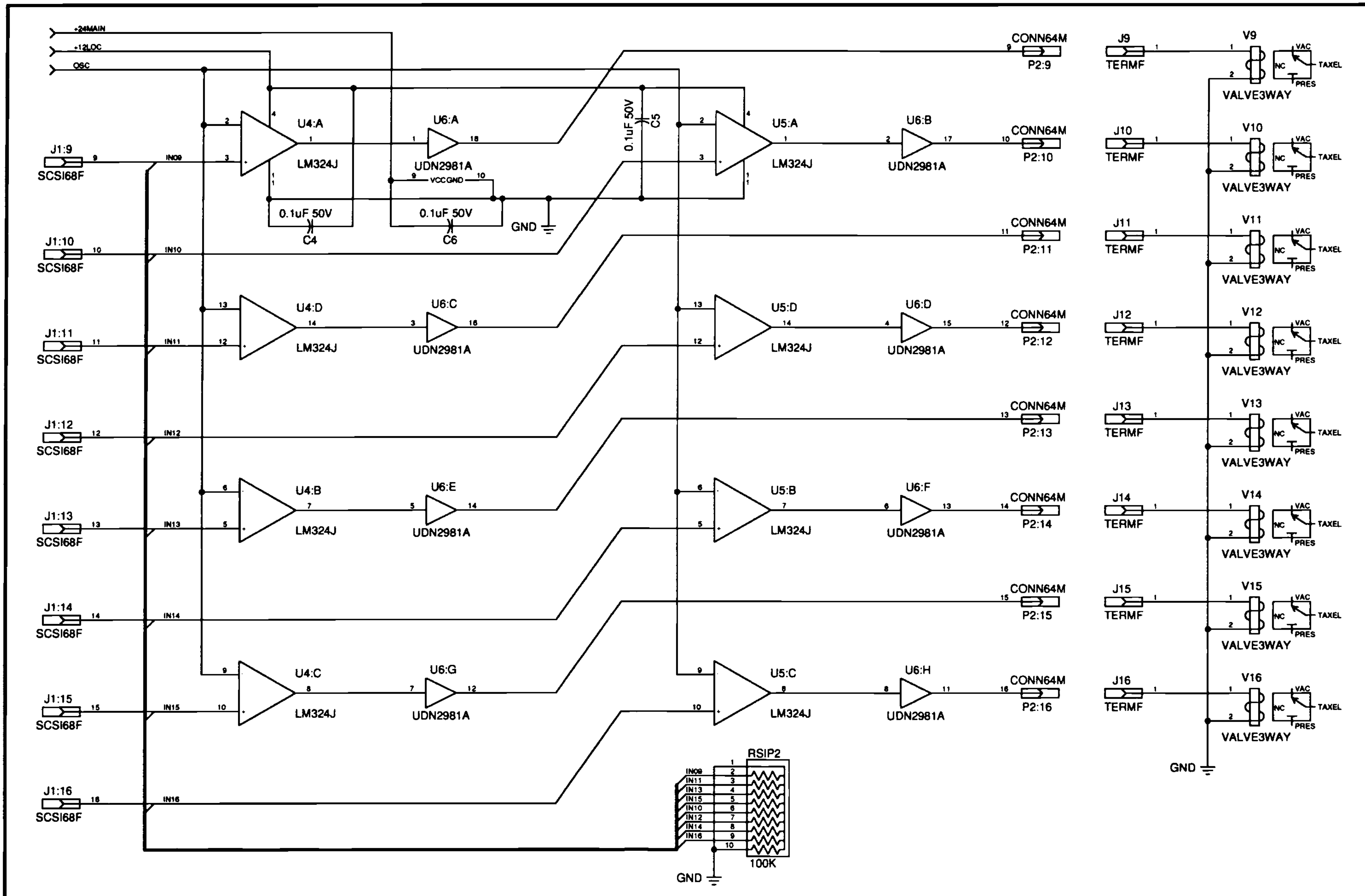
5 THE FOLLOWING NETS SHOULD BE PLACED ON INDIVIDUAL PCB LAYERS
+24MAIN
GROUND

6. VOLTAGE REG (VR1) LEADS MUST BE FILED SO PACKAGE SITS FLUSH WITH PCB.

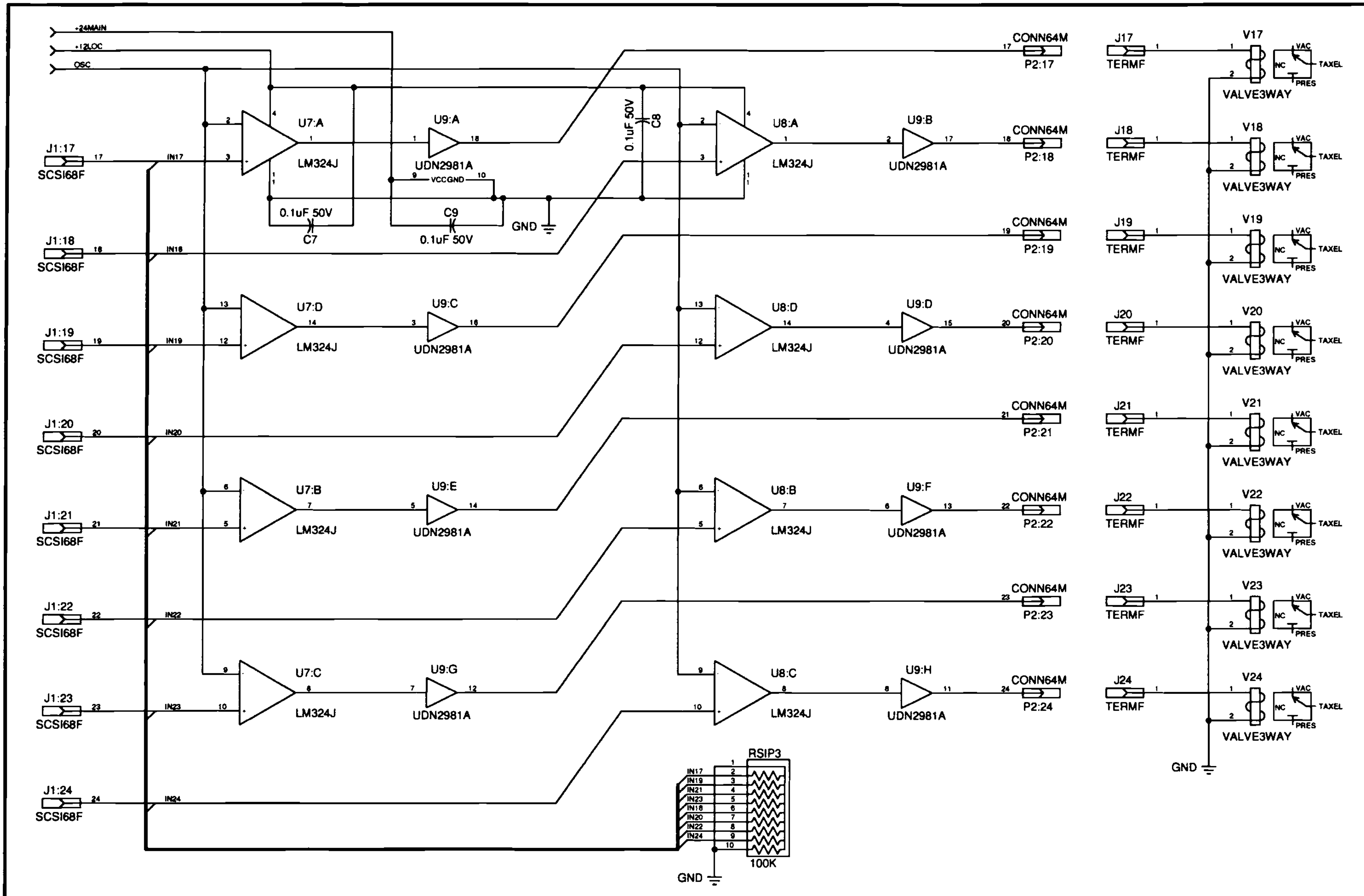
Title: PWM CTRL and VALVE DRIVER: Interface (PCB Ver 1)	Dwg: VALCTRL4.S01	Sheet 1 of 9	Date: 6 OCT 94	By: GKW
BEGEJ CORPORATION	Classification: CONFIDENTIAL AND PROPRIETARY INFORMATION.	Distrib: INTERNAL ONLY. NOT FOR PUBLIC RELEASE.		



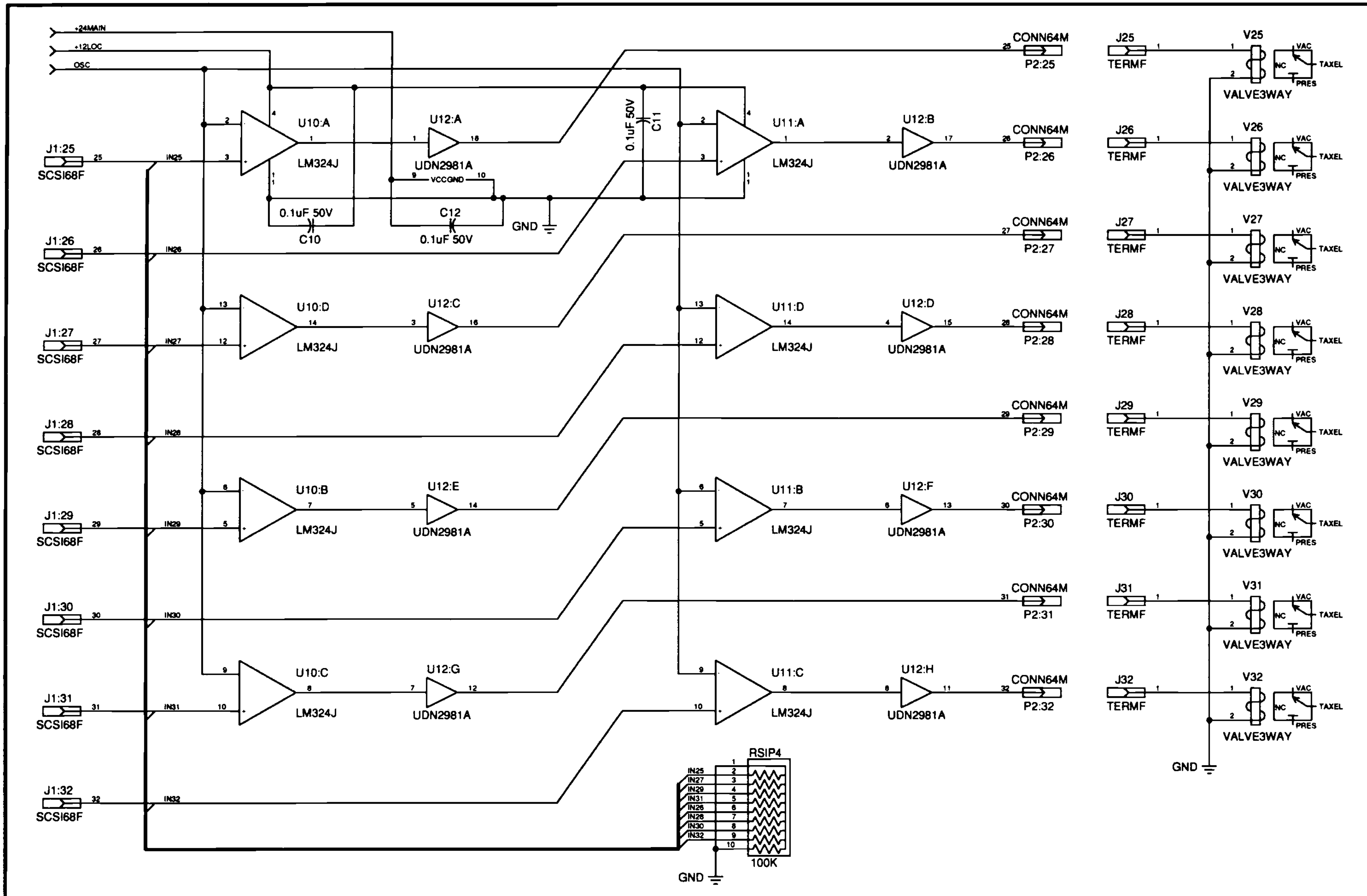
Title: PWM CTRL and VALVE DRIVER: CH 1-8 (PCB Ver 1)	Dwg: VALCTRL4.S02	Sheet 2 of 9	Date: 6 OCT 94	By: GKW
BEGEJ CORPORATION	Classification: CONFIDENTIAL AND PROPRIETARY INFORMATION.	Distrib: INTERNAL ONLY. NOT FOR PUBLIC RELEASE.		



Title: PWM CTRL and VALVE DRIVER: CH 9-16 (PCB Ver 1)	Dwg: VALCTRL4.S03	Sheet 3 of 9	Date: 6 OCT 94	By: GKW
BEGEJ CORPORATION	Classification: CONFIDENTIAL AND PROPRIETARY INFORMATION.	Distrib: INTERNAL ONLY. NOT FOR PUBLIC RELEASE.		



Title: PWM CTRL and VALVE DRIVER: CH 17-24 (PCB Ver 1)	Dwg: VALCTRL4.S04	Sheet 4 of 9	Date: 6 OCT 94	By: GKW
BEGEJ CORPORATION	Classification: CONFIDENTIAL AND PROPRIETARY INFORMATION.	Distrib: INTERNAL ONLY. NOT FOR PUBLIC RELEASE.		



Title: PWM CTRL and VALVE DRIVER: CH 25-32 (PCB Ver 1)	Dwg: VALCTRL4.S05	Sheet 5 of 9	Date: 6 OCT 94	By: GKW

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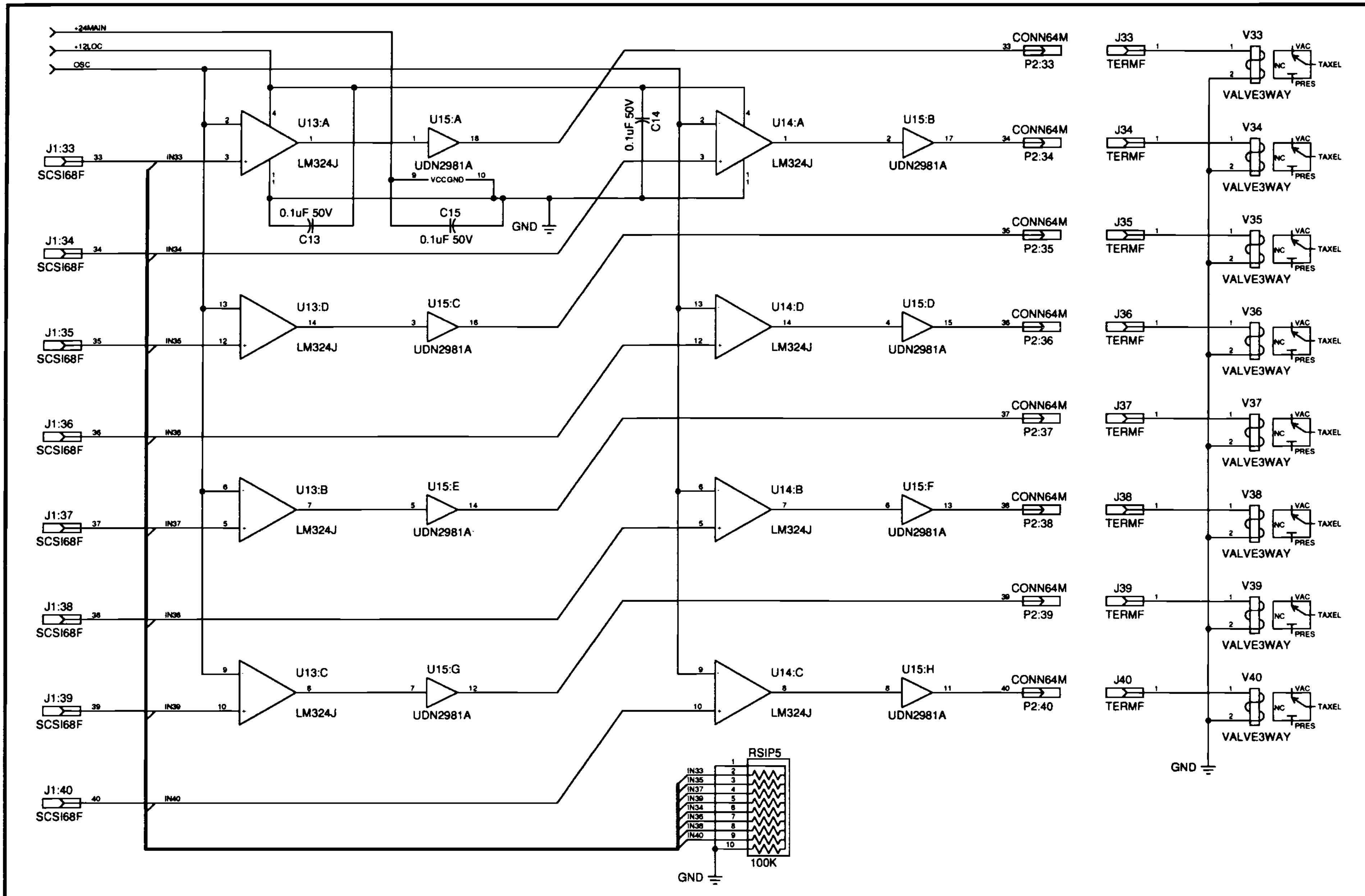
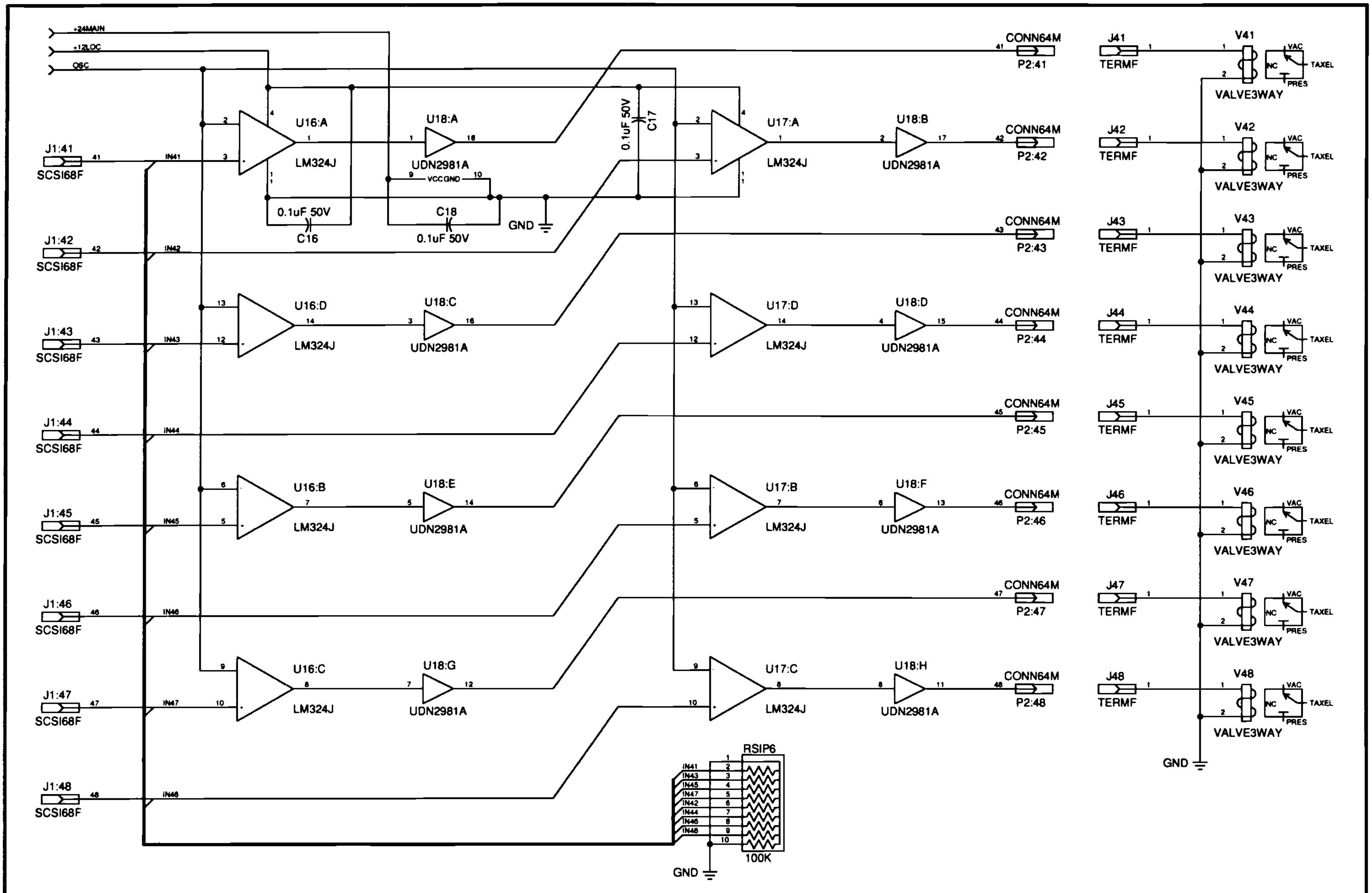
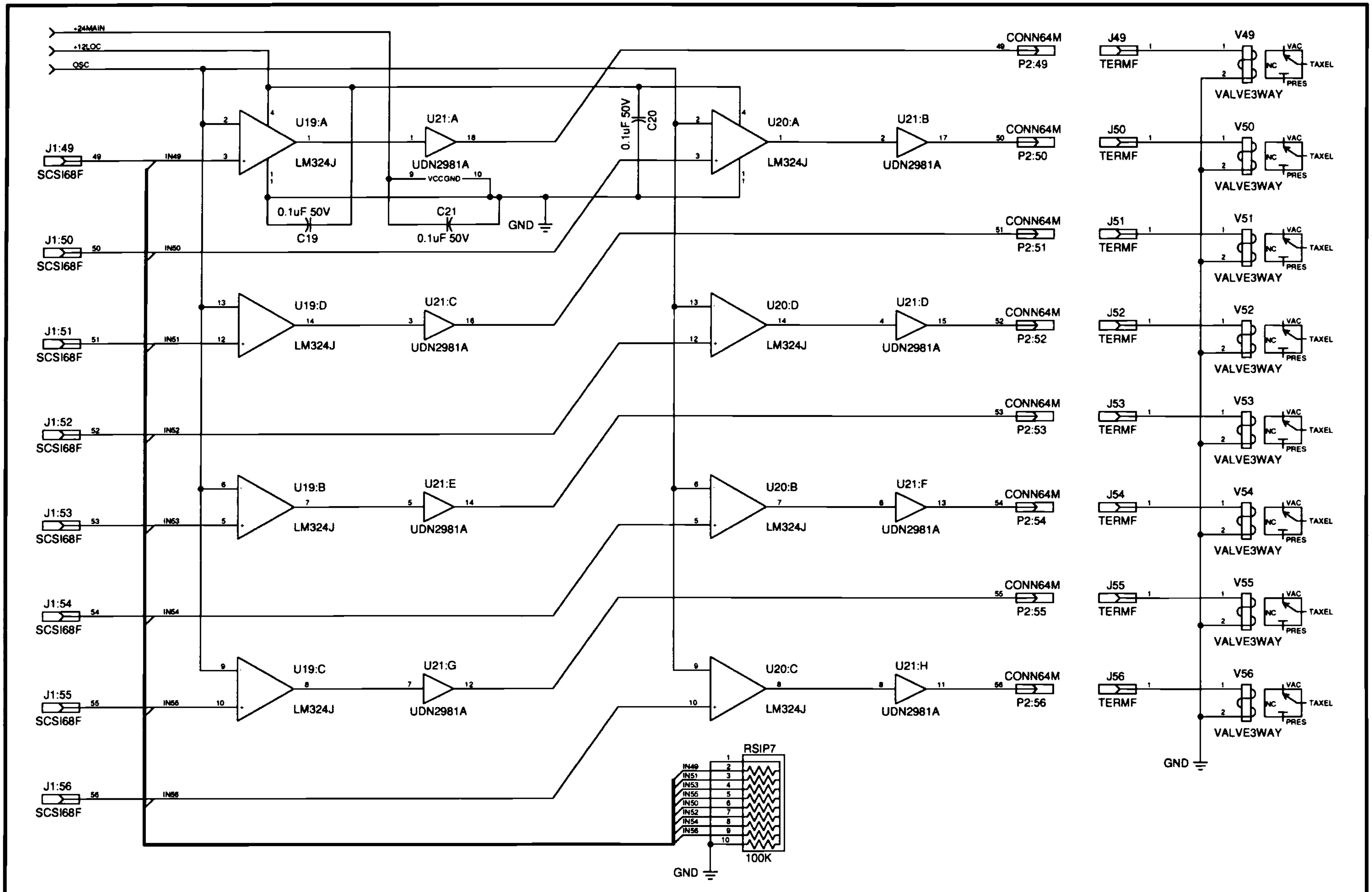


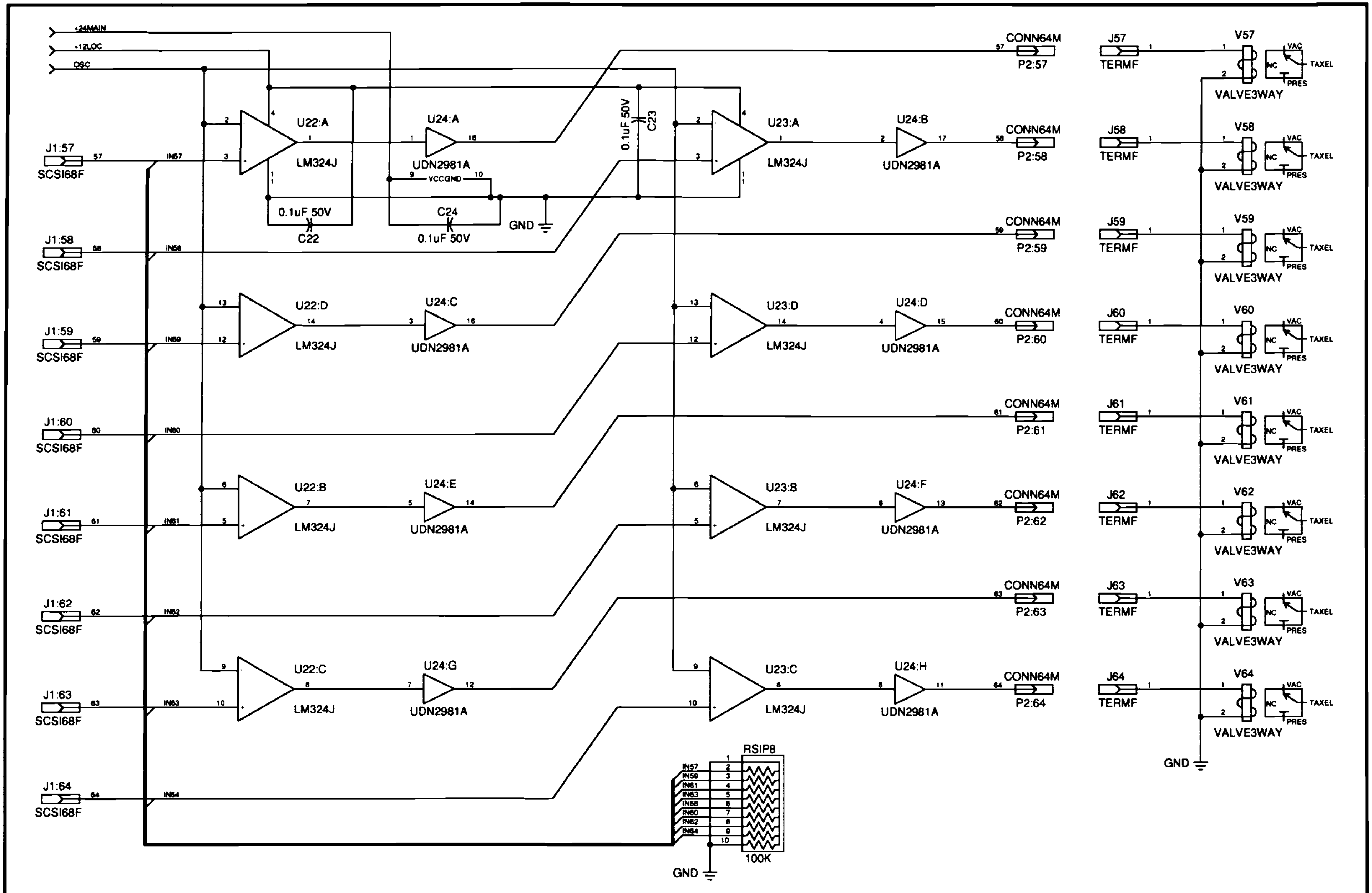
Title: PWM CTRL and VALVE DRIVER: CH 33-40 (PCB Ver 1)	Dwg: VALCTRL4.S06	Sheet 6 of 9	Date: 6 OCT 94	By: GKW
BEGEJ CORPORATION	Classification: CONFIDENTIAL AND PROPRIETARY INFORMATION.	Distrib: INTERNAL ONLY. NOT FOR PUBLIC RELEASE.		



Title: PWM CTRL and VALVE DRIVER: CH 41-48 (PCB Ver 1)	Dwg: VALCTRL4.S07	Sheet 7 of 9	Date: 6 OCT 94	By: GKW
BEGEJ CORPORATION	Classification: CONFIDENTIAL AND PROPRIETARY INFORMATION.	Distrib: INTERNAL ONLY. NOT FOR PUBLIC RELEASE.		



Title: PWM CTRL and VALVE DRIVER: CH 49-56 (PCB Ver 1)	Dwg: VALCTRL4.S08	Sheet 8 of 9	Date: 6 OCT 94	By: GKW
BEGEJ CORPORATION	Classification: CONFIDENTIAL AND PROPRIETARY INFORMATION.		Distrib: INTERNAL ONLY. NOT FOR PUBLIC RELEASE.	



Title: PWM CTRL and VALVE DRIVER: CH 57-64 (PCB Ver 1)	Dwg: VALCTRL4.S09	Sheet 9 of 9	Date: 6 OCT 94	By: GKW

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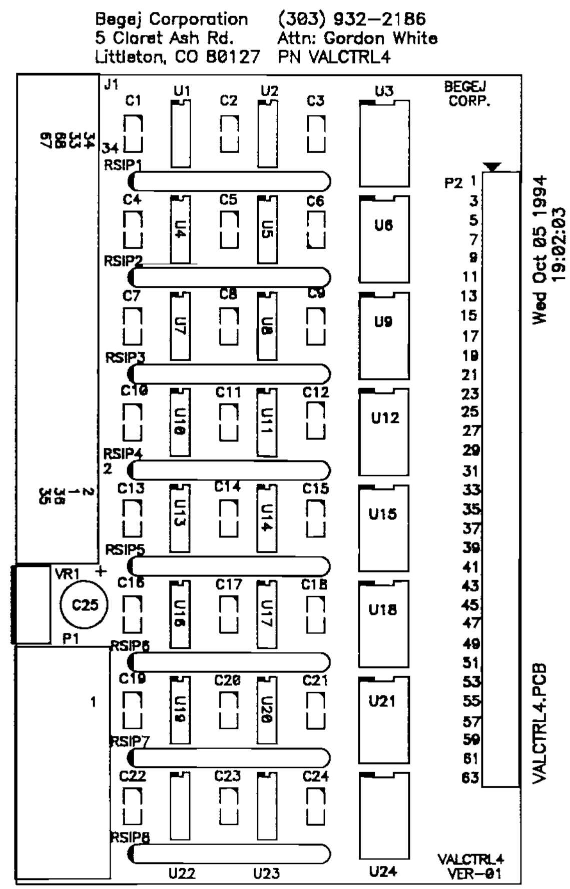
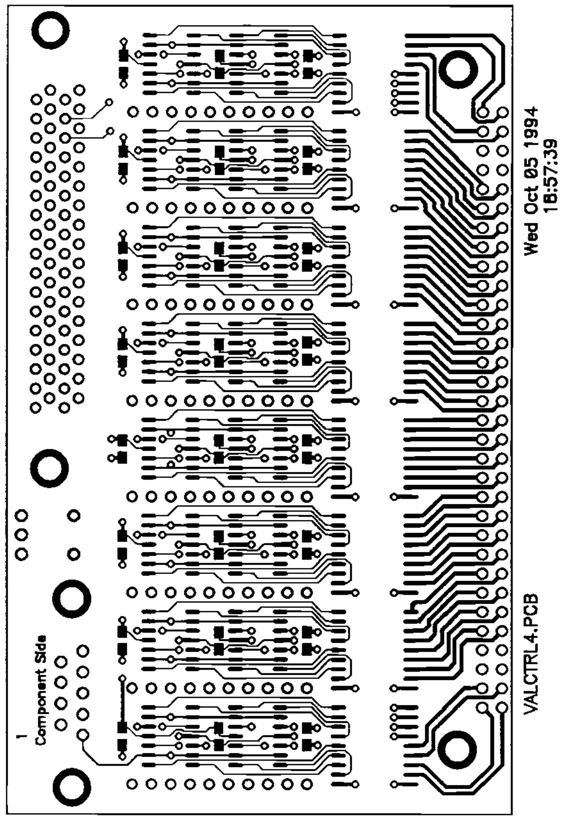


Silk Screen

Title	PWM CTRL and VALVE DRIVER
Size	A
Number	VALCTRL4
Rev	-01
Date	Wed Oct 05 1994
Drawn by	ABD
Filename	VALCTRL4.PCB
Sheet	of

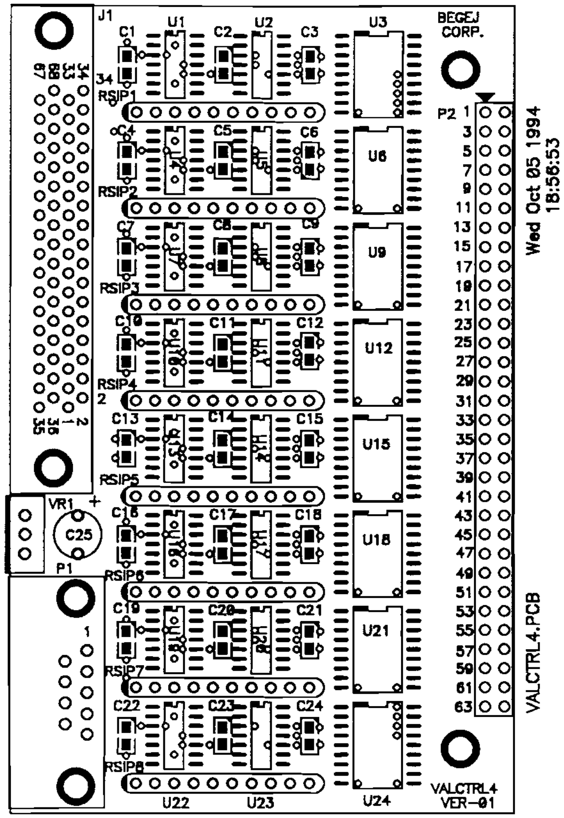
Begej Corporation (303) 932–2186
5 Claret Ash Rd. Attn: Gordon White
Littleton, CO 80127 PN VALCTRL4



Component Side (L1)

Title	PWM CTRL and VALVE DRIVER		
Size: A	Number: VALCTRL4		Rev: –01
Date	Wed Oct 05 1994	Drawn by	ABD
Filename	VALCTRL4.PCB	Sheet	of

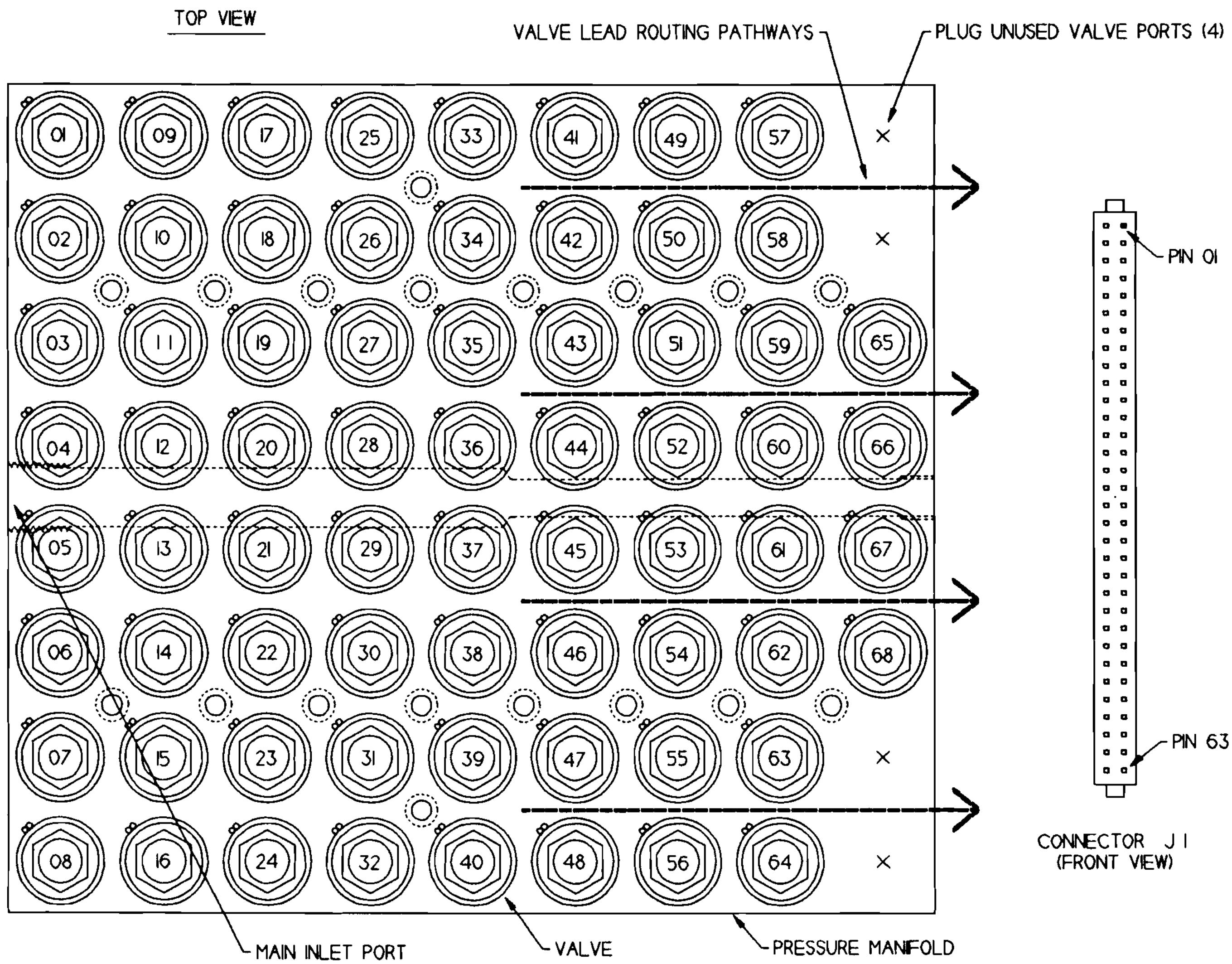
Begej Corporation (303) 932-2186
5 Claret Ash Rd. Attn: Gordon White
Littleton, CO 80127 PN VALCTRL4



Silk Screen

Top Assembly Dwg.

Title	PWM CTRL and VALVE DRIVER	
Size A	Number VALCTRL4	Rev -01
Date Wed Oct 05 1994	Drawn by ABD	
Filename VALCTRL4.PCB	Sheet of	



NOTES

1. SOLDER ONE LEAD (E.G. BROWN) OF EACH VALVE TO VALVE CASE.
2. MASS-TERMINATE REMAINING VALVE LEAD (E.G. ORANGE) INTO 2X32 IDC RECEPTACLE CONNECTOR (J 1):
   VALVE 01 TO J 1-01
   VALVE 02 TO J 1-02
   ETC
   VALVE 64 TO J 1-64
3. SPARE VALVES 65-68 ARE USED AS NEEDED BY DISASSEMBLING J 1, REMOVING THE LEAD FROM THE DEFECTIVE VALVE, AND INSERTING THE LEAD FOR THE SUBSTITUTE VALVE IN ITS PLACE.
4. FOLD CABLE OVER VACUUM MANIFOLD AND MATE J 1 WITH HEADER P2 ON PWM PCB.

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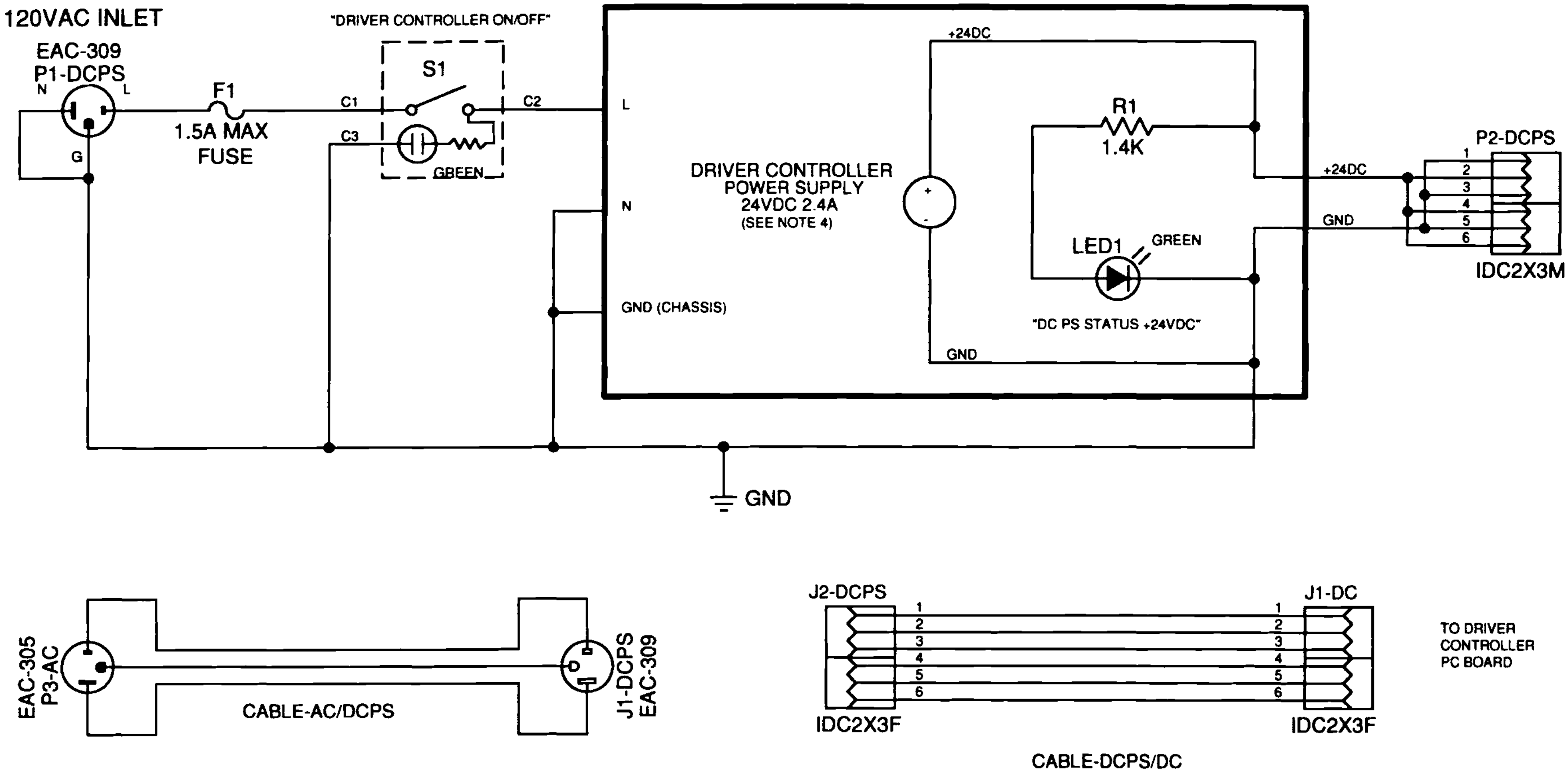
METRIC	CONTRACT NO. NAS9-18901 PH-2 WAM TACT. DRV.	BEGEJ CORPORATION		5 CLARET ASH ROAD LITTLETON, CO 80127 TEL/FAX: (303) 932-2186	
THIRD ANGLE PROJECTION	APPROVALS	DATE	TITLE VALVE LEAD TERMINATION (68 VALVES, 64 TAXELS)		
TOL: X ±0.1 mm, X.X ±0.05mm, X.XX ±0.02mm			SIZE:	DWG. NO. TDRV3001	REV. 17 JAN 95
	FINAL:		SCALE:	LAYER: MULTI	SHEET: 1 OF 1

APPENDIX C

ELECTRICAL SCHEMATICS for the DISPLAY DRIVER CONTROLLER (DDC)

This section contains the electrical schematic diagrams for the Display Driver Controller module for the TDS, in addition to the PCB physical layout for the PWM waveform and interlock logic board. The electrical schematics were created with the TANGO SCHEMATIC software package from Accel Technologies, version 1.5 (DOS). The PCB design work was performed by an external design service using TANGO PCB PLUS, version 2.30A (DOS).

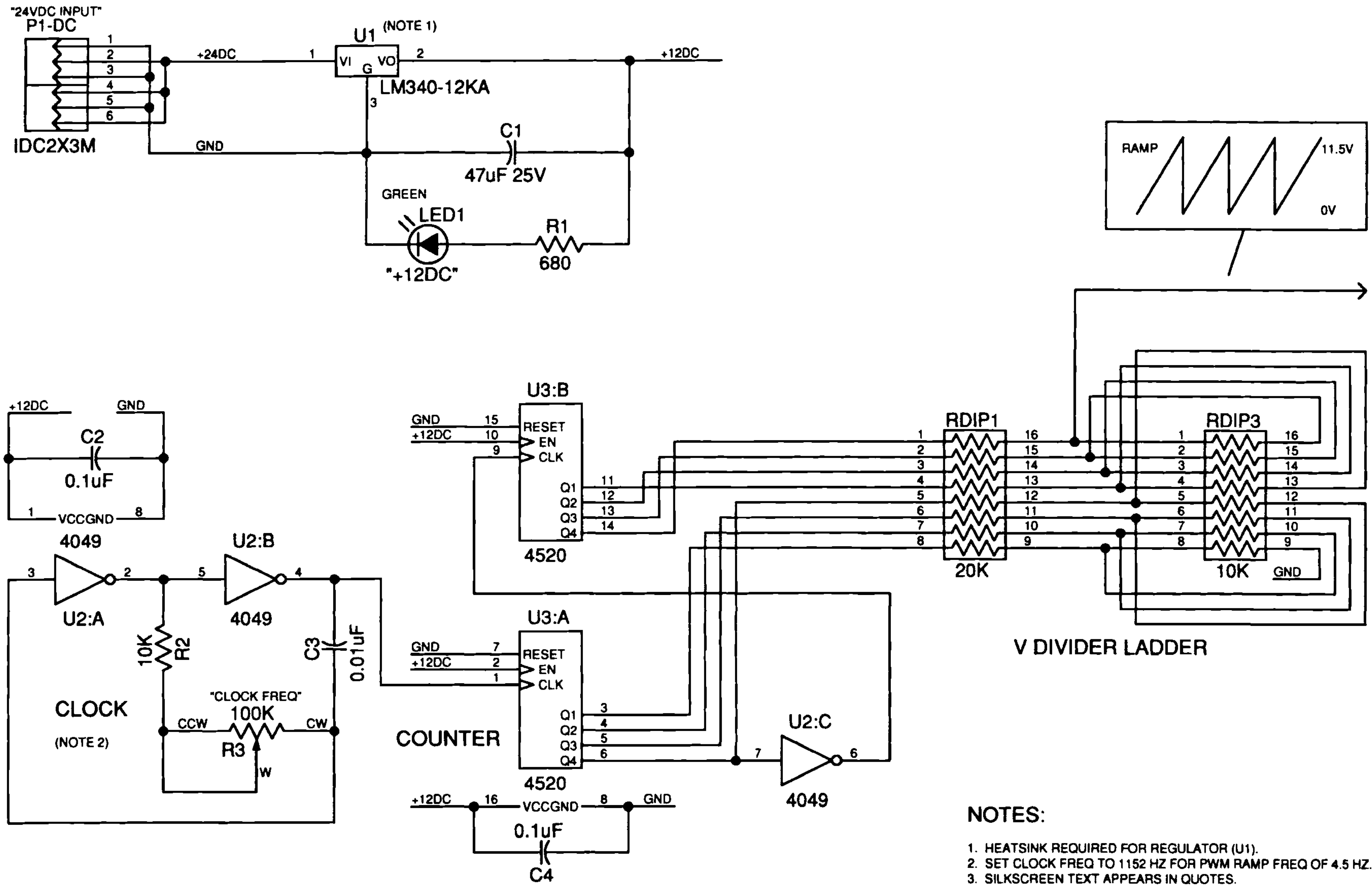


NOTES:

1. S1 MOUNTS ON FRONT PANEL.
2. P1-DCPS, F1 AND F2 MOUNT ON REAR PANEL.
3. LED1 IS LOCATED AT THE POWER SUPPLY TERMINALS.
4. MIN/MAX CURRENT DRAW 0.14/0.22A (RELAY OFF/ON)

DRV_DRC.S15

Title: DISPLAY CONTROLLER - DC POWER SUPPLY	Dwg: DRV_C_PS.S01	Sheet	Date: 03 APR 96	By: SB
BEGEJ CORPORATION	Classif: CONFIDENTIAL AND PROPRIETARY INFORMATION	Distrib: INTERNAL ONLY - NOT FOR PUBLIC RELEASE		



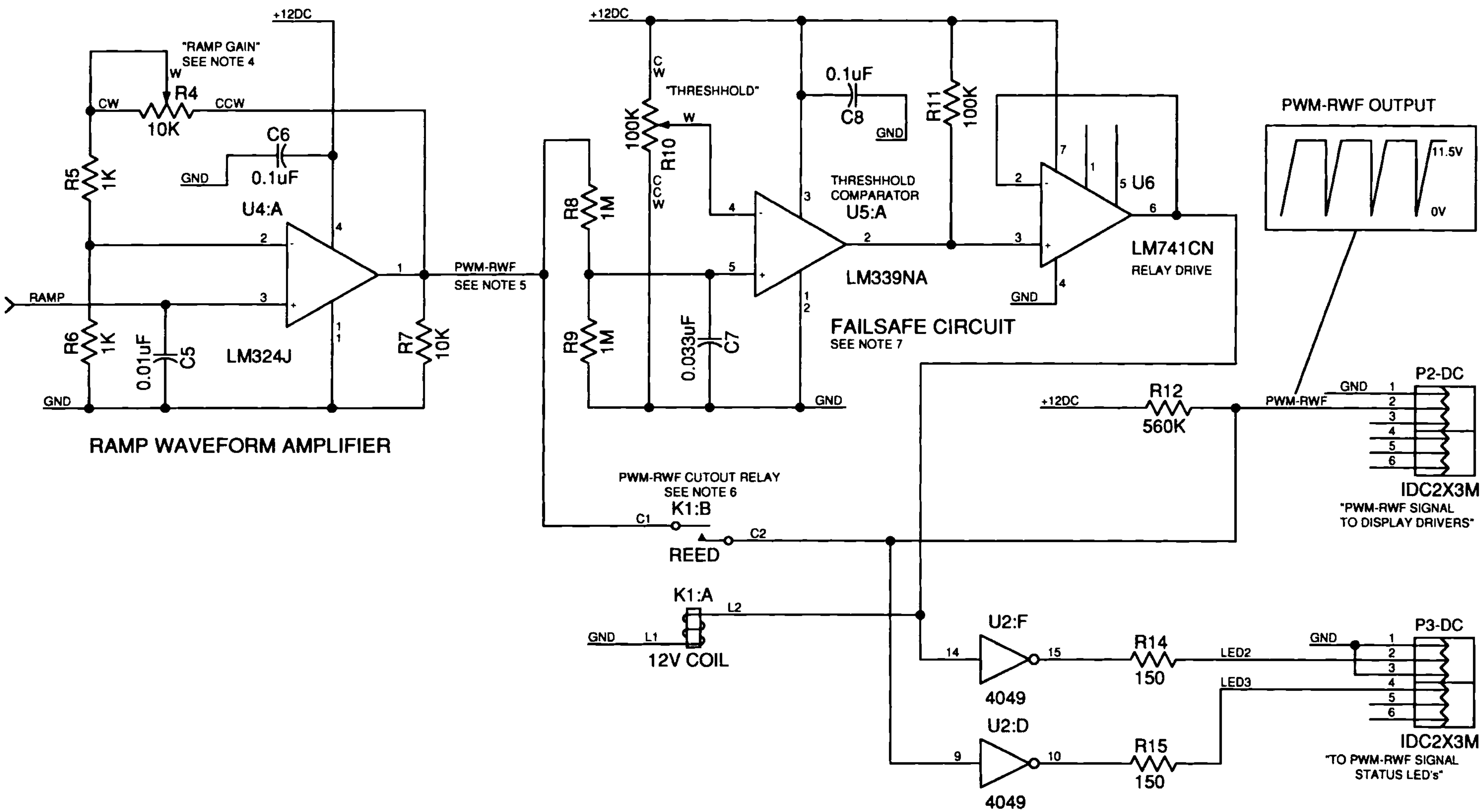
NOTES:

1. HEATSINK REQUIRED FOR REGULATOR (U1).
2. SET CLOCK FREQ TO 1152 HZ FOR PWM RAMP FREQ OF 4.5 HZ.
3. SILKSCREEN TEXT APPEARS IN QUOTES.

DRV_DRC.S20

Title: DRIVER CONTROLLER BOARD: PWM RAMP WAVEFORM GENERATOR (RWG)	Dwg: DRV_CTRL.S01	Sheet 1 OF 3	Date: 04 APR 96	By: SB

BEGEJ CORPORATION	Classif: CONFIDENTIAL AND PROPRIETARY INFORMATION	Distrib: INTERNAL ONLY - NOT FOR PUBLIC RELEASE

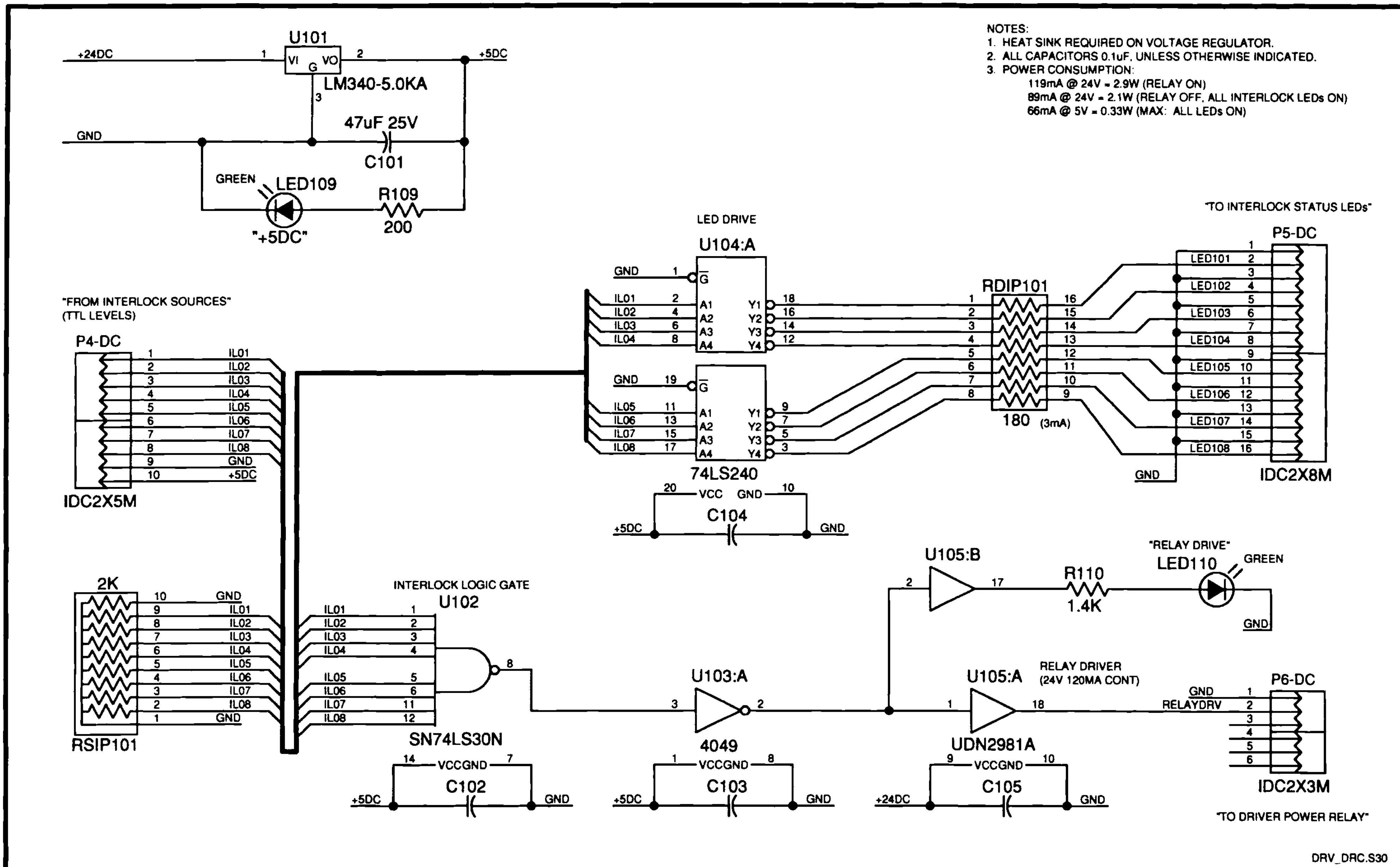


NOTES:

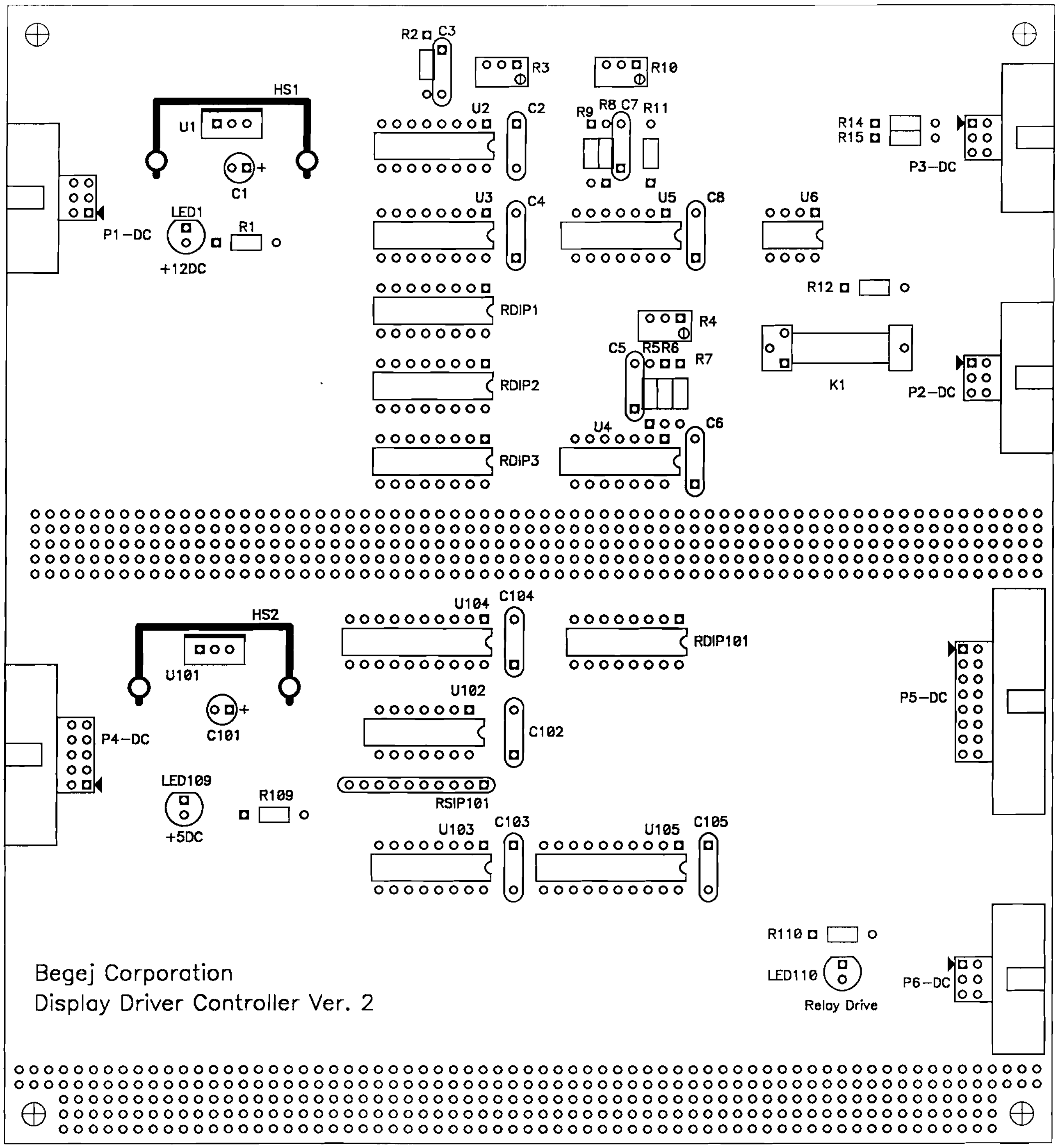
4. ADJUST GAIN (R4) TO PROVIDE 10% PWM DUTY FACTOR WITH RESPECT TO A 5V LEVEL.
5. MAX CURRENT DRAW PER TAXEL = 5UA (2.8 MA FOR 512 TAXELS)
6. RWF CUTOUT RELAY CAUSES OUTPUT AT P2-RWG TO GO TO 12V IF RWG BECOMES UNCAL.
7. FAILSAFE CIRCUIT INHIBITS PWM-RWF SIGNAL SHOULD LATTER DEVIATE FROM LIMITS.

DRV_DRC.S25

Title: DRIVER CONTROLLER BOARD: PWM RAMP WAVEFORM GENERATOR OUTPUT	Dwg: DRV_CTRL.S02	Sheet 2 OF 3	Date: 05 APR 96	By: SB
BEGEJ CORPORATION	Classif: CONFIDENTIAL AND PROPRIETARY INFORMATION	Distrib: INTERNAL ONLY - NOT FOR PUBLIC RELEASE		

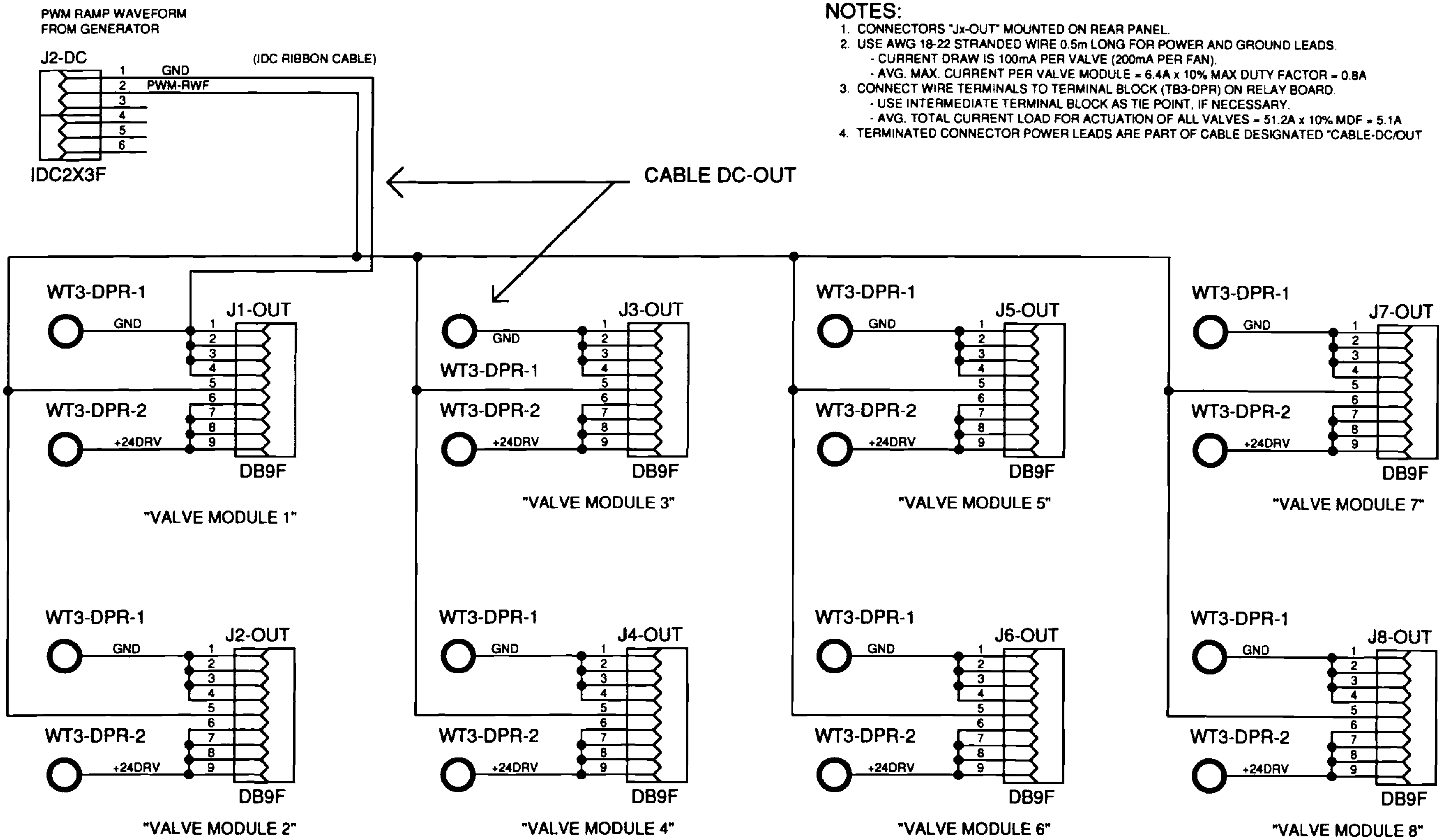


Title: INTERLOCK LOGIC AND POWER RELAY CONTROL	DRV_CTRL.S03	Sheet 3 of 3	Date: 05 APR 96	By: SB
BEGEJ CORPORATION	Classif: CONFIDENTIAL AND PROPRIETARY INFORMATION	Distrib: INTERNAL ONLY - NOT FOR PUBLIC RELEASE		



PCB version of the Driver Controller Board (see **Figure 44** and **Figure 45**). Top half generates PWM ramp waveform at 4.5 Hz, whereas bottom half implements the interlock logic and activates the relay controlling routing of the 24 VDC Display Power Supply voltage. Drawing DRV-CTRL.PCB.

NOTES:
1. CONNECTORS "Jx-OUT" MOUNTED ON REAR PANEL.
2. USE AWG 18-22 STRANDED WIRE 0.5m LONG FOR POWER AND GROUND LEADS.
   - CURRENT DRAW IS 100mA PER VALVE (200mA PER FAN).
   - AVG. MAX. CURRENT PER VALVE MODULE = 6.4A x 10% MAX DUTY FACTOR = 0.8A
3. CONNECT WIRE TERMINALS TO TERMINAL BLOCK (TB3-DPR) ON RELAY BOARD.
   - USE INTERMEDIATE TERMINAL BLOCK AS TIE POINT, IF NECESSARY.
   - AVG. TOTAL CURRENT LOAD FOR ACTUATION OF ALL VALVES = 51.2A x 10% MDF = 5.1A
4. TERMINATED CONNECTOR POWER LEADS ARE PART OF CABLE DESIGNATED "CABLE-DC/OUT



**** AS-BUILT VERSION ****

DRV_DRC.S35

Title: DISPLAY DRIVER OUTPUT CONNECTORS	Dwg: OUT_CONS.S02	Sheet	Date: 21 MAY 96	By: SB

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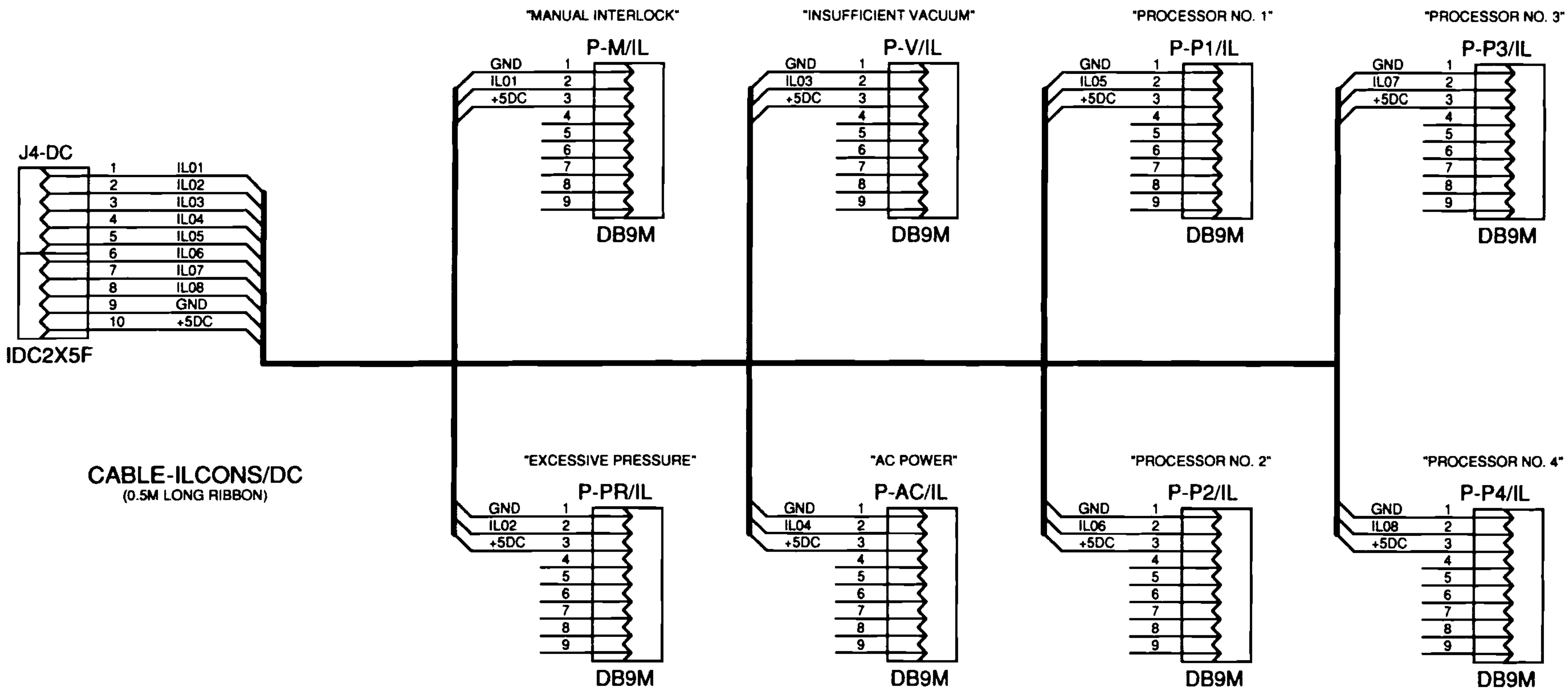
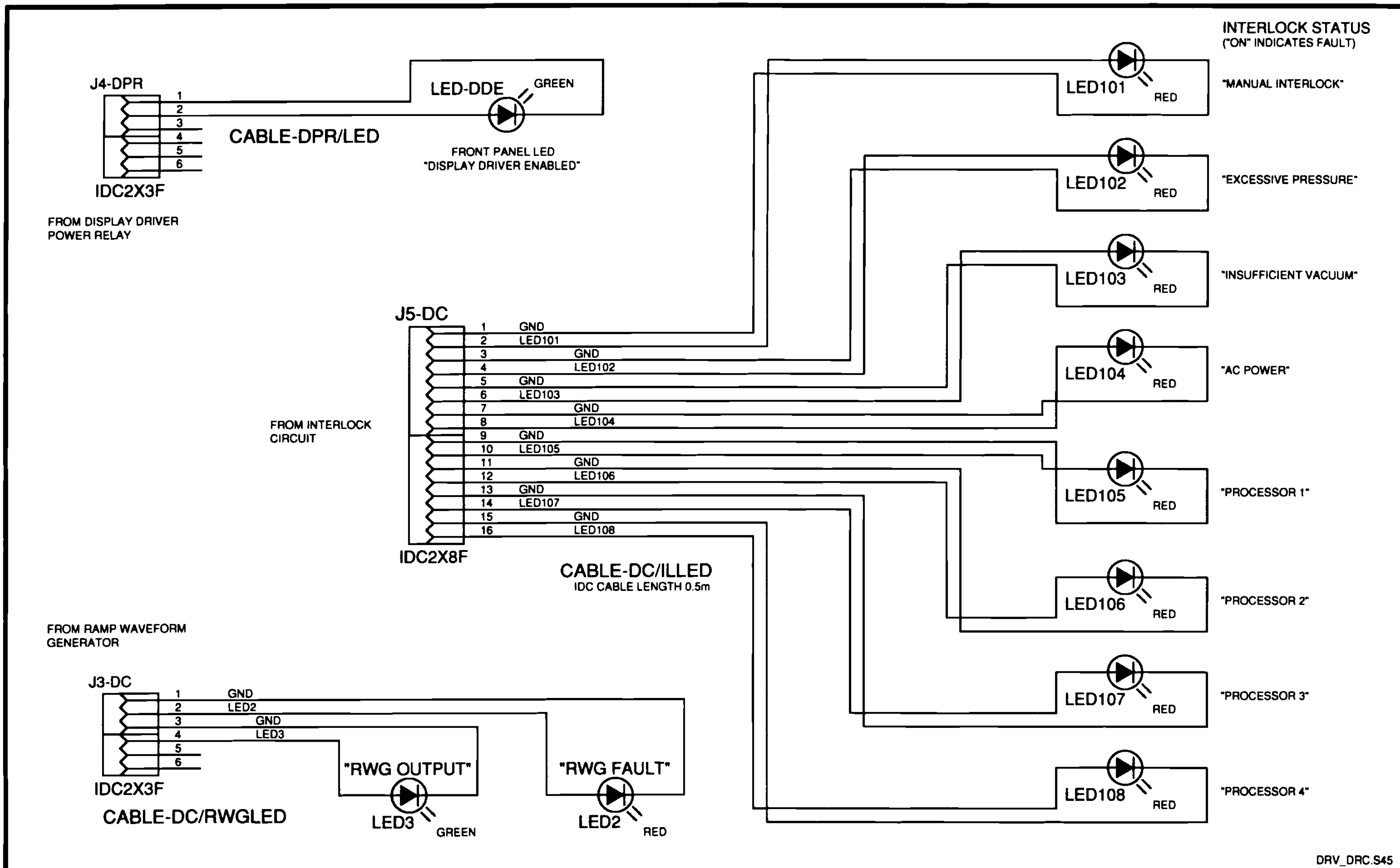


NOTES:

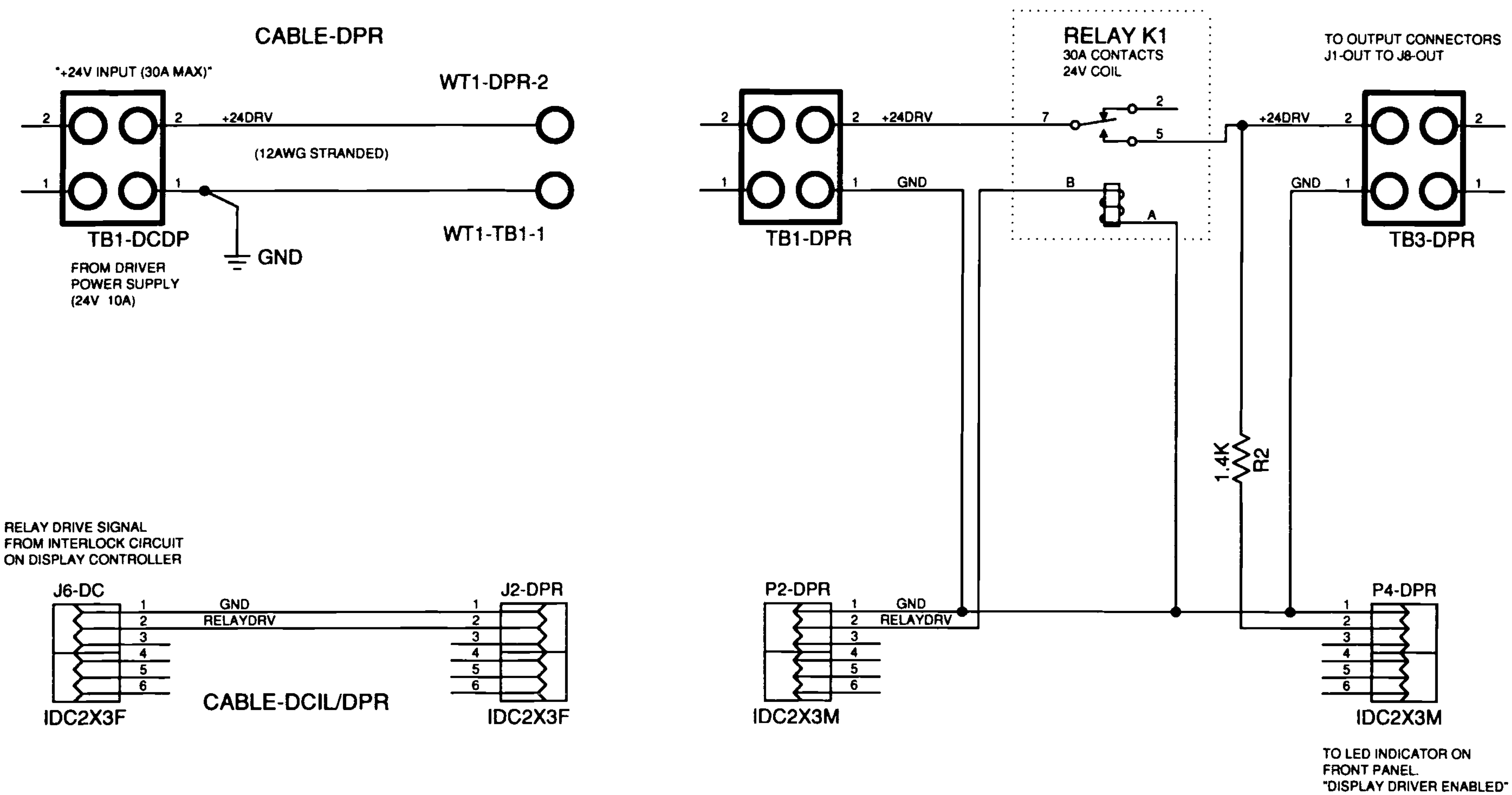
1. ALL DB9 CONNECTORS MOUNTED ON BACK PANEL OF ENCLOSURE

DRV_DRC.S40

INTERLOCK CONNECTORS (REAR PANEL)	Dwg: IL_CONS.S01	Sheet	Date: 23 APR 96	By: SB
BEGEJ CORPORATION	Classif: CONFIDENTIAL AND PROPRIETARY INFORMATION	Distrib: INTERNAL ONLY - NOT FOR PUBLIC RELEASE		



Title: FRONT PANEL LEDs FOR DRIVER CONTROLLER	Dwg: FP_LEDS.S01	Sheet	Date: 23 APR 96	By: SB
BEGEJ CORPORATION	Classif: CONFIDENTIAL AND PROPRIETARY INFORMATION	Distrib: INTERNAL ONLY - NOT FOR PUBLIC RELEASE		



NOTES:

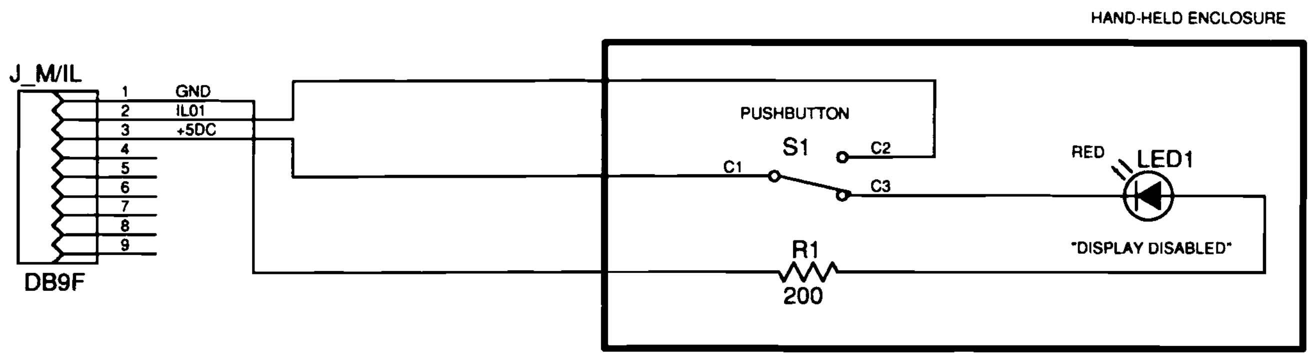
1. CURRENT DRAW IS 100mA PER VALVE AND 200mA PER FAN
2. PCB DISCONNECT STRIPS XXX AND XXX RATED AT 15A MAX
3. TERMINAL BLOCK TB1 LOCATED ON REAR PANEL.
4. LED2 LOCATED ON FRON PANEL.

**** AS BUILT ****

DRV_DRC.S50

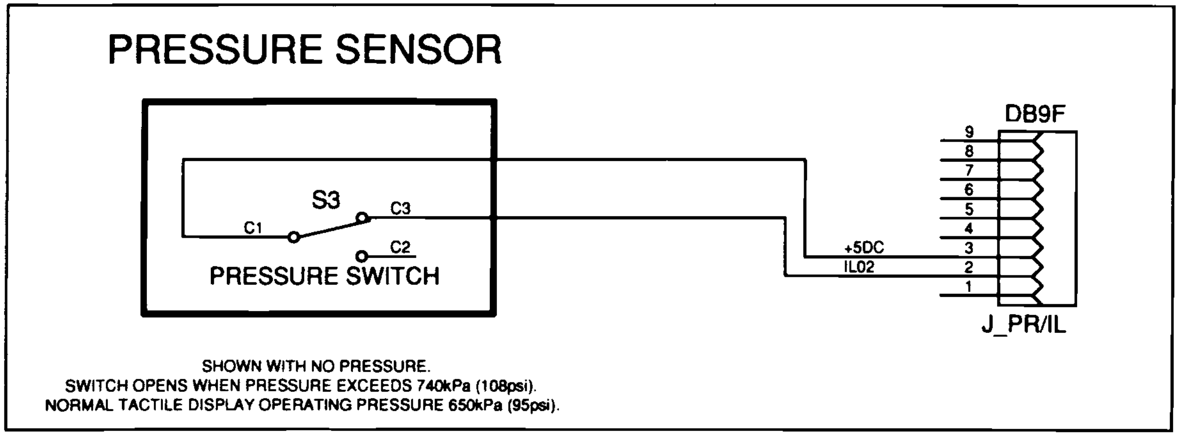
Title: OUTPUT POWER CONTROL RELAY (+24V)	Dwg: DP_RELAY.S01	Sheet	Date: 29 APR 96	By: SB

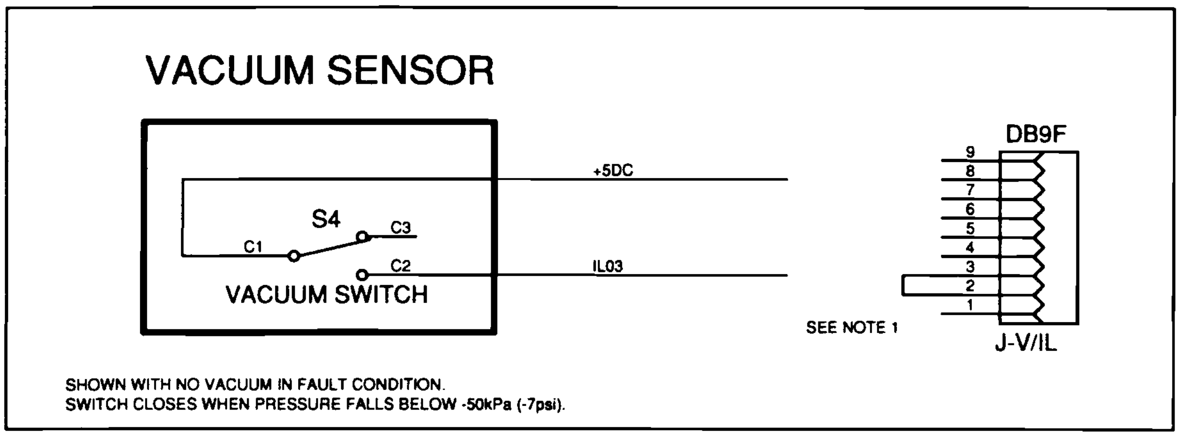
BEGEJ CORPORATION	Classif: CONFIDENTIAL AND PROPRIETARY INFORMATION	Distrib: INTERNAL ONLY - NOT FOR PUBLIC RELEASE



Title: REMOTE MANUAL INTERLOCK SWITCH	Dwg: ILMANUAL.S01	Sheet	Date: 16 APR 96	By: SB

BEGEJ CORPORATION	Classif: CONFIDENTIAL AND PROPRIETARY INFORMATION	Distrib: INTERNAL ONLY - NOT FOR PUBLIC RELEASE





NOTES:

1. VACUUM INTERLOCK NOT USED IN FINAL DELIVERED VERSION OF TACTILE DISPLAY.

DRV_DRC.S60

Title: PNEUMATIC INTERLOCK SWITCHS	Dwg: ILPNEUM.S01	Sheet	Date: 02 MAY 96	By: SB

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APPENDIX D

INSTRUCTIONS for OPERATION of the TACTILE DISPLAY SYSTEM

D.1. Warnings, Cautions, and Notes

WARNING

DO NOT bypass the AC Power Center, as it is an integral part of the safety interlock system. It has a latched output that is required to insure that all system components are reset and startup proceeds in an orderly manner in the event of a AC power outage (this especially applies to the Tactile Data Processor). Bypassing the AC Power Center would jeopardize this function and possibly lead to taxel destruction and/or operator injury in the event of massive uncontrolled taxel inflation.

WARNING

DO NOT replace the Driver Power Supply with a unit capable of delivering more than 40 A peak at 24 VDC, as this would enable the damaging or dangerous actuation of ALL 512 taxels in the event of an unexpected control system hardware failure or application programming error.

CAUTION

DO NOT activate any taxels without the presence of an elastic fabric cover, as uncontrolled expansion and taxel membrane failure may immediately occur. The elastic fabric acts as a restraint against uncontrolled expansion and provides additional force acting to restore the taxel membrane to its unexcited position.

CAUTION

DO NOT apply inputs to the Tactile Sensor Analog Input A/D cards outside the range 0 to 5.4V, as immediate and permanent damage shall be inflicted to the card. (Note: the inputs from the FSR tactile sensor signal conditioner are maintained in the range 0 to 5.0V for all normal sensor operation and fault conditions, including internal shorting of the sensor and "hot" removal or installation.)

NOTE Regarding A/D Inputs

Use shorting terminators on all unused tactile sensor signal connectors (A/D cards) so as to prevent spurious readings on adjacent channels. If only a fraction of the sensor inputs associated with a cable are utilized, then the remaining unused inputs on that cable should also be shorted to ground.

NOTE Regarding A/D Cable Installation or Removal

The IDC-64 cables attached to the A/D connectors J1 and J2 must be installed with the A/D card placed in its slot and sitting approximately 10 mm above the motherboard socket. IDC connector J2 is first fed through the cable slot at the rear of the computer chassis and seated, followed by the insertion and seating of J1 on the other cable. The A/D card may now be seated in the motherboard socket. Cable or card removal may be accomplished in the reverse order.

NOTE Regarding D/A SCSI Cable Installation or Removal

Installation of the SCSI 68-pin cables to the D/A cards or valve modules (display drivers) should be performed carefully due to the relative fragility of the connector pins and shell structures. Prior to **every** installation, the pins on the connectors should be inspected for bending or other misalignment. Also, the shell on the mating female connector also inspected for splitting or cracking.

D.2. Tactile Display System Facility Requirements

The TDS requires approximately 3 A at 120 VAC, and a 690-1040 kPa (100-150 psi) air source that is free of OIL and WATER. Neither contaminant may be permitted to condense or accumulate in the TEFLON® pneumatic lines or the display taxels. As the exact nature or condition of the user's air supply system is not known with regard to oil and water content, the TDS has been provided with a SECONDARY air filtration element for the removal of bulk and vapor-phase oil and/or water. However, this capacity was intended only for back-up or short-term operation during installation of the TDS, and should not be relied upon as the primary means of air-line filtration and cleaning.

The internal water trap and air dryer should be periodically inspected. If water or oil is found to accumulate or drain in any significant amount in the trap, another source of air should be used or the quality of the existing air source improved.

The air pressure regulator within the TDS has been pre-set to the normal taxel operating pressure of 650 kPa (95 psi), where the maximum system operating pressure is 690 kPa (100 psi). The interlock pressure switchpoint has been set to 740 kPa (108 psi), and setting the regulator above this pressure will disable the TDS.

D.3. System Activation

The TDS is a turnkey system and has been designed to be simple to activate. After connecting AC power and air to the system, the system is turned ON with the following procedure:

- Insure power switches for all modules are ON
- Insert bootable floppy disks (DOS 5.0) containing program into drives
- Turn TDS system on:
    - Main Switch at AC Power Center: ON
    - Latch pushbutton at AC Power Center: ON
- Wait for processors to boot up and wait for program to start

To shut the system down:

- Main Switch at AC Power Center: OFF

General Notes:

- Most front panel power switches on various subsystem components have been left functional, with the exception of the processor module. Should the TDS not boot-up or display other signs of malfunction, check each switch to insure the subsystem has not been accidentally turned off. In particular, check the monitor, KVM switch (the green light at the far left must be ON, and is easy to miss in the clutter of other green indicators), the Tactile Display Controller and Display Power Supply. The main power switch the to Tactile Data Processors has been DISABLED to prevent possible taxel damage or operator injury from transient processor conditions during startup or shutdown.

D.4. Taxel Evaluation Software

This section describes some of the features of the taxel testing and evaluation code developed by the contractor for in-house testing of various tactile sensor and display devices. The code is written in C using the Microsoft compiler, DOS version 7. Much of the code is dated, not particularly user friendly, and in some cases incomplete, as the code body has been continually recycled and extended to suit the brief needs of different programs over the years. If difficulties arise, then Ctrl-C will halt program execution in most cases. Otherwise, a soft or hard reboot may be required.

Startup:

- Insure power switches for all modules are ON
- Insert floppy disks containing "RUNWAM.EXE" into drives
- Turn TDS system on:
  - Main Switch at AC Power Center: ON
  - Latch switch at AC Power Center: ON
- Wait for processors to boot up and RUNWAM to start

Use the KVM switch to cycle through to each processor subsystem (128 taxels each) and set the software on each to the same function:

System Activation:

This procedure turns off the interlock fault lights on the Display Driver Controller and allows primary power to be delivered to the display drivers.

- Set KVM to at processor number 1 (taxels 1-128)
- Start at Main Menu (Number 000)
- Select Item 6 (Menu 000): "Manual Tactile Display Control"
- Select Item 5 (Menu 130): "Enable/Disable Display Suit"
- Enter "1" to activate
- Interlock fault light (red LED) for processor 1 should now go off. (If it remains on, select Item 5 again and repeat.)
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

Change D/A Output Dwell Time (default = 0.0005 s):

This parameter determines the D/A dwell time at each channel, and has been set to the default value of 0.0005 s. This value may be decreased to speed up system response time (at the cost of accuracy), or the commanded response made to be more accurate by increasing this value (at the cost of system response time).

- Set KVM to at processor number 1 (taxels 1-128)
- Select Item 3 (Menu 130): "Define Output Dwell Time (sec)"
- Enter new dwell time in seconds
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

Define Taxel Inflation Limit:

The taxel inflation limit is set in two ways. An absolute limit is set in hardware by limiting the maximum PWM duty cycle to 10%, which corresponds to a taxel inflation height of 3.5 mm. It may be further limited in software by specifying a maximum inflation level from 0-100% of this inflation height.

- Set KVM to at processor number 1 (taxels 1-128)
- Select Item 4 (Menu 130): "Define Inflation Limit (% of max)"
- Enter new limit in %
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

Set Inflation level for a Single Taxel:

Each taxel may be individually addressed and its inflation height or level set from 0-100% of the maximum permitted by hardware (i.e., default is 3.5 mm) or reset in software (see above). The default upon bootup is 100%.

- Set KVM to at processor number 1 (taxels 1-128)
- Select Item 6 (Menu 130): "Set Inflation Value for a Single Taxel"
- Enter module number for current processor:
    - Processor 1, Module 1 corresponds to global taxel 1-64
    - Processor 1, Module 2 corresponds to global taxel 65-128
    - Processor 2, Module 1 corresponds to global taxel 129-192
    - Processor 2, Module 2 corresponds to global taxel 193-256

- Processor 3, Module 1 corresponds to global taxel 257-320
    - Processor 3, Module 2 corresponds to global taxel 321-384
    - Processor 4, Module 1 corresponds to global taxel 385-448
    - Processor 4, Module 2 corresponds to global taxel 449-512
- Enter local taxel number 1-64 for any module
- Enter new inflation level 0-100%
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

Note: the appearance of a negative value on any parameter listing simply means that particular parameter has not been previously defined.

Vary Activation on One Taxel:

For taxel testing and characterization purposes, a function was added that allowed one to more easily change the actuation level of the same taxel.

- Set KVM to at processor number 1 (taxels 1-128)
- Select Item 7 (Menu 130): "Cycle on One Taxel"
- Enter module number for current processor:
    - Processor 1, Module 1 corresponds to global taxel 1-64
    - Processor 1, Module 2 corresponds to global taxel 65-128
    - Processor 2, Module 1 corresponds to global taxel 129-192
    - Processor 2, Module 2 corresponds to global taxel 193-256
    - Processor 3, Module 1 corresponds to global taxel 257-320
    - Processor 3, Module 2 corresponds to global taxel 321-384
    - Processor 4, Module 1 corresponds to global taxel 385-448
    - Processor 4, Module 2 corresponds to global taxel 449-512
- Enter local taxel number 1-64 for any module
- Enter new inflation level 0-100%
- Enter new inflation level 0-100%
- Etc.
- Stop by entering out-of-range value (e.g., 999)
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

Set All Taxel in a Module to Same Inflation Level:

All taxels in the same module may be simultaneously set to the same actuation level. (Note that this may be very disconcerting or surprising to someone wearing the suit, especially if the taxels are turned on at 100%.)

- Set KVM to at processor number 1 (taxels 1-128)
- Select Item 8 (Menu 130): "Set All Taxels to One Inflation Level"
- Enter module number for current processor:
    - Processor 1, Module 1 corresponds to global taxel 1-64
    - Processor 1, Module 2 corresponds to global taxel 65-128
    - Processor 2, Module 1 corresponds to global taxel 129-192
    - Processor 2, Module 2 corresponds to global taxel 193-256
    - Processor 3, Module 1 corresponds to global taxel 257-320
    - Processor 3, Module 2 corresponds to global taxel 321-384
    - Processor 4, Module 1 corresponds to global taxel 385-448
    - Processor 4, Module 2 corresponds to global taxel 449-512
- Enter inflation level 0-100%
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

<u>List Inflation Levels for all Taxels in a Module:</u>

The commanded inflation levels for a particular driver module may be listed on the screen with this command.

- Set KVM to at processor number 1 (taxels 1-128)
- Select Item 9 (Menu 130): "List Inflation Values for all Taxels"
- Enter module number for current processor:
    - Processor 1, Module 1 corresponds to global taxel 1-64
    - Processor 1, Module 2 corresponds to global taxel 65-128
    - Processor 2, Module 1 corresponds to global taxel 129-192
    - Processor 2, Module 2 corresponds to global taxel 193-256
    - Processor 3, Module 1 corresponds to global taxel 257-320
    - Processor 3, Module 2 corresponds to global taxel 321-384
    - Processor 4, Module 1 corresponds to global taxel 385-448
    - Processor 4, Module 2 corresponds to global taxel 449-512
- (List is displayed)
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

<u>List A/D Tactile Sensor Inputs:</u>

The actual inputs to the A/D cards from external signal sources (e.g., tactile sensors or synthetic data generators) may be displayed in semi-real time with this command.

- Set KVM to at processor number 1 (taxels 1-128)
- Start at Main Menu (Number 000)
- Select Item 8 (Menu 000): "Run Tactile Display Suit"
- Select Item 3 (Menu 150): "List A/D Inputs"
- Enter module number for current processor:
    - Processor 1, Module 1 corresponds to global taxel 1-64
    - Processor 1, Module 2 corresponds to global taxel 65-128
    - Processor 2, Module 1 corresponds to global taxel 129-192
    - Processor 2, Module 2 corresponds to global taxel 193-256
    - Processor 3, Module 1 corresponds to global taxel 257-320
    - Processor 3, Module 2 corresponds to global taxel 321-384
    - Processor 4, Module 1 corresponds to global taxel 385-448
    - Processor 4, Module 2 corresponds to global taxel 449-512
- Select type of Signal Conditioning
    - Select "1" for None (values range from 0-255)
    - Select "2" for None/PFS (values range from 0-100%)
    - Select "3" for Linearization via lookup table (not fully implemented)
    - Select "4" for Linearization via lookup table (not fully implemented)
- Select display mode (data for 64 taxels is displayed)
    - Select "1" for Single Frame
    - Select "2" for Continuous Display (Halt with Ctrl-C.)
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

Run TDS with Tactile Sensor Inputs:

The TDS can be set to run continuously with a real or synthetic tactile sensor signals applied to the A/D inputs. Each processor cycle time was measured to be approximately 50 ms, i.e., inputs were measured, conditioned, and outputted to the display driver for 128 taxels (2 driver modules) in 50 ms. As each of the four processor subsystems were running in parallel, the cycle time for the entire suit of 512 taxels was also 50 ms.

- Set KVM to at processor number 1 (taxels 1-128)
- Select Item 4 (Menu 150): "Run Tactile Display"
- Enter module number for current processor:
    - Processor 1, Module 1 corresponds to global taxel 1-64
    - Processor 1, Module 2 corresponds to global taxel 65-128
    - Processor 2, Module 1 corresponds to global taxel 129-192
    - Processor 2, Module 2 corresponds to global taxel 193-256

    - Processor 3, Module 1 corresponds to global taxel 257-320
    - Processor 3, Module 2 corresponds to global taxel 321-384
    - Processor 4, Module 1 corresponds to global taxel 385-448
    - Processor 4, Module 2 corresponds to global taxel 449-512
- Select type of Signal Conditioning (Note: no choice is presently available, as "None" is automatically selected)
    - Select "1" for None (values range from 0-255)
    - Select "2" for None/PFS (values range from 0-100%)
    - Select "3" for Linearization via lookup table (not fully implemented)
    - Select "4" for Linearization via lookup table (not fully implemented)
- (System will list processing type at top of screen and continuously update the number of complete 128-taxel scans performed. Halt with Ctrl-C.)
- Use KVM to cycle through rest of processors and repeat above procedure for taxels 129-512.

D.5. Taxel Repair and Replacement

The TDS was delivered with the following spare parts kit intended for the repair and replacement of taxels or taxel components should then become damaged or otherwise fail:

- Spare taxels (10 complete units)
- Kit of spare taxel parts (approximately 20 taxels)
- Tube of Silicone lubricant grease (for the wear disks)
- Taxel assembly kit (collar tool, rubber sheet, tubing expansion awl)
- Label installation tool
- Snapring installation and removal tool
- Spare zippers (2, unmodified stock)
- Spool of LYCRA® thread

The procedures for various taxel repair and replacement tasks are presented below.

Tubing attachment to manifold adapter and taxel:

- Slide TYGON® label cover onto TEFLON® tube.
- Slide tube collar onto TEFLON® tube.
- Flare end of tube with flaring tool. Use bare fingers or thin rubber sheet to grip TEFLON® tube, as sandpaper may leave possibly deleterious marks on the surface finish.
- Push adapter tube into flared TEFLON® tube a distance of 3-4 mm.
- Place adapter on a firm surface, and use collar tool (pliers with bored tip) to push collar onto adapter nipple. Care must be taken not to allow the collar and adapter tube axes to become significantly misaligned, as puncture or severe deformation of the TEFLON® tube may result.
- Repeat above procedure for attachment of tube to taxel (except omit TYGON® label cover).

Tubing Label Installation:

- Cut label from label sheet
- Press label onto TEFLON® tube with label installation tool.
- Without allowing the TEFLON® tube to move relative to the installation tool, pull the TYGON® cover over the label.
- Remove label tool from underneath cover.
- Spin label tube several times to verify that label is securely retained.

Tubing Label Removal:

- Insert label tool between under the TYGON® label holder until most or all the label is covered by the tool tip.
- Holding the tool stationary relative to the TEFLON® tubing, pull the TYGON® label cover away from the label.

Taxel Preparation for Installation:

- Remove taxel assembly (i.e., taxel, tube, and manifold adapter) from storage bag
- Remove any skewing at the taxel or manifold termination by heating the TEFLON® tube (but not the taxel or manifold crimp collar) in a hot air gun (set on HIGH) for a few seconds, and manually working the tube shape or angle into a straightened configuration.
- Remove the coil set along the length of the TEFLON® tube by stretching the tube between a fixed anchor on one end and an elastic anchor at the other (e.g., short length of rubber band or latex tubing) and slowly moving a hot air gun over the length of the tube.
- Allow tube to cool, then remove from the end supports

Taxel Installation onto Display Panel:

- Lay out taxel placement pattern on back (hidden) side of display panel fabric with inert white marker (e.g., white acrylic artist's medium such as LIQUITEX 1045-432, diluted at least 1:1 with water). Do not use paint pens or other markers utilizing petroleum distillates or xylene, as such solvents may have a deleterious effect on the LYCRA® elastomer or other cloth components. Care should be taken to apply only the minimal amount of marker required to provide visibility of the taxel placement spot without causing bleedthrough to the active side of the cloth or creating a thick deposit which may interfere with taxel operation or longevity.
- Apply light film of silicone grease to surface of taxel and apply wear disk. The amount of lubricant grease should be such as to provide some adhesion to permit subsequent handling, but not so excessive as to squeeze out during use and bleed through the LYCRA® cloth and other garments. Avoid getting the grease on the fingers during handling, as it very tenacious and may be readily dispersed to contaminate unintended areas.
- Place snapring in installation tool, and place ring against cloth from the hidden side of the cloth. (Note: to avoid damage to the snapring by overexpansion, insure that the limiting screw on snapring tool has been set to allow only sufficient clearance for the ring to clear the cloth-covered taxel diameter, and no more.)

- Stretch and adjust fabric only enough to provide an adequate indication of the ring position with regard to the desired taxel positioning spot. (Alternatively, if a small light bulb or light table is positioned behind the cloth, then a silhouette of the snapring borehole may be clearly observed and utilized to accurately position the taxel.)
- Once centering of the ring and removal of folds in the cloth has been achieved, open the ring with the tool while simultaneously pushing the taxel into ring through the cloth.
- Remove snapring tool.
- Rotate the taxel body and tubing into the desired orientation by grasping the cloth and snapring with the fingers of one hand and turn the body with the fingers of the other hand using the tube nipple as a lever.
- Rotate snapring ears into desired alignment by pinching the taxel and cloth between the fingers of one hand and rotating the ring with a finger or fingernail of the other hand. If the ring fails to rotate relatively easily, loosen its grip by use of the tool.
- If the taxel must be laterally repositioned, do not attempt to slide it over the cloth as it will cause misalignment of the wear disc. Instead, remove the snapring and pull the taxel off completely, then repeat the above installation procedure.

Cable Sheath Installation:

- Wrap the sheath about the pneumatic cable, install zipper pull at tactile display panel end of cable sheath, close a 100-200 mm length of the zipper, and sew end of zipper closed with thread.
- Attach sheath snaps to display panel snaps.
- Close remaining length of zipper by wrapping sheath in a helical manner about the pneumatic cable, maintaining a period of 250-350 mm.
- Adjust placement and routing of cable bundle and manually attach (by sewing) eyelet to sheath at desired anchor point.

Taxel Installation into Driver Manifold:

- Select the shortest tube and cut off any molding sprue on the hex nut face of the manifold adapter nut. Verify that the nut spins freely over the adapter core.
- Insert adapter into manifold and use light pressure to start the nut so as to avoid damaging the relatively-delicate nylon threads. Use fingers to install adapter if manifold location is readily accessible and the neighborhood is not too crowded, otherwise use metal scribe point applied at the top face periphery of the adapter nut.
- After reliable thread engagement (e.g., 2-3 threads), use adapter tool to tighten nut until no axial play is detectable in adapter core as it is pulled back and forth during nut engagement.

- Tighten nut another 1/3 turn to complete installation of the tubing adapter in the manifold.
- After all adapters have been inserted into the manifold, tie the cable with 5-7 loops of LYCRA® fiber. The resultant band must be loose, as even mild pressure over a long period of time will cause local constrictions in the TEFLON® tubing due to cold flow. Three to four LYCRA® bands should be sufficient to secure the loose tubing and organize the cable.
- Test all channels individually to insure the fittings were installed without leaks and to verify proper functioning of each taxel.

Tubing Cable Sheath Termination:

- Terminate sheath with anchor ring sewn into end of sheath or at a location dictated by the remaining length of cable.
- Place anchor rings onto stud in same order as manifolds. Use 20 mm spacer between the top and bottom four cables.
- If necessary, adjust position of cable bundle relative to through-hole in panels by adjusting height of lower locknuts on anchor stud.
- Cap anchor stud with pair of locked nuts, leaving 1-2 mm clearance between top anchor and locknuts so as to permit cable tilt and rotation during use.

D.6. Suit Customization

The TDS was delivered with all taxels installed on standard display panels and the panels pre-attached to a medium-sized SPANDEX® bicycle shirt. Additionally, a display suit kit was also included to enable the customer to custom-fit the panels onto a suit for another user. The kit contents included:

- SPANDEX® bicycling shirt, size S
- Eight pairs of zipper tabstrips (4 pairs with VELCRO®, 4 plain)
- VELCRO® tape for arm panels (50 mm wide, 2-3 m long)
- Shoulder cable ties (2) and extra snaps (2)
- Sewing kit (needles, thread)

D.7. Custom Software Development

It is STRONGLY recommended that the inlet pressure regulator be turned down to less than 70 kPa (10 psi) during any software development activities or hardware changes to avoid damage or destruction of the taxels should something unexpected occur.

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16. Abstract

The objective of this Phase II program was to design a second-generation Tactile Display System (TDS) suitable for teleoperator control of a dual whole-arm manipulator (WAM) and other teleoperation or VR simulation tasks involving tactile interaction with real or simulated environments. This program objective was achieved and a complete turnkey TDS was fabricated and delivered to the sponsoring organization. The tactile display consisted of an elastic fabric suit worn on the upper torso, and contained a total of 512 tactile display elements (taxels) housed in eight modular display panels distributed over the forearms (2 panels), upper arms (2), upper chest (2) and stomach (2). Each taxel measured Ø11.8 mm by 5 mm high, and was operated in a vibratory mode (4.5 Hz) with a variable displacement amplitude from 0-3.5 mm. The taxels were attached to the suit fabric by removable clips, thereby allowing great flexibility in creating taxel distributions optimized for particular applications. The TDS suit could be donned/doffed in 10/2 minutes, respectively, and was found to generate robust tactile stimulation signals even through multiple layers of intervening fabric.

17. Key Words (Suggested by Author(s))

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