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DESIGN AND DEVELOPMENT OF A FULL-SCALE ANATOMICAL LOAD DISTRIBUTION ANALYZER

R. Rodzen, et al

IIT Research Institute

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DESIGN AND DEVELOPMENT OF A FULL-SCALE ANATOMICAL LOAD DISTRIBUTION ANALYZER

by

R. Rodzen, C. Ogden,
F. Scribano, M. Burns

IIT Research Institute
Chicago, Illinois
and

E. R. Barron

U. S. Army Natick Laboratories

Contract No. DAGG 17-70-C-0161

November 1972

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Natick, Massachusetts 01760

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13. ABSTRACT

In a continuing effort to reduce discomfort in the wearing of ceramic body armor, the measurement of stresses upon the body has been an important approach toward achieving the best possible configuration for rigid plates. A device for making such measurements has been developed in the form of a "Full-Scale Anatomical Load Distribution Analyzer" which is capable of simultaneously measuring and displaying pressure, pressure changes, load magnitude and the distribution of forces transmitted to the torso by aircrew and infantry armor, load carrying equipment, combat clothing, seat configurations and seat restraint and parachute harnesses.

The system consists of a sensor vest incorporating 248 miniature sensors. A three-dimensional anatomical unit visually displays load magnitudes and distribution of forces transmitted to the torso by lights which change color depending upon the load. In addition to the mentioned uses, the approach has a broad base application for improved personal equipment such as helmet suspensions and for certain specialized medical equipment.

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LOADS (FORCES)	9		4			
MEASURING INSTRUMENTS	10		9			
INSTRUMENTS	10		9			
BODY ARMOR	4		4			
SUSPENDING (HANGING)	4		4			
DEVELOPMENT			8			
DESIGN			8			
FABRICATION			8			

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Details of illustrations in this document may be better studied on microfiche

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U. S. ARMY NATICK LABORATORIES
Natick, Massachusetts 01760

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FOREWORD

This is the final report on the development and fabrication of a "Full-Scale Anatomical Load Distribution Analyzer", a device which measures and displays forces transmitted to the torso (in both static and dynamic modes) by body armor, combat clothing and load carrying equipment.

Display of this instrument at the 1971 Conference of Survival and Flight Equipment (SAFE), the Association of the U. S. Army Annual Meeting and to representatives of other Department of Defense agencies, NASA, and the Department of Transportation, indicated broad usage for this device as a design and evaluation tool for the development and improvement of body armor, load carrying equipment, aircraft and vehicle seat restraint systems, parachute harnesses, helmet shapes and suspensions and seat configurations.

Mr. Edward R. Barron, Chief, Body Armor Branch, Clothing and Personal Life Support Equipment Laboratory, U. S. Army Natick Laboratories, served as the project officer. Mr. Barron conceived the basic idea and objectivity for this project. His invaluable technical experience, guidance and recommendations produced a new analytical research instrument reflecting a significant advance in the field of bioengineering and design of individual equipment.

Acknowledgements are extended to Dr. C. K. Bensel and Dr. J. McGinnis, Human Factors Psychology Group, Behavioral Sciences Division, Pioneering Research Laboratory at NLABS, for their valuable contributions.

Mr. J. Augustine, Department of the Army Air Mobility Research and Development Complex, provided support from the U. S. Army Materiel Command. His awareness in recognizing the application of the load distribution analyzer to the improvement of aircrew and other aircraft equipment is appreciated.

This program was conducted by IIT Research Institute under Contract No. DAAG17-70-C-0161. The Project Reference for NLABS was 1F164204D154.

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ILLUSTRATIONS (concl)

ABSTRACT

In a continuing effort to reduce discomfort in the wearing of ceramic body armor, the measurement of stresses upon the body has been an important approach toward achieving the best possible configuration for rigid plates.

A device for making such measurements has been developed in the form of a "Full-Scale Anatomical Load Distribution Analyzer" which is capable of simultaneously measuring and displaying pressure, pressure changes, load magnitude and the distribution of forces transmitted to the torso by aircrew and infantry armor, load carrying equipment, combat clothing, seat configurations and seat restraint and parachute harnesses.

The system consists of a sensor vest incorporating 248 miniature sensors. A three-dimensional anatomical unit visually displays load magnitudes and distribution of forces transmitted to the torso by lights which change color depending upon the load.

In addition to the mentioned uses, the approach has a broad base application for improved personal equipment such as helmet suspensions and for certain specialized medical equipment.

DESIGN, DEVELOPMENT AND FABRICATION OF A FULL-SCALE ANATOMICAL LOAD DISTRIBUTION ANALYZER

INTRODUCTION

The design of body armor systems has become more complex due to increasing battlefield hazards. To provide increased protection to military personnel, rigid body armor materials are now being extensively employed. However, the use of rigid components increases the complexity of fit, comfort and evaluation of design concepts. Normally, rigid elements are empirically designed and prototypes fabricated which are initially evaluated and later transposed into items used for field evaluation. This approach is expensive and time-consuming. The field evaluation determines where the items are an improvement to existing items and aids in establishing their acceptability with the Army population. The results of these evaluations are usually subjective and depend upon observations made by men wearing prototype equipment during field trails and exercises. Questionnaires in which the test participant is asked to comment on the characteristics of an item are analyzed. Seldom can quantitative information be derived upon which to base future design changes which must undergo another series of time-consuming and expensive tests for evaluation.

A need exists for an instrument or device which can measure forces imposed on the human body by protective body armor or load carrying equipment. The design, development and fabrication of a full-scale anatomical load distribution analyzer was undertaken with the goal of providing a device which could instantaneously and continuously present visual data related to the efficacy of a variety of load bearing or suspension systems used to distribute loads on the human torso.

The full anatomical system approach permits viewing the complete torso under load in static or dynamic modes and visually depicts shifting load patterns and magnitudes as a test participant articulates. With this device it becomes possible for an investigator to analyze equipment designed to be worn on the body in terms of load distribution on optimum load bearing and less sensitive areas of the torso.

The full-scale anatomical system utilizes a cloth sensor garment containing 248 sensors whose output is displayed on full-scale anatomical torso manikins. A manikin is split longitudinally to permit viewing the front and back of the display simultaneously. The sensor garment is electrically interconnected to the display through an umbilical line long enough to provide a test subject mobility for negotiating through a broad variety of prescribed movements.

The instrument visually shows pressure changes, load magnitudes and distribution of forces transmitted to the torso in static and dynamic modes.

The system has distinct advantages over a predecessor system developed under an earlier research effort which used a sensor garment with sensors covering the right side of the torso (front and back) only, and a light display readout capable of scanning partial zones or quadrants of the torso at one viewing (Ref. 1). During 1971, a human factors study was conducted using psychomotor tasks to detect and attempt to measure any encumbering effects of several types of body armor and load carrying equipment on the soldier's motor performance (Ref. 2). The predecessor system was used as part of this study to measure pressure at various locations on the test subjects torso as each task was performed.

This initial application of the analyzer system indicated that pressure distribution patterns changed with the type of movement and also varied as a function of load weight and design characteristics. The analysis performed on the data included determination of the load imposed at given torso locations throughout performance of a task, as well as total torso load. Based upon the results of this study, it was concluded that the analyzer system would be valuable for appraising design features and for comparing equipment items. However, it was extremely difficult to correlate sensor location on the torso with the display output, and the methods required to record and analyze the data were tedius and time-consuming.

The advantages of the improved full-scale anatomical load distribution analyzer approach may be summarized as follows:

- It eliminates the requirements for switching through different zones (or quadrants) to view a particular group of sensors.

- The full anatomical instrumentation permits a simultaneous sensing and immediate viewing of all load points on the entire torso.

- Sensor location on the torso can be immediately determined visually and without interpolation from the full anatomical display.

- A memory capability has been incorporated to provide a researcher with extended viewing time for studying display data without continuous input from a test subject.

- Data displayed can be recorded for reference and further evaluation.

- The performance activity of the test subject and display data can be recorded on motion picture film.

The potential value of the full-scale anatomical system as an analytical instrument for evaluating or comparing load bearing or suspension systems used for distributing loads on the human torso has not been fully realized. Other applications of the system have not been explored to the fullest extent in this research effort and new uses for the system have already been suggested as additional experience is gained.

This report presents information regarding the development of an improved load sensing garment, load sensor and visual display, together with an overview of the completed system and preliminary evaluations of several personal equipment items.

PART I. SUMMARY OF PROTOTYPE CONFIGURATION AND FUNCTION

A. FULL-SCALE ANATOMICAL LOAD DISTRIBUTION ANALYZER

The full-scale anatomical system consists of the following basic components: (1) load sensing garment assembly consisting of load sensor mounting assemblies, load sensors, and electrical interconnecting umbilical line assembly; (2) front and rear torso display consoles; (3) power supply package; and (4) remote control unit (Figure 1).

1. Load Sensing Garment Assembly

The load sensing garment is a front closure vest containing 248 sensors extending from the illiac crest line to the suprasternal notch, over both shoulders and down the back. The sensors are arranged in a matrix on the vest as shown in Figure 2. The load sensors are mounted on flexible mylar tapes arranged in a vertical pattern and configured to follow the lines of the torso. Sensor spacing varies with location on the torso. In general, vertical spacing is approximately 2 in. maximum narrowing down in such areas as the shoulder. Minimum horizontal spacing is approximately 1-1/4 in. with the vest in a relaxed position. In this position the circumference of the vest at the chest is 36 in. Each vertical sensor tape terminates in a connector mounted at the bottom of the tape which mates with a main connector wiring harness. This harness is an integral part of the umbilical line leading from the sensor garment to the front and rear torso display consoles (Figure 1).

The sensor garment is designed to be worn by the 1st through 99th percentile man for chest circumference, based on the latest available anthropometric Army data as of the date of this report (Ref. 3). The vest was designed to fit this broad range of subjects because of the prohibitive cost of fabricating sensor vests in sizes. However, the elastic qualities of the vest proved satisfactory and performed well. Flexible fabrics and limiting tapes interconnecting the vertical sensor strips permit vest expansion for variations in chest size. Sensor garment length cannot be adjusted. An outer cover of stretchable material permits size variations without

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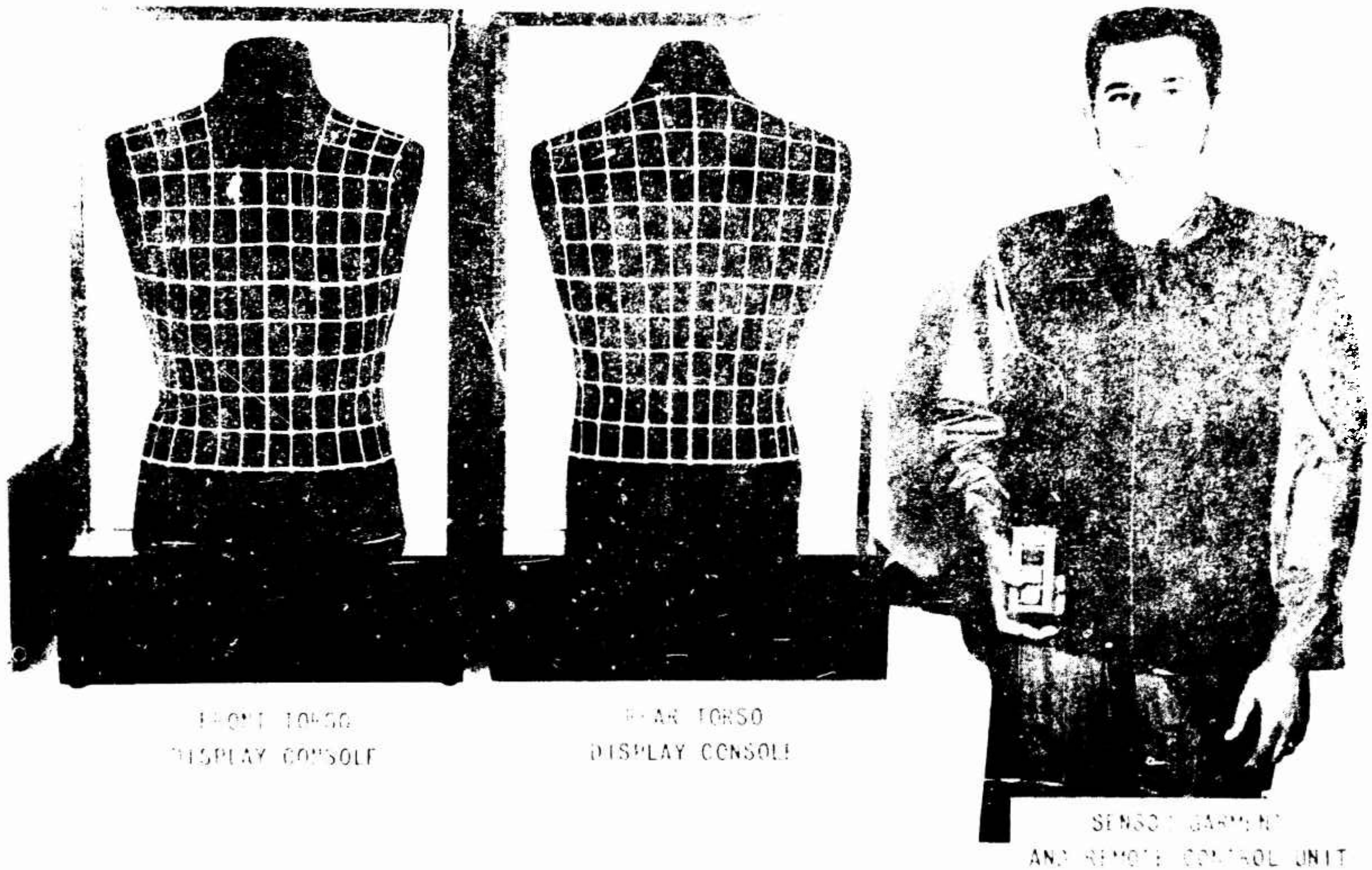


Figure 1 - Full-Scale Anatomical System

preloading the sensors which might result in false sensor outputs. The sensor garment in its relaxed position was designed to fit the 55th percentile man for chest circumference. Above this percentile, spacing between sensor tapes increases to allow for larger chest circumferences.

The front closure is offset vertically to the right of the torso centerline to permit a row of sensors to be positioned on the vertical centerline. The interconnecting 40 ft umbilical line is stored on a rotating reel to prevent kinking or damage (Figure 2). The reel also protects the umbilical line in shipping or during testing.

The sensor garment has a low profile (approximately 3/8 in. at the sensors) and minimal bulk because of its unique design. These features minimize interaction between test items, sensor garment and the torso. The complete vest weighs 6 lb.

2. Load Sensor and Mounting

An improved progressive electrical contact sensor was designed as the load sensing element of the sensor vest (Ref. 1). The basic components of the sensor are a phenolic base, three leaf spring contacts, calibration screws for each leaf spring, a main contact leaf spring, a spherical cap through which external loads were applied, and a cap support spring (Figure 3). The sensor is 11/16 in. in diameter and 1/4 in. deep.

The final sensor assembly was accomplished with hollow rivets to secure the sensor to a mylar tape and completed circuit which includes four electrical contacts. The sensor was then soldered at the rivet connections to insure good electrical contact with the printed circuit on the tape.

Each leaf spring contact was accurately calibrated to represent a specific load range as defined in the following section. Loads were applied through the spherical dome which permitted the sensor to detect normal and oblique forces. The spherical dome, which can tip about a point of contact with the phenolic base, senses oblique forces.

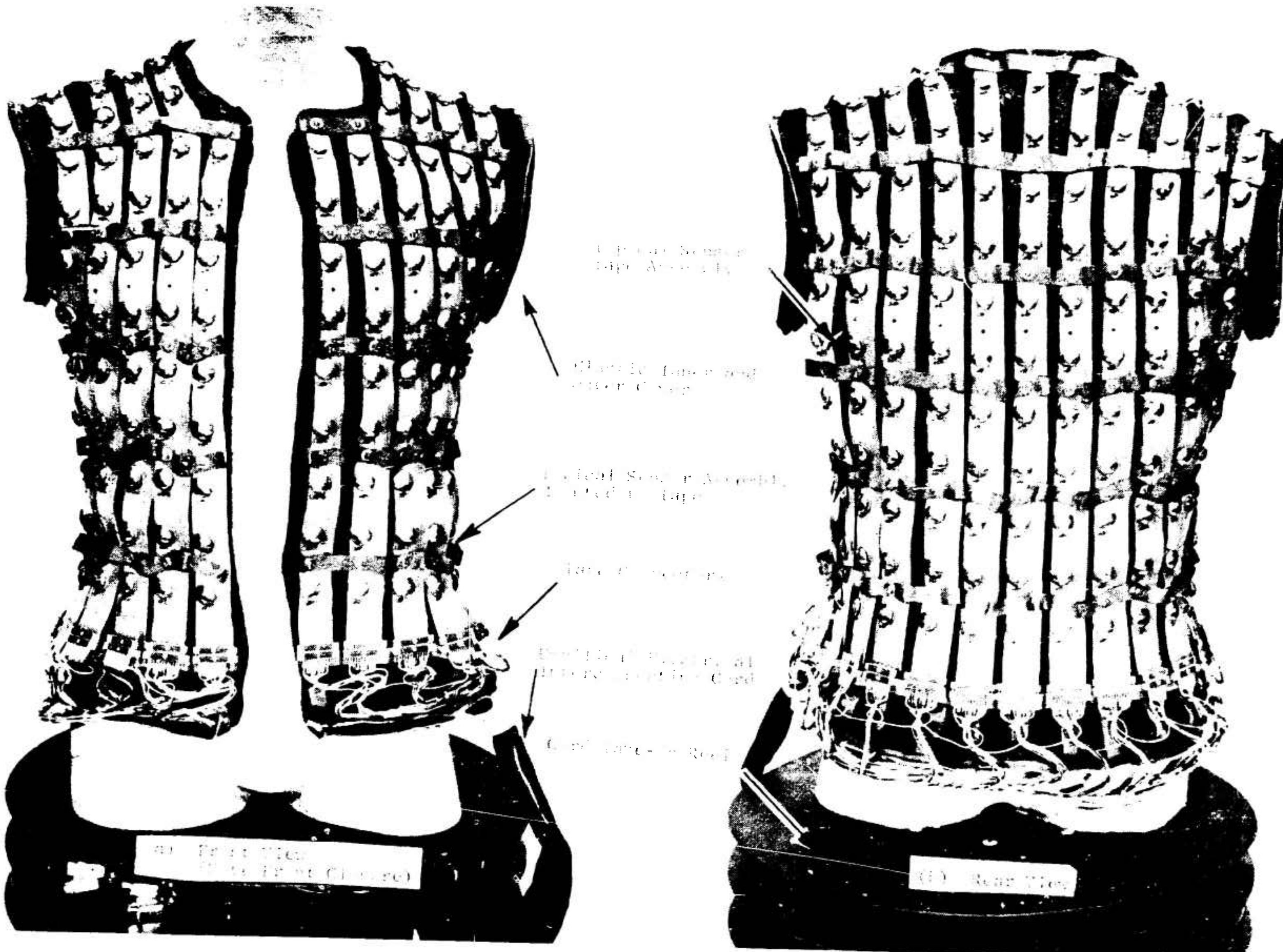
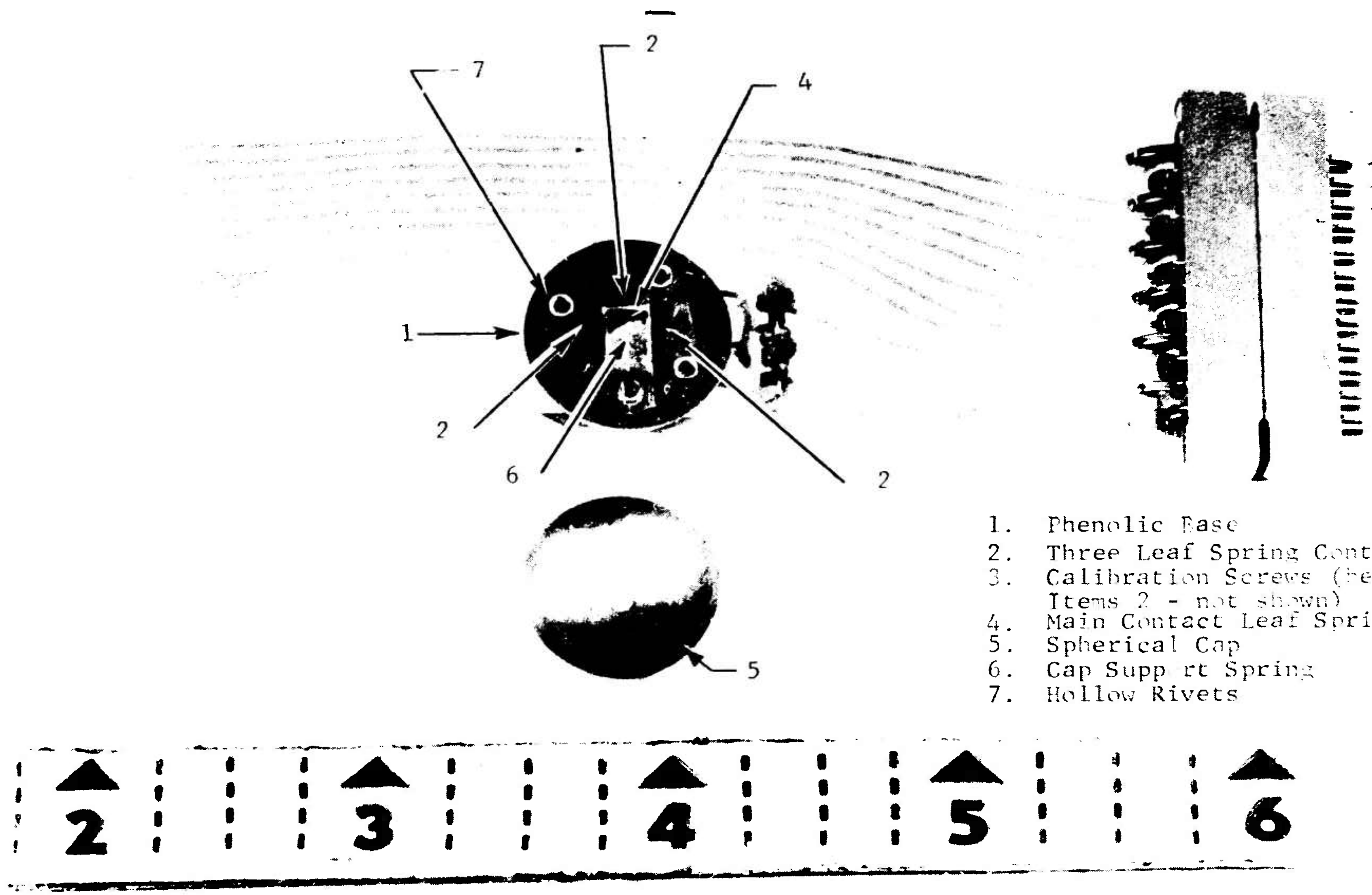


Figure 2 - L ad Sensing Garment - Assembly
(Snown Without Outer Cover)



1. Phenolic Base
2. Three Leaf Spring Contacts
3. Calibration Screws (beneath Items 2 - not shown)
4. Main Contact Leaf Spring
5. Spherical Cap
6. Cap Support Spring
7. Hollow Rivets

Figure 3 - Typical Sensor Assembly and Mounting to Mylar Printed Circuit Board (Sensor Cover Shown Removed)

Desirable characteristics inherent in the progressive electrical contact sensor design are as follows: (1) the sensor is rugged, simple, and dependable; (2) it is easily calibrated; (3) its relatively small size makes it especially suited for application in a sensor garment; and (4) its output signal does not require amplification or special signal conditioning equipment.

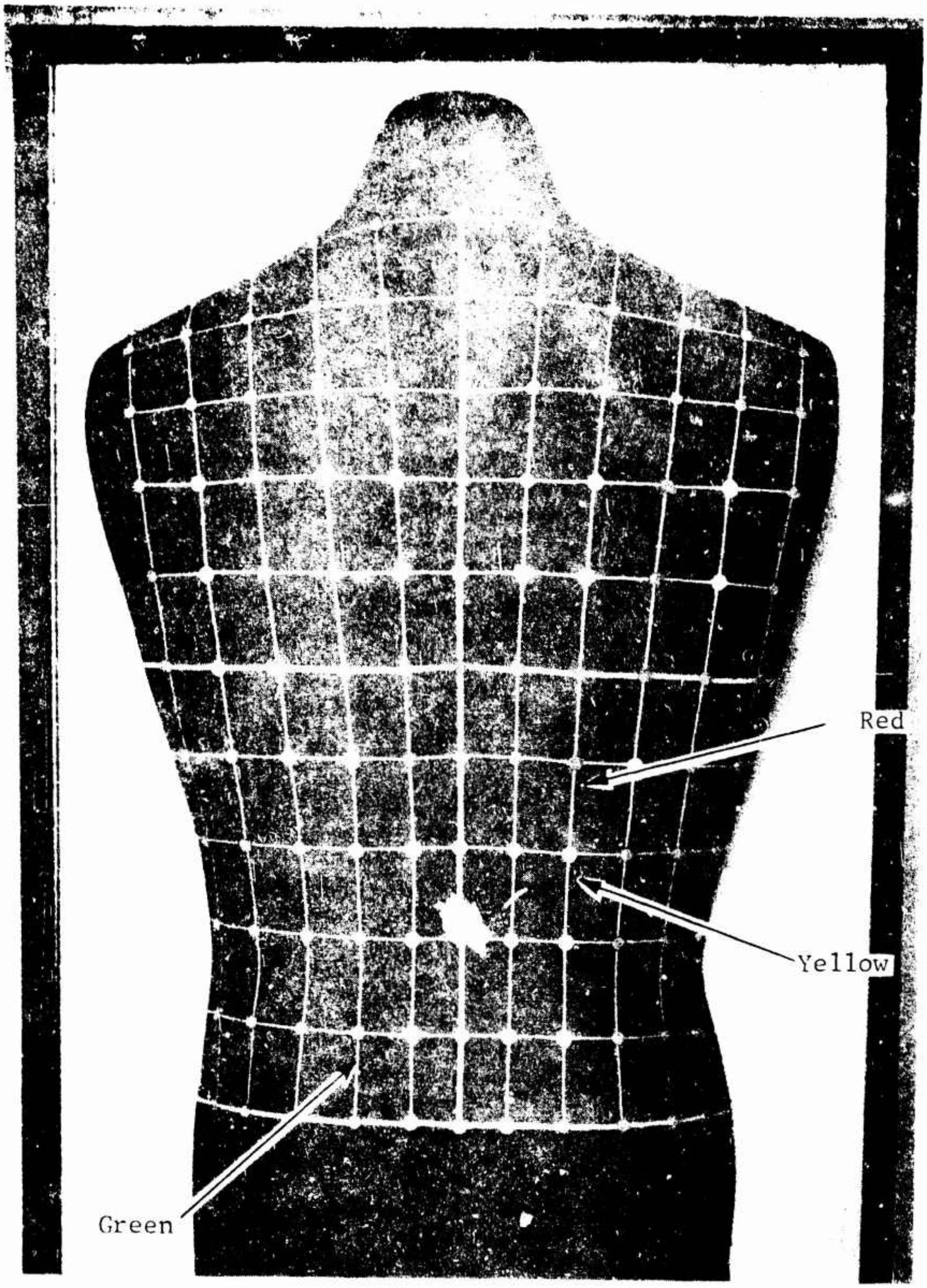
3. Visual Displays

The visual displays consist of a front torso display console and a rear torso display console (Figure 1). A three-dimensional display manikin was split transversly in a vertical plane slicing through the shoulder, neck and underarms resulting in a three-dimensional front and rear torso. The manikin halves were mounted to the front panel of a display console, which contains electronic components and circuitry related to the display.

The front torso manikin contains a total of 127 lamps which are capable of displaying any one of three colors depending on the loads imposed on the body. A green lamp represents loads of 1/2 lb and up, a yellow lamp, 1 lb and up, and a red lamp, 1-1/2 lb and up. The rear torso manikin contains 121 lamps capable of displaying the load ranges just described (Figure 4). Each tricolored lamp on the display manikins is electrically interconnected to a sensor on the load sensing garment.

A "lamp check" switch located on the back panel of the rear torso console permits the Tri-A-Lite colored lamps to be checked before running a test. Defective lamps can be easily replaced because of their plug-in feature.

The front and rear torso manikins are divided into a grid pattern using vertical and horizontal tapes. The tapes are white and the manikin halves black for contrast (Figure 4). A sensor lamp is positioned at each gridline intersection. This approach has an advantage in that loads transmitted to the torso can be visually located without interpolation and correlated to a specific sensor through the system of horizontal and vertical gridline numbers.



Note: Green lights indicate loads 1/2 lb and over; yellow, 1 lb and over; red, 1-1/2 lb and over.

Figure 4 - Full-Scale Anatomical Load Distribution System (Rear View) With Typical Load Distribution Pattern Shown

Horizontal gridlines are numbered 0 to 24 from left to right and vertical gridlines from 0 to 11 bottom to top, to correspond to the sensor locations on the sensor vest (Figure 2). The grid numbers are labeled horizontally on the manikins and vertically on the console faces. It is important when setting up the display that the front torso console be positioned to the left of the rear torso console when viewed from the front for numerical continuity and because of the physical lengths of the interconnecting cables leading to the sensor garment.

The consoles support the printed circuit boards which contain the logic circuitry for controlling the display lights. Wiring harnesses, power supply switching relays, connectors for the sensor garment, remote control unit and main power supply package are also mounted in the consoles. Front and rear access panels (hinged at the front, removable on the rear) permit complete freedom for servicing or replacing component parts.

4. <u>Power Package and Remote Control Unit</u>

The power package for the full-scale anatomical load analyzer system consists of two separate power supplies mounted on the same chassis and located in a common inclosure. One supply is a commercial unit purchased from Wanlass Electric Company, a subsidiary of Ambac Industries, Inc., Santa Ana, California. This supply furnishes a voltage regulated, filtered, dc output of 6.8 v. The second supply is constructed of readily available commercial parts and furnishes an unregulated, unfiltered, dc voltage output of 7 v.

The power supply is a separate package, or module, and plugs into a connector mounted on the back of the rear torso display console. Power is then delivered to the sensor garment through the umbilical line and also to the remote control unit and the front torso control console through a jumper cable. The power supply package weighs approximately 30 lb and is contained in a sheet metal housing with its own carrying handle for transportability (Figure 1).

B. SYSTEM OPERATION

The preparation of the full-scale anatomical load analyzer system for a test sequence consists of the following typical operations:

1. Set up display consoles with the front torso console to the left of the rear torso console when viewed from the front.

2. Connect the power supply, power supply jumper cable from rear torso to front torso console, sensor garment connectors, and remote control unit connector to the rear of the torso consoles.

3. Turn on the power supply and allow it to warm up while checking the filtered and unfiltered pilot lights. If a light or lights are out, check the fuse or fuses. The white light is for filtered power supply, the red light is for unfiltered power supply.

4. Actuate the "lamp test" switch on the back of the rear torso console to check out the display lights for all three colors on both displays.

5. Have the test participant don the sensor garment vest. Activate the continuous button (green) on the remote control switch and manually press the sensors on the sensor garment to insure function.

6. Have the test participant don the item to be evaluated and select the mode of operation.

The functions of the remote control unit shown in Figure 5 may be defined as follows:

- Continuous Mode. The continuous mode is the dynamic mode where the display lights are continuously displaying loads being transmitted to the torso during movement. Information is not stored on the displays in this mode.

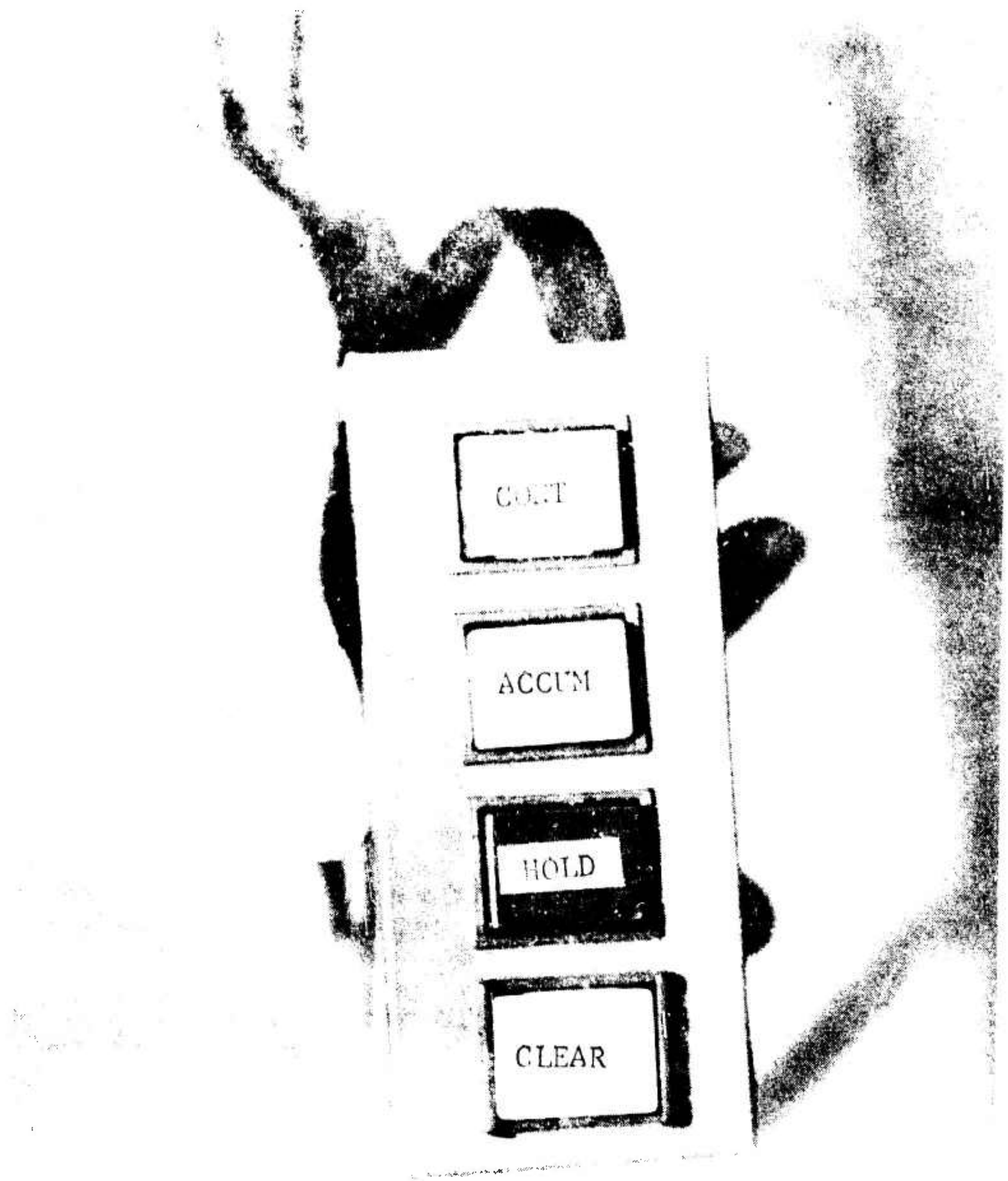


Figure 5 - Remote Control Unit

- Accummulate Mode. In the accummulate mode, the highest load value imposed on the torso during a series of movements is recorded on the display and retained for further evaluation or data recording.

- Hold Mode. If during a series of movements, the investigator is interested in a particular phase of the movement or a load pattern of particular interest, pressing the hold button freezes that information onto the displays for evaluation at the investigator's leisure or for data recording.

- Clear Mode. The clear mode cancels out all previous information from the displays and clears the system for further operation.

C. DATA PRESENTATION

The information presented on the full-scale anatomical load analyzer system consoles may be permanently stored on IBM cards, Figure 6. Printed cards were designed which pictorially represent the front and rear of the sensor garment and the location of each sensor on the garment, permitting the punching of data into the card using the IBM Port-A-Punch system shown in Figure 6. The punch stylus is used to transfer information from the displays to the IBM card by punching the sensor location and the load range indicated by the colored lamps on the display. One of three perforated slots vertically oriented on the IBM card is punched to record the load range. The left hand slot represents green lights (1/2 lb and up), the middle slot represents yellow lights (1 lb and up) and the right hand slot represents red lights (1-1/2 lb and up). The front torso IBM card has a total of 127 horizontally oriented rectangles with three vertically oriented, partially punched, slots per rectangle. These represent the exact number and location of sensors in the front sensor garment. The back torso IBM card has 121 horizontal rectangles with three vertical slots per rectangle representing the back of the sensor garment.

A system of colored tapes is used on the Port-A-Punch as a visual aid in interpreting load ranges. The use of color greatly simplifies data interpretation.

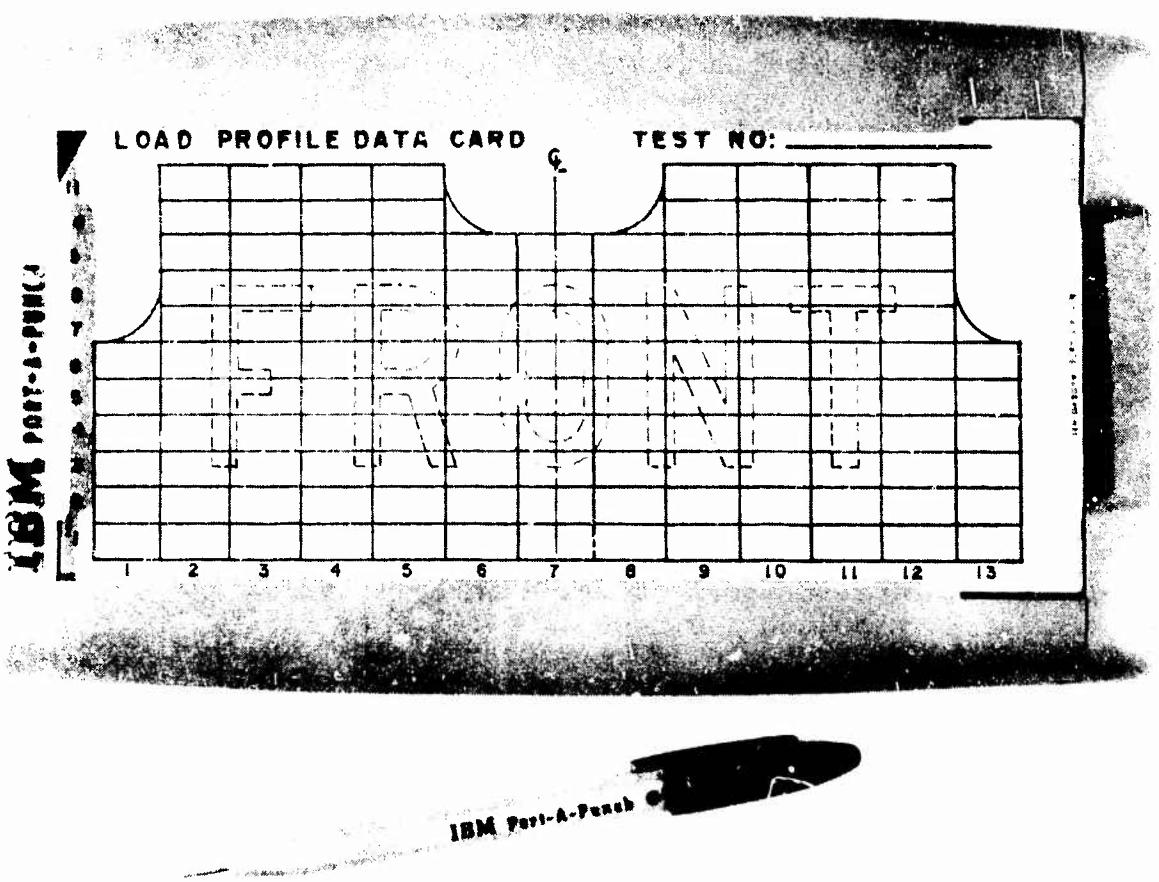


Figure 6 - Data Recording Card and Port-A-Punch System

D. SYSTEMS EVALUATION AND DATA INTERPRETATION

The full-scale anatomical load analyzer device was used to evaluate five aircrew and infantry body armor and one load carrying system. One of the aircrew body armor suspension systems (Ref. 4) evaluated is shown in Figure 7. It represents test item 5 listed below:

1. Experimental, infantry body armor, fragmentation protective 3/4 collar vest, lightweight, water repellent nylon 128, size medium (weight 6 lb, 8 oz).

2. Experimental, aircrew body armor, spall, fragment, small arms protective vest with front and back armor plates, size medium (weight 28 lb, 4 oz).

3. Experimental, aircrew body armor, spall, fragment, small arms protective vest with front plate and nomex raschel weave back unit, size medium (weight 13 lb, 8 oz) (Ref. 4).

4. Experimental, infantry body armor, fragmentation protective 3/4 collar vest, lightweight, "XP", size medium (weight 6 lb, 4 oz).

5. Experimental, aircrew body armor, raschel knit, tension web suspension vest with anatomical front and back plates (weight 30 lb, 8 oz), with experimental waist augmentation belt (weight 32 lb, 0 oz) (Ref. 4).

6. Standard rucksack carrier and standard load carrying equipment belt with canteens filled with water (weight 58 lb, 8 oz).

Two test participants were used to evaluate each of the six items. The participants were anthropometrically selected to fit the personal equipment being tested. The sensor garment was worn beneath the test item and the test participant was negotiated through a series of prescribed psychomotor movements described as follows:

Figure 7 - [illegible] Aircrew Body Armor System With
[illegible] Distribution Augmentation Belt

1. Head movement, vertical to dorsal
2. Finger touching
3. Shoulder flexion
4. Shoulder abduction
5. Duck walk in figure eight pattern
6. Combat crawl in figure eight pattern
7. Standing erect
8. Seated erect
9. Seated leaning forward
10. An arm overlap test

The results of the tests for the 10 items were recorded on IBM cards (Figure 6). Based upon these data, comparisons were made between suspension systems and also the load distribution efficacy of specific systems.

The data entered on the IBM cards also were used to determine which areas of the torso were carrying the loads distributed by the various test items. Data interpretation was aided by earlier work in torso sensitivity studies which defined the optimum load bearing areas of the torso (Ref. 1). By combining these two sources of information, an evaluation of the test items became possible.

Load distribution and location of excessive pressure points were the design criteria used in the system evaluation. The results of this evaluation are presented in Part III, Section B and Part IV, Conclusions, of this report.

PART II. FINAL PROTOTYPE DESIGN CONSIDERATIONS

A. SENSOR DESIGN AND FABRICATION

An advanced progressive contact sensor was designed, developed, and fabricated. The latest design eliminated mechanical sticking, simplified calibration, and reduced calibration sensitivity.

The basic components and subassemblies for this improved sensor design are shown in Figure 8. An insulated phenolic disc, 1/16 in. thick and 3/4 in. in diameter, forms the base to which all sensor components are mounted (Figure 8a). The sensor has three leaf spring type contacts and a main contact spring made from phosphor bronze (0.0035 in. thick), silver plated (Figures 8b and c). The dome support leaf spring was fabricated from the same material (Figure 8d). The spherical dome cap uses a nickel silver material, 0.010 in. thick, unplated (Figure 8c).

Eyelets were used as rivets to assemble the sensor components to the phenolic base and to the flexible mylar printed circuit strip as a simultaneous operation. A typical sensor subassembly is shown in Figures 8f and g. The three leaf spring contacts were assembled with 0.058-in. diameter, 1/8-in. long eyelets and the main contact and dome support leaf spring with a 0.087-in. diameter, 1/8-in. long eyelet. Three #0-80-in. diameter, 3/32-in. long socket set screws threaded into tapped holes in the phenolic base permitted calibration of the leaf spring contacts for the three load ranges (Figure 8g). The position of the set screws along the edge of the contact furtheset away from the point of contact with the main leaf spring significantly reduces calibration sensitivity by increasing the moment arm of the applied force and reducing spring deflection under load. This approach permits finer calibration adjustments and also eliminates the danger of overstressing the contacts by exceeding the yield point.

The final step in the sensor assembly was to solder the spherical dome cap to the cap support leaf spring (Figure 8h). Sensor height after assembly was 9/32 in. The edge of the cap closest to the rivet attachment point was placed in contact with the phenolic base during assembly to give a clamshell appearance. This approach provides a free floating sensor cap capable of detecting

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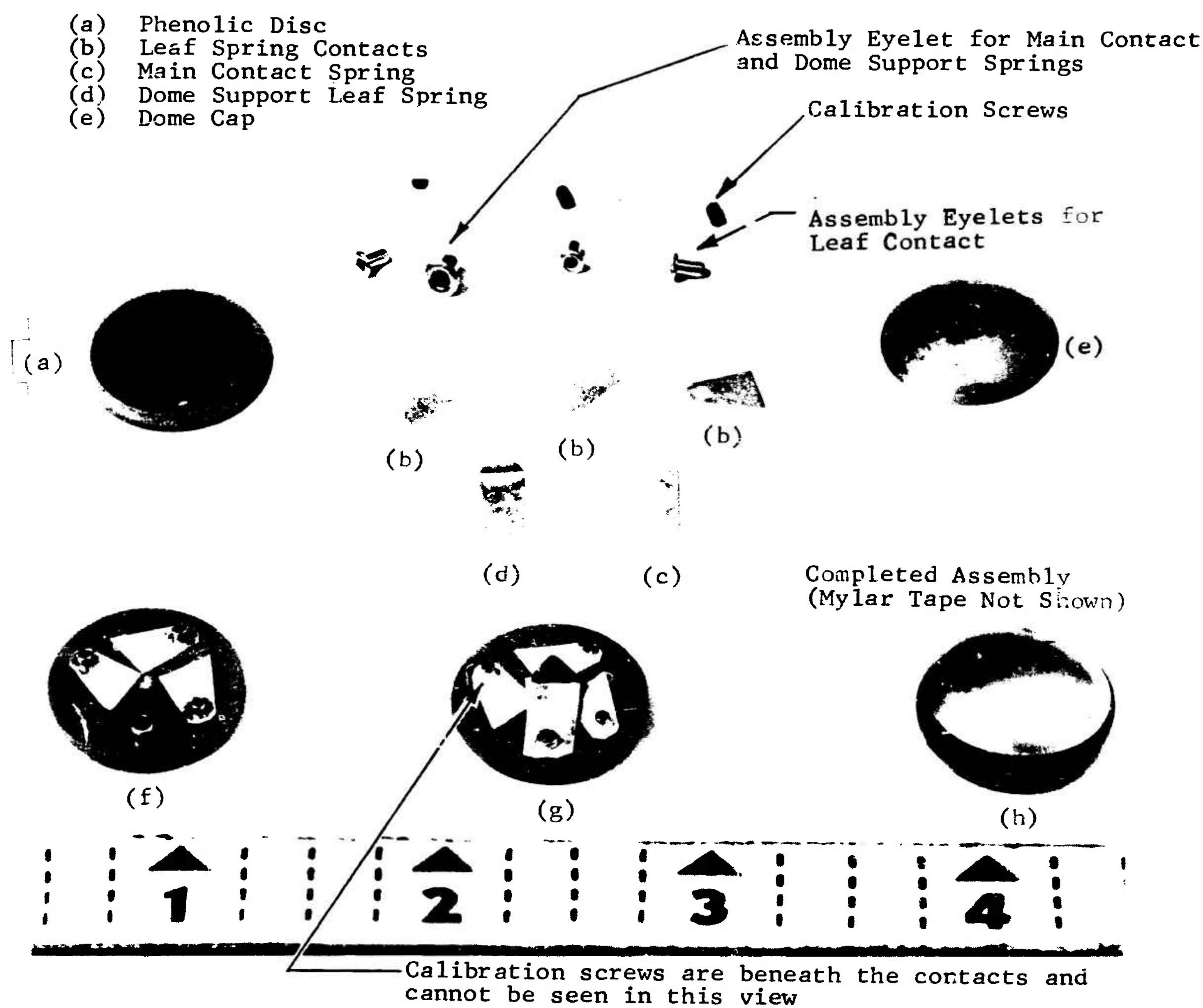


Figure 8 - Layout of Sensor Componenents, Sensor Subassembly and Final Assembly

normal or oblique force vectors. It is also completely free from mechanical friction making sticking impossible.

The principle of sensor operation is that loads impinging on the spherical dome cover cause the cover support spring and main contact springs to deflect resulting in impingement on one or all of the leaf spring contacts, depending on the force magnitude. The leaf spring contacts were mechanically calibrated with the set screw adjustments to read increments of 1/2 lb and up, 1 lb and up, and 1-1/2 lb and up. Potential sensor damage is minimized by permitting the spherical dome cap to bottom on the phenolic base without overstressing the spring components. However, it is possible to deform the cap with an excess of 25 lb.

The advantages of the latest progressive electrical contact sensor may be summarized as follows:

- Rugged, simple, and dependable.
- Relatively small size and low profile.
- The sensor cannot stick because of the free floating spherical cap.
- The sensor may be easily calibrated and calibration sensitivity is greatly reduced permitting finer load range adjustment.
- Sensor durability is greatly improved by permitting the spherical cap to bottom out on the phenolic base without overstressing the component parts.
- Improved electrical contact is achieved by riveting the sensor components directly to the flexible mylar printed circuit tape and then soldering the hollow eyelets in place to insure good electrical contact (Figure 3).

B. SENSOR GARMENT IMPROVEMENTS, DESIGN AND FABRICATION

The full-scale anatomical load sensing garment covers the entire torso with a spaced sensor array (Figures 9 and 2). It is a front donning garment with a zipper closure offset approximately 2 in. to the right of the front torso centerline to permit a vertical row

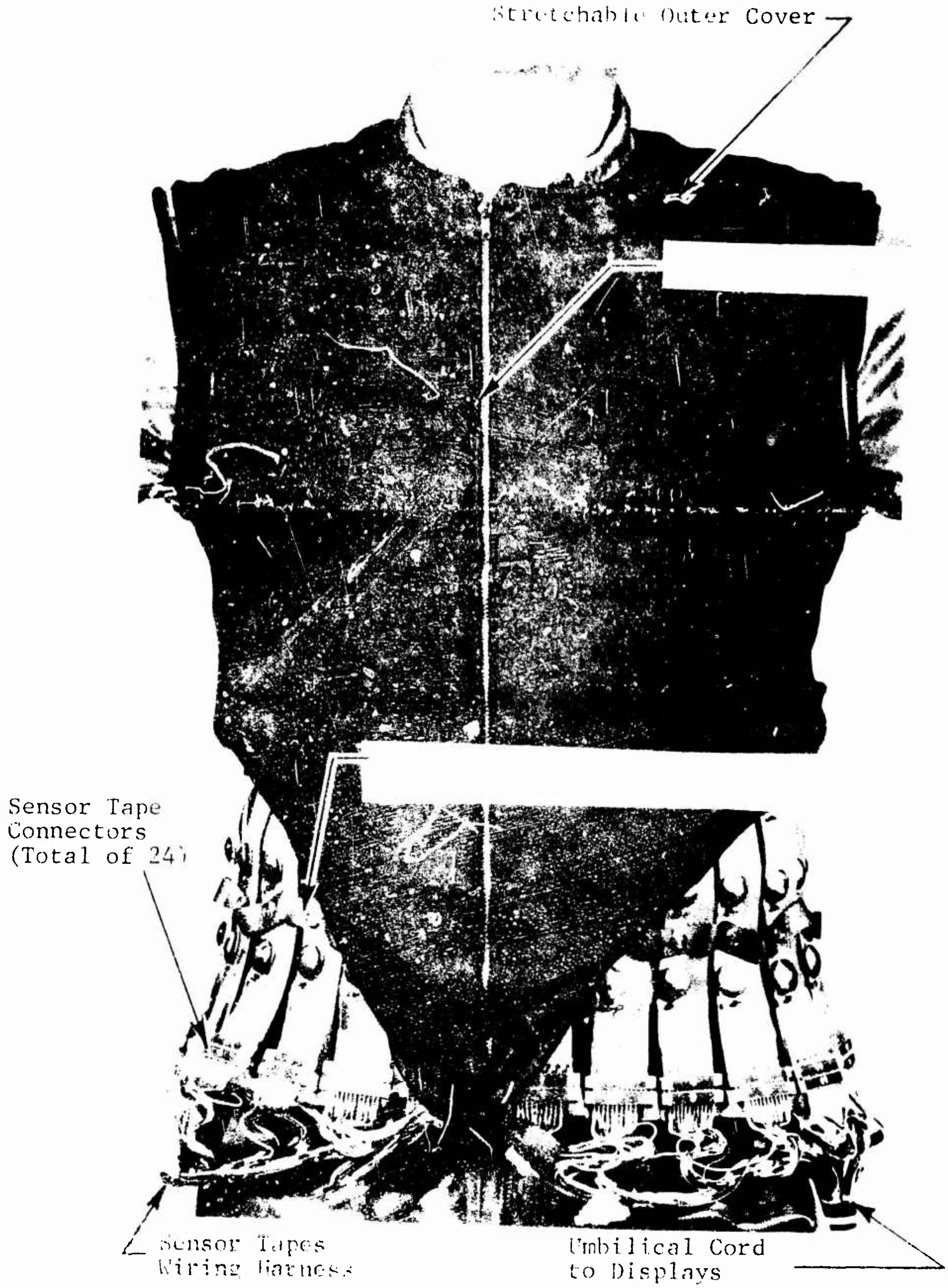


Figure 9 - Sensor Garment Final Assembly

of sensors to be placed on the centerline. Sensor spacing varies with location on the torso, but, in general, vertical spacing is approximately 2 in. narrowing down in the shoulder areas and horizontal spacing is approximately 1-1/4 in. with the vest in a relaxed position. In this position the vest is 36 in. in circumference around the chest.

The vest is designed to expand circumferentially using a system of limiting tapes interconnecting the sensor mounting strips (Figure 9). It can easily accommodate up to the 99th percentile man for chest circumference (Ref. 3).

Vest length is not adjustable and is designed to cover the 75th percentile man for waist back length of 18 in. The top sensor, located on the front torso centerline, is positioned on the suprasternal notch and the 9th sensor in this row is located 16 in. down (sensor spacing of 2 in.). The bottom row of sensors in the sensor garment floats with respect to location on the torso depending on torso length of the test participant.

The sensor garment contains a total of 248 sensors. A total of 127 sensors is positioned on the front of the garment and 121 sensors on the rear (Figure 2). The sensors are mounted on flexible mylar tapes with a typical mounting of a singular sensor shown in Figure 10. As described in the previous section of this report, the sensor components were assembled to the tapes with eyelets. They serve as rivets and solder points for good electrical connections.

The vest contains a total of 24 vertically oriented mylar strips, each specially shaped to conform to the torso configuration (Figures 10 and 2). The flexible mylar tapes were made using Type Pi-621F copper clad mylar, 0.0044 in. thick, manufactured by Kepro. The circuitry was masked and etched on each tape. The tapes contain a common power bus leading to each sensor mounting pad and an output lead from each sensor. Each mylar strip terminates in an Elco connector (Sub-Miniature Varicon Connector - 12 pins - Series 8129). Two resistors forming a portion of the voltage divider network used in the sensor logic circuitry, are also mounted with each sensor on the mylar tape.

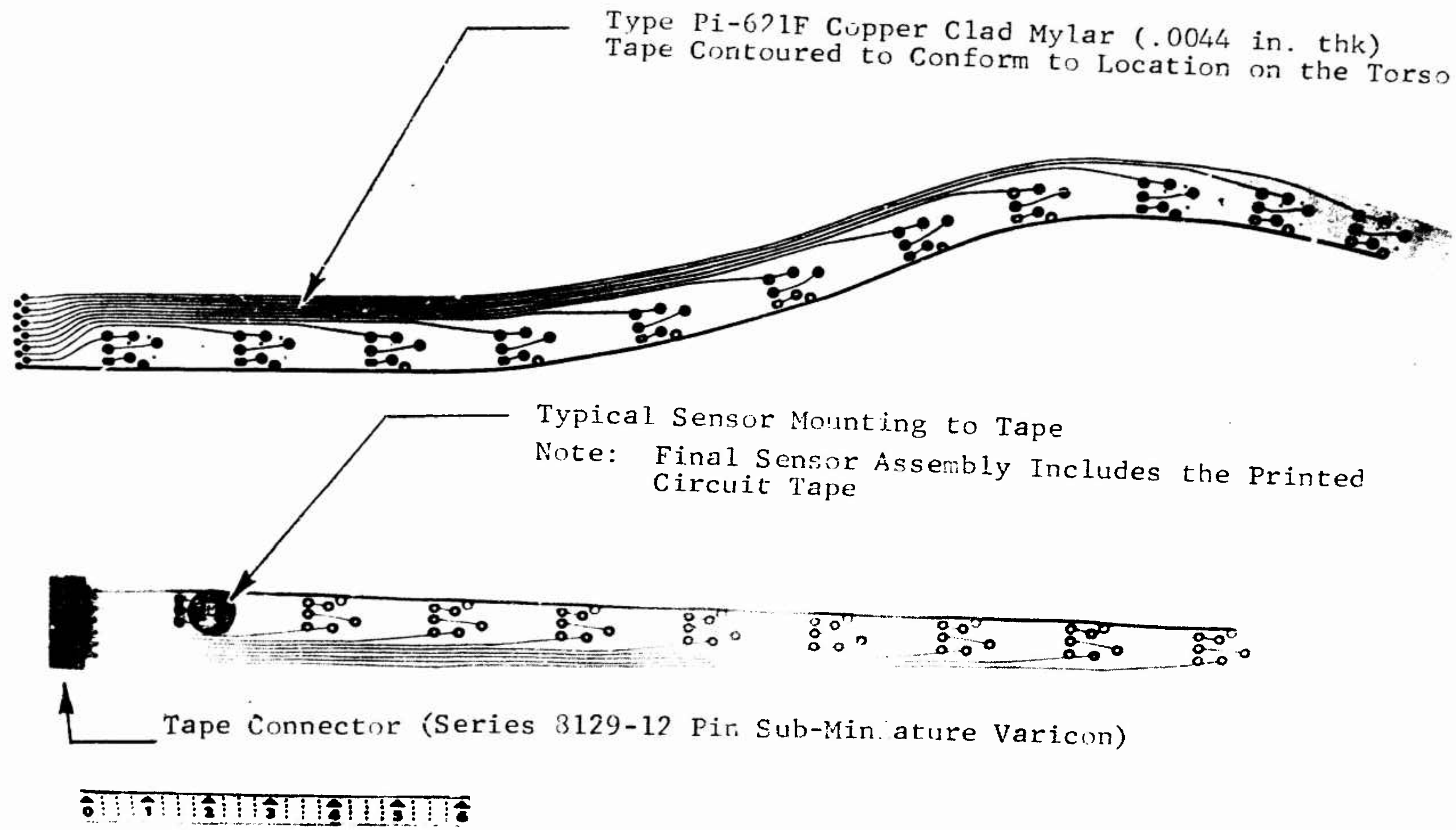


Figure 10 - Typical Flexible Mylar Printed Circuit Tape

The flexible mylar printed circuit tape approach was used to (1) simplify vest wiring; (2) improve vest flexibility during wearer articulation; and (3) minimize vest profile or bulk. The number of sensors per tape varies from 6 to 11 depending on the tape location on the torso. A row of nine sensors are positioned on the front torso centerline and a row of 11 sensors on the back torso centerline. The top sensor of the front row is positioned at the suprasternal notch and the top sensor of the back row is at the seventh cervicle. The sensor garment is symmetrical about the vertical centerline making it possible to reduce the number of printed circuit tape shapes to 19 configurations.

The finished tape assemblies are positioned and retained circumferentially with 1/2-in. wide nylon limiting tapes secured to the vertical mylar strips with snaps as shown in Figure 2 and 9. The terminating connector of each sensor strip is tied into mating connectors of a wiring harness forming one end of a 40 ft long umbilical line which leads to the light display consoles. The wiring harness is divided at the front closure to permit donning. It leads away from the vest on the left hand side of the wearer (Figure 11). To support the weight of the umbilical line, a fabric loop extends upward over the left shoulder of the wearer to support its weight.

The electrically interconnecting umbilical line and supporting loop is an integral part of the vest and cannot be easily separated. The 40 ft length was specified to permit a test participant to freely negotiate through a series of prescribed psychomotor test movements without restriction. The umbilical line terminates in six connectors which plug into the back side of the front and rear torso consoles. The connectors are numbered and the cable lengths are varied to minimize the possibility of making wrong connections. Connectors with different numbers of pins are also used to reduce potential error. A total of 249 leads emanate from the vest and pass through the umbilical line to the six connectors. The connectors are defined in Figure 11.

A plastic sheath is used to cover the umbilical line for protection against snagging or damage. A windup reel was also designed and fabricated on which the umbilical line could be safely stored and shipped (Figure 2).

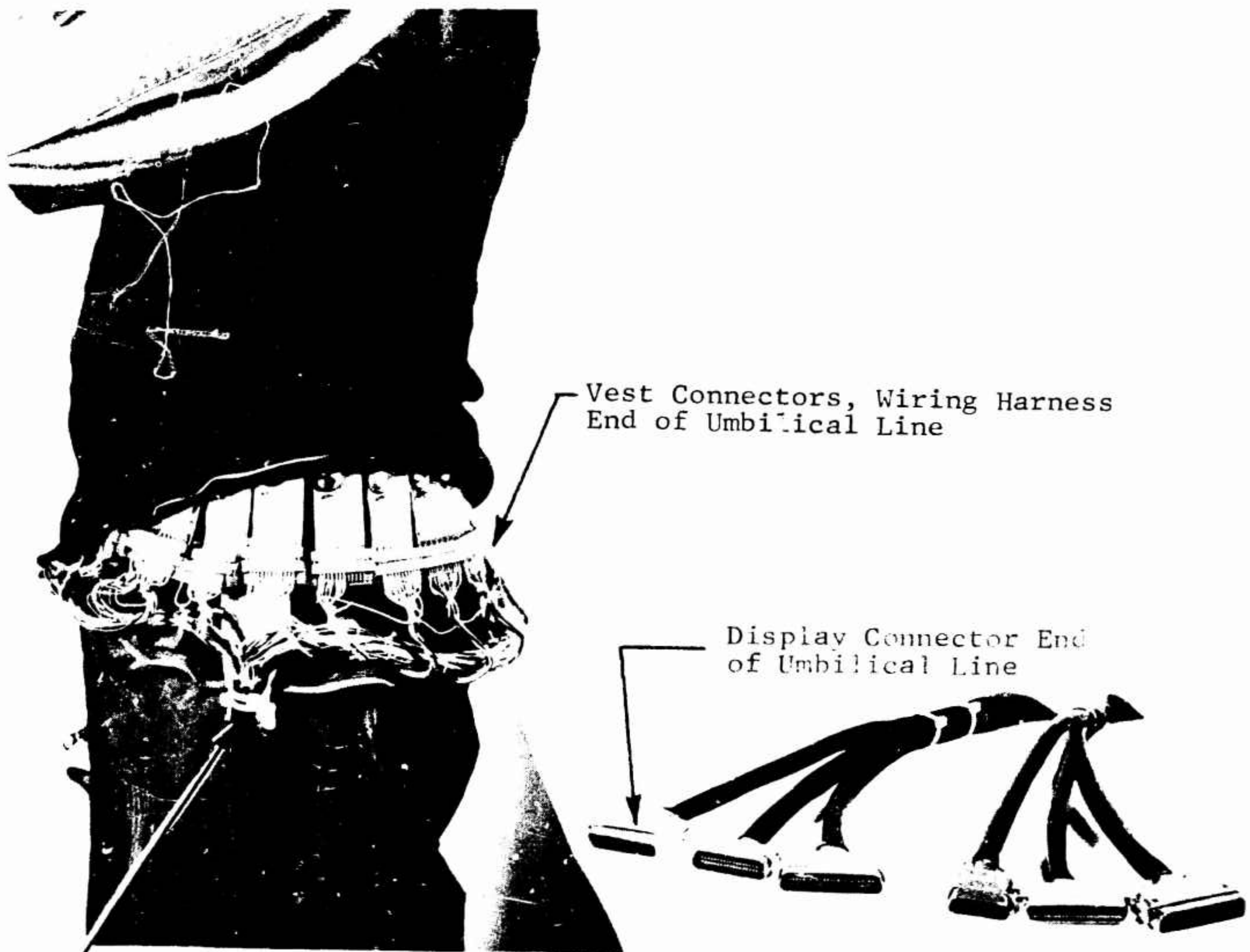


Figure 11 - Integration of Umbilical Line in the Sensor Vest

An inner and outer cover of stretchable double knit nylon completely encases the sensor tapes and wiring harness assemblies (Figures 9 and 11). Size variations can be easily accommodated by the stretchable fabric without preloading the sensors. A front closure zipper offset to the right hand side of the torso centerline by several inches permits simple donning of the vest. Zippers around the arm holes and around the bottom of the vest permit assembly to the sensor tape assemblies and simplify servicing or trouble shooting of sensor circuitry. The completed vest weighs 6 lb exclusive of the weight of the umbilical line.

Preliminary laboratory and field testing of the sensor vest assembly indicated that excessive flexure of the mylar tapes could induce fatigue cracks in the printed circuitry causing electrical breaks or open circuits. This situation was particularly critical for the front tapes at the waist area where bending forward tended to bend the tapes back on themselves in several loops. Breaks also occurred at the voltage divider resistors directly adjacent to the sensor assembly (Figure 10).

The basic concept of flexible printed circuitry is sound and future designs could incorporate advanced tape assemblies which would endure multiple flextures without circuit breaks. The approach employed in this program appeared sound at the time of fabrication; it could not be foreseen that tape reliability might be less than optimum.

The tapes were modified to improve reliability using two approaches (Figure 12). The first approach was to use #28 stranded wire (insulated) to connect the sensors directly to the connectors (Figure 12a). Adequate strain relief loops were provided and wires were physically arranged to minimize wire elongation with tape flexture. Wires were arranged in parallel paths with the insulated outer cover of each wire in contact with an adjacent wire. The wires were then fused to each other by using an appropriate solvent which softened the insulation and achieved a bond.

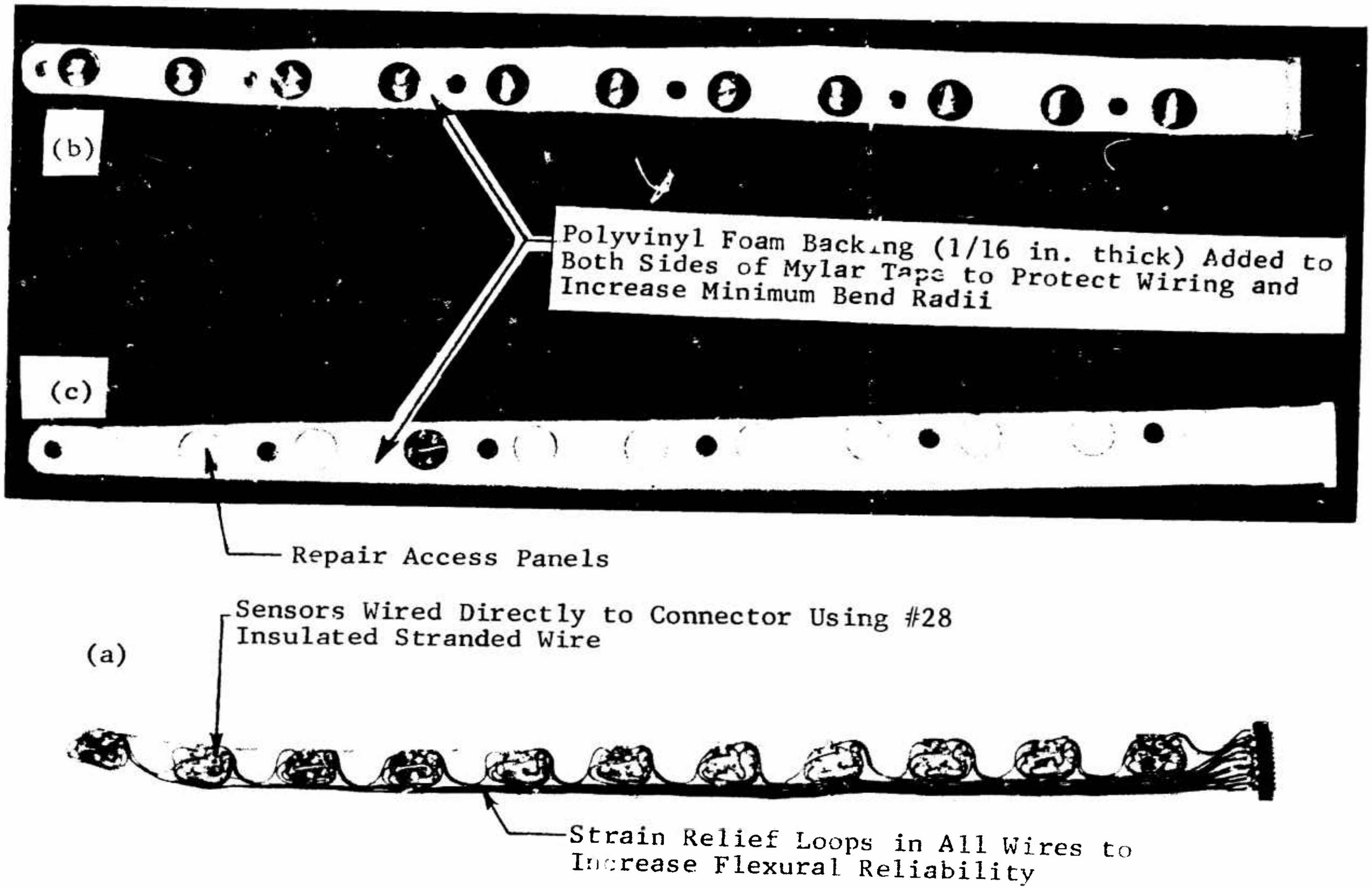


Figure 12 - Reliability Modifications to Sensor Tape Assemblies

Polyvinyl foam with an adhesive backing was then cut to the individual tape configurations and secured to the front and back sides of each tape. Clearance holes were cut in the foam for the sensors and securing snaps (Figure 12b). Access panels were provided for servicing or replacing sensors (Figure 12c). The polyvinyl foam overlaps the mylar tape edge by 1/16 in. to provide a firm bond between the front and rear foam strips. The opposite edge was treated with a solvent to form a secure bond. The finished assembly increased the permissible minimum bend radius to approximately 1/4 in. and provided protection to the sensor wiring by eliminating kinking or uncontrolled wire movement.

The modifications increased the sensor vest weight by 1-1/2 lb. Bulk was also increased but did not affect vest function. The vest assembly is slightly stiffer than before but difference to the wearer is not grossly perceptable. Sensors were recalibrated to compensate for the soldering distortion, and the interaction between the sensor and the body could not be determined from tests. In summary, it appears that the approach taken for improving reliability does not seriously modify sensor garment performance.

C. VISUAL DISPLAY DESIGN AND FABRICATION

The full-scale anatomical load analyzer consists of a front torso console and a rear torso console (Figure 13). The consoles are 35-3/4 in. high, 20-3/4 in. wide and 16-3/4 in. deep. They weigh approximately 40 lb each.

An anthropometric manikin was purchased for the displays. It is a plastic manikin which could be easily cut and drilled for our specific application. The selection of this manikin is based on a survey of commercially available manikins conducted earlier in the program and the fabrication of an anatomical fiberglass manikin by IITRI. The manikin selected proved to be superior to other candidates and was chosen for final fabrication for appearance and stability.

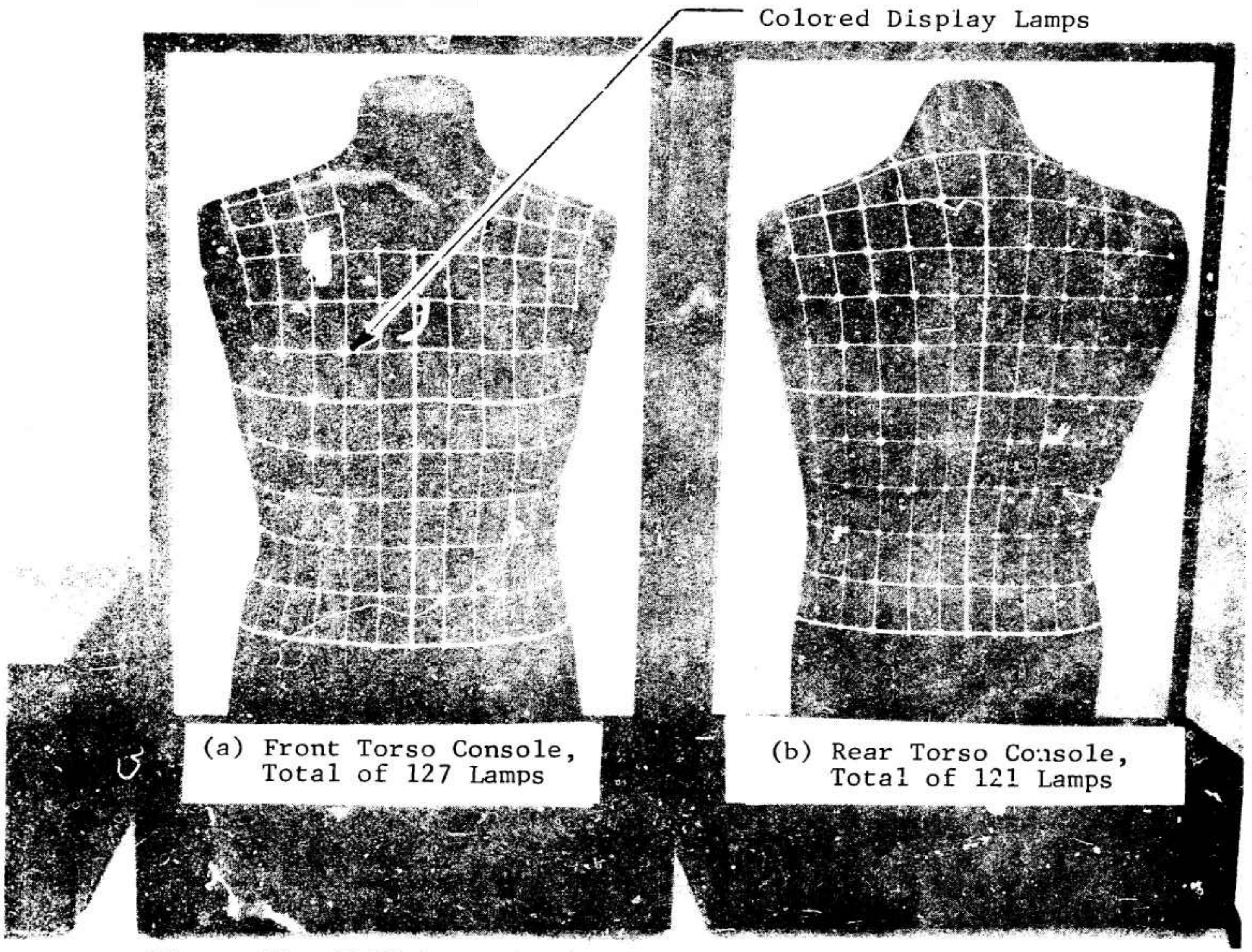


Figure 13 - Full Anatomical Visual Display Consoles

The manikin was split transversely along the shoulders and neck, through the arm areas and down the sides as shown in Figure 13. The sensor locations corresponding to the sensor locations on the sensor garment were laid out and holes drilled in the manikin halves to accept Tri-A-Lite lamps selected to display the load ranges. The holes were sized to permit a press fit of the lamps in place by hand. The retention force is great enough to insure positive positioning of the lamps and permits ease of lamp replacement in the event of failure.

The front and rear torso manikins are painted flat black to insure good contrast with the tricolored lamps. White tape is secured to the torso halves in a system of vertical and horizontal gridlines for ease of sensor identification and location. Vertical and horizontal numbers attached to the displays permit simple and rapid reference to any sensor of interest.

The manikin halves were assembled to the front panels of their respective displays which hinge outward for final assembly and servicing (Figure 14). The display consoles are basically of wooden construction with some metallic rigidizing components which also serve to support the electronic components as shown in Figures 14 and 15.

A rear view of the consoles shows the printed circuit card racks which contain the logic circuits for the display lamps, lamp check switch (Figure 15a), and the connectors and interconnecting cables to the power supply, remote control unit and the sensor garment (Figure 15b). Perforated back panels complete the enclosure and can be easily removed for servicing or replacement of printed circuit boards or other electronic components such as the control relays located in the rear torso console (Figure 16). The hinged panel shown in this figure also provides access to the contacts of the lamp check switch and connector wiring harnesses. The connectors are clearly labeled on the display cabinets to minimize error (Figure 15b).

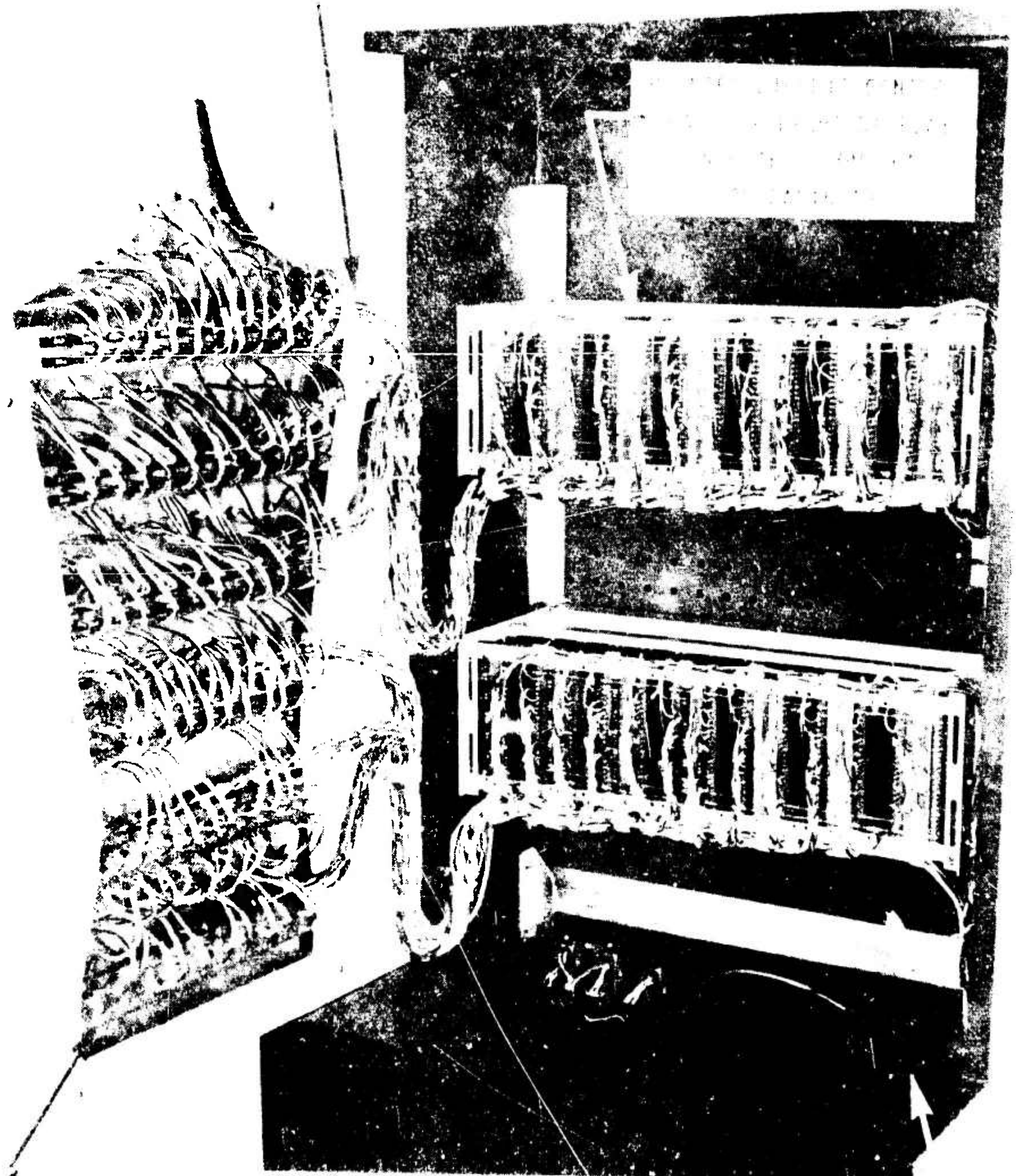


Figure 14 - Typical Display Console Assembly with Front Panel in Open Position for Servicing

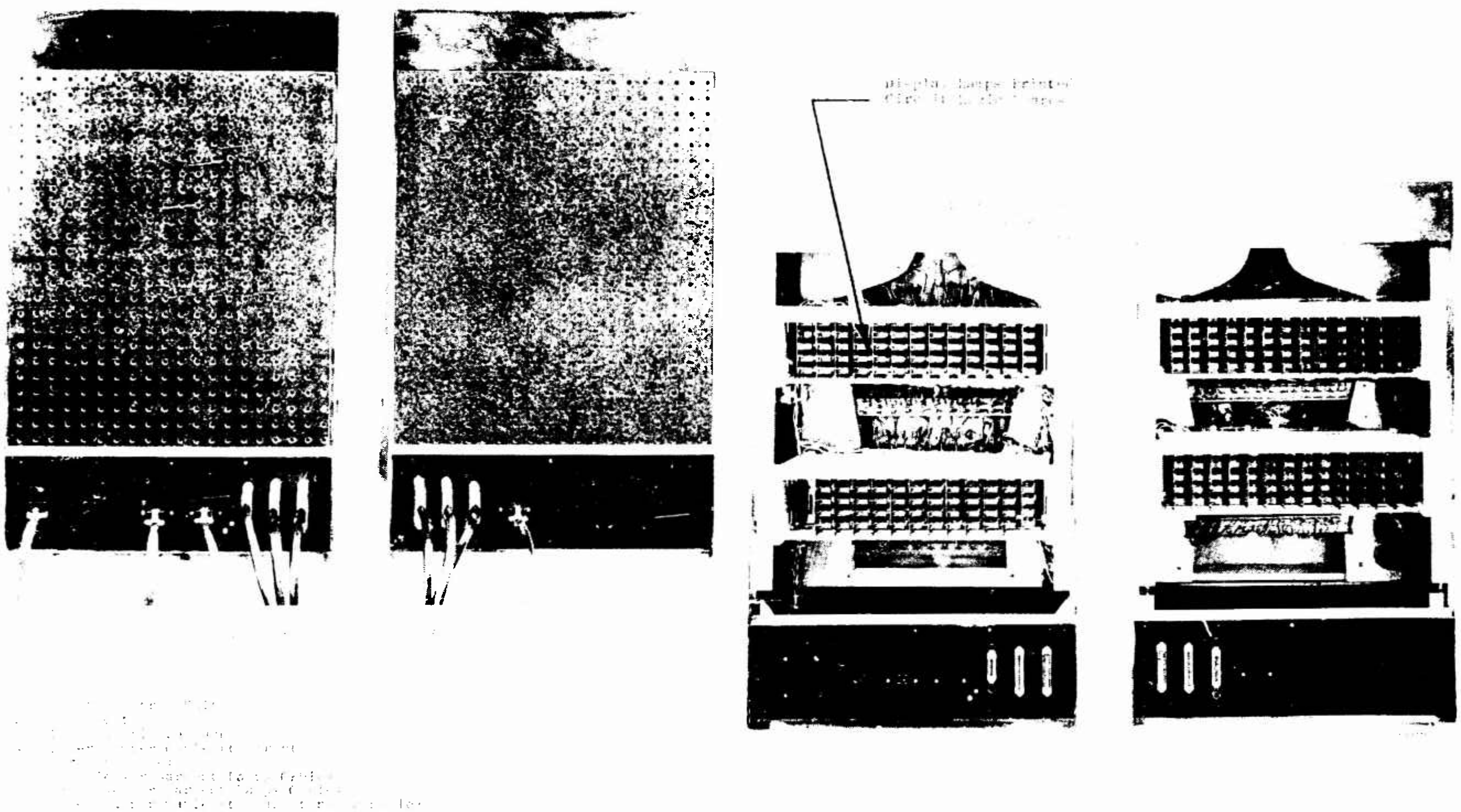


Figure 15a and b - Electronic Components Packaging and Connector Arrangement

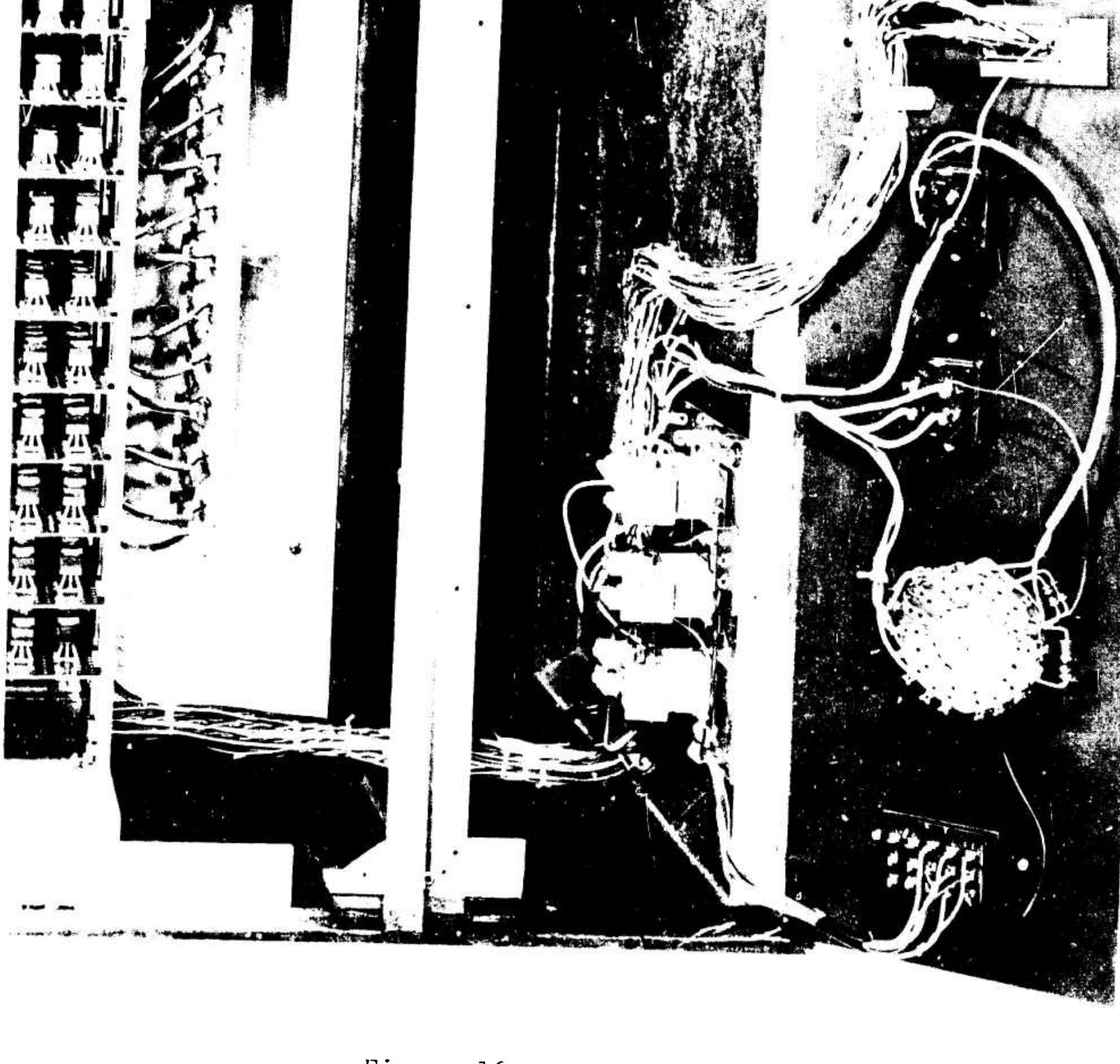


Figure 16 - Control Relays

The connectors and controls shown in Figure 15 are labeled from left to right as follows:

1. Remote control unit connector
2. Lamp test switch
3. Power supply unit connector
4. Power jumper cable from rear torso to front torso console
5. Sensor garment connectors (3) from rear of sensor garment through the 40 ft umbilical line
6. Sensor garment connectors (3) from front of sensor garment through the 40 ft umbilical line
7. Front torso console power connector (input taken from rear torso console).

The tricolored lights contrast significantly with the black manikin background even under ambient lighting conditions. In a partially darkened room, the effect is dramatic and conveys pressure patterns and shifting of these patterns as a result of dynamic movements.

The advantages of the full-scale anatomical distribution load analyzer are: (1) it permits viewing load patterns being distributed on the entire torso instantaneously and simultaneously; (2) analysis of any load bearing or protective device worn on the human body can be accomplished under static or dynamic conditions; (3) shifting load patterns can be observed during articulation; and (4) the capability of being able to store a pattern of particular interest is a positive feature.

The Tri-A-Lite lamps used in the display contain three colored bulbs (green, amber and red) in a single cartridge with a translucent lens cap. Each of the lamp bulbs is controlled by a specially designed logic circuit which permits one of the three colors to be turned on depending on the load seen by the sensor garment. A discussion of this logic circuitry follows in subsection D of this report. The Tri-A-Lite lamps were purchased from the Chicago Miniature Lamp Company in Chicago, Illinois, Part No. CML 9501-RGY. They operate on 5 v and draw 115 ma/bulb.

The display consoles weigh approximately 45 lb each making them transportable. Special shipping cases with lifting handles and casterable wheels on the base permit ease of handling and protection of the displays during shipping (Figure 17).

D. ELECTRONIC DESIGN, FUNCTION, AND FABRICATION

1. Circuit Description

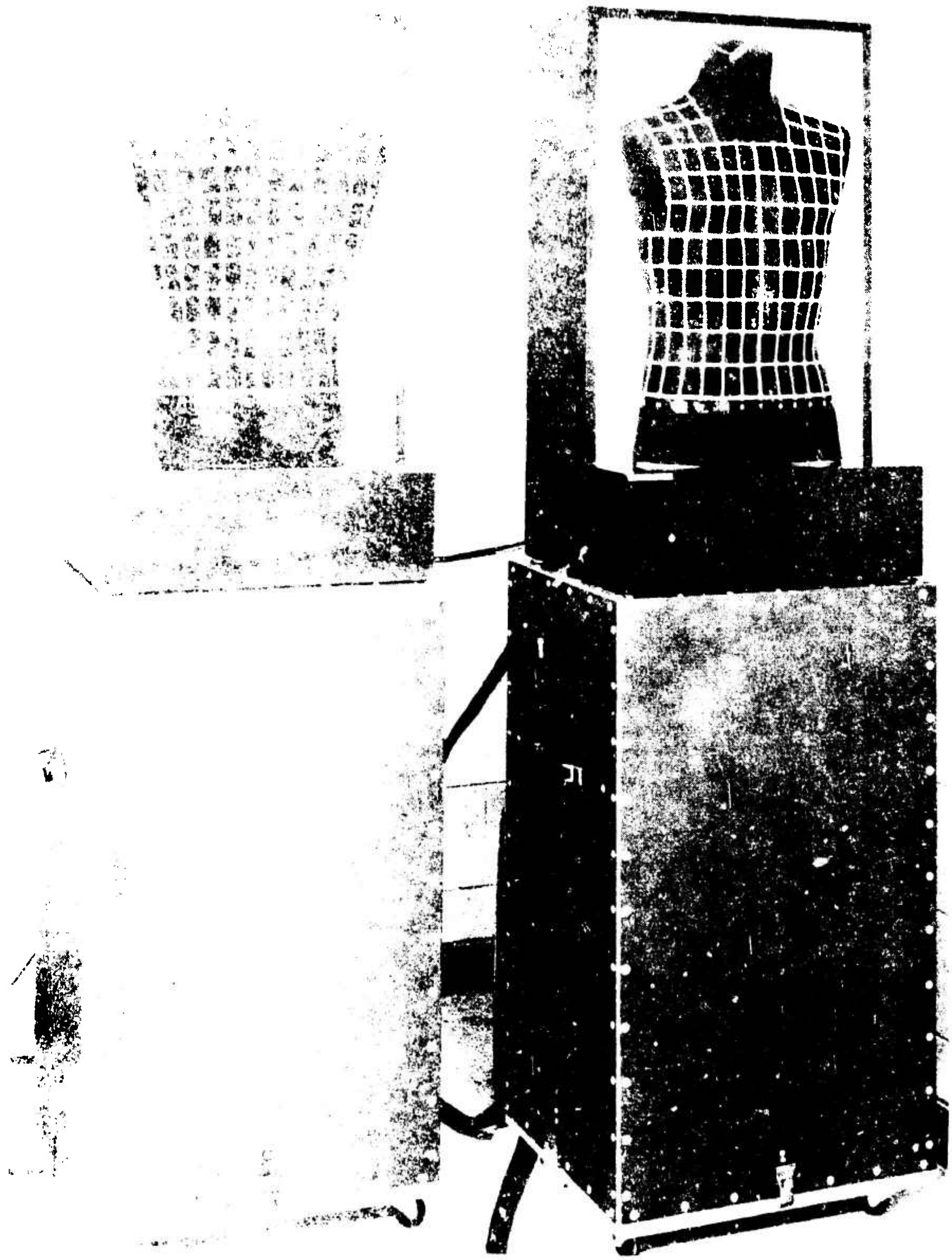
The load profile analyzer circuit contains three basic elements: the progressive contact sensors, the lamps and their trigger circuits, and the power supply with its control circuit.

a. Sensor

The sensors are progressive contact switches with a single input contact and three adjustable output contacts (Figure 8). Application of a load to the sensor dome (e) causes the main contact spring (c) and dome support leaf spring (d) to progressively mate with the leaf spring contacts (b) which are adjustable by means of small set screws. Leaf b4 is adjusted to make contact at 0.5 lb, leaf b2 at 1 lb and leaf b3 at 1.5 lb.

Two-hundred and forty-eight sensors have been combined into the sensor garment or vest. The sensors are mounted on mylar tapes that form 24 vertical columns of sensors. Each column contains 11 sensors except for the two underarm tapes which contain six sensors each and the three tapes at the center front of the vest which contain nine sensors each. Since each sensor has three output contacts, it is necessary to transfer 744 bits of information (248 sensors x 3 outputs each) to the display unit.

To eliminate having a separate wire for each contact in each sensor, a resistor network was developed to allow the three bits of information to be handled on one lead from each sensor. Two resistors, R11 and R12 which comprise part of the voltage divider network as shown on the basic sensor circuit, are mounted adjacent to each sensor on the mylar tape (Figure 18). Therefore, only 249 leads are necessary between the sensor vest and the display units.



... with Shipping Cases

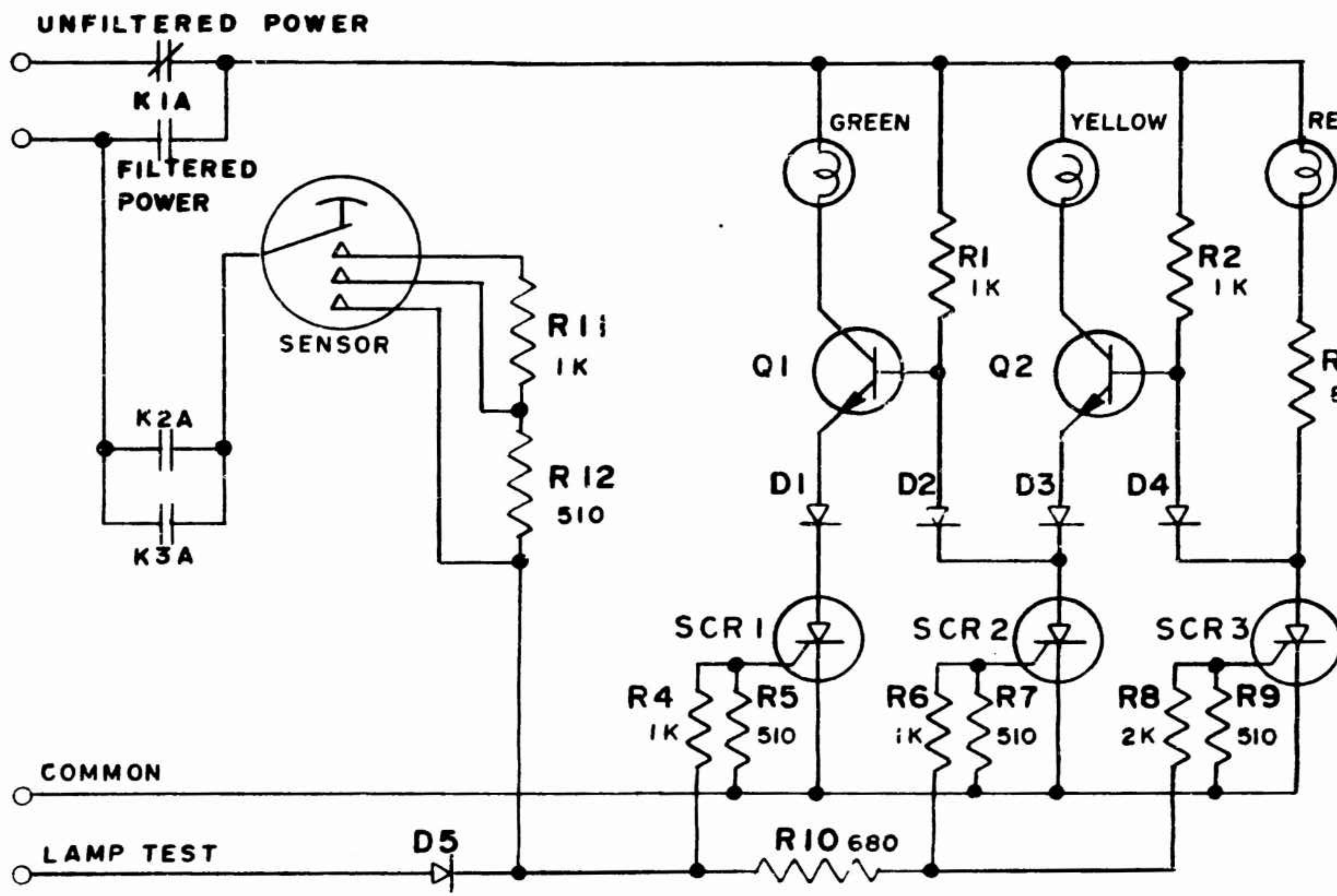


Figure 18 - Basic Sensor Circuit

b. Lamp and Trigger Circuit

The lamp and trigger circuit consists of one Tri-A-Lite lamp module and its associated circuitry, which is part of a printed circuit card, for each sensor. The lamp unit consists of three individual lamps with red, yellow, and green filters mounted in one housing. The lowest load range (1/2 lb) causes the green lamp to light, the middle range (1 lb) causes the yellow lamp to light and the green to go out. The highest range causes the red lamp (over 1-1/2 lb) to light and the yellow and green lamps to be in the off mode.

The lamp functions are accomplished by the circuitry shown in Figure 18. The location of these circuit components on the cards is shown in Figure 19. Each card contains circuitry for five lamp units and associated sensors. The cards are mounted in racks directly behind the lamps in the display consoles (Figure 20).

Depending upon the operating mode that is selected, the common input lead to all sensors is connected to the regulated filtered power supply by either relay contact K2A or K3A (Figure 18). When the first contact of the sensor is closed, the regulated 6.8 v dc is applied to resistor R11. This creates a sufficient voltage at the junction of R4, R5 and the gate of SCR1 to cause the silicon controlled rectifier (SCR) to conduct. Since the base of Q1 is positively biased through R1, current will flow and the green lamp will turn on. The voltages at the gates of SCR2 and SCR3 are not sufficient to start conduction.

When the second leaf of the sensor makes contact the regulated voltage is applied directly to the junction of resistors R11 and R12 causing the gate voltages of both SCR1 and SCR2 to be high enough to cause both SCR's to conduct. Since the base of Q2 is positively biased through R2, current will flow and the yellow lamp will turn on. The gate voltage for SCR3 is still below the conduction point.

When the third leaf makes contact, the regulated voltage is applied to the junction of R12, R4 and R10. This causes the gate voltages of all three SCR's to be high enough to cause conduction, turning on the red lamp. The series dropping resistor, R3, for the red lamp provides a voltage drop equivalent to Q1 and Q2.

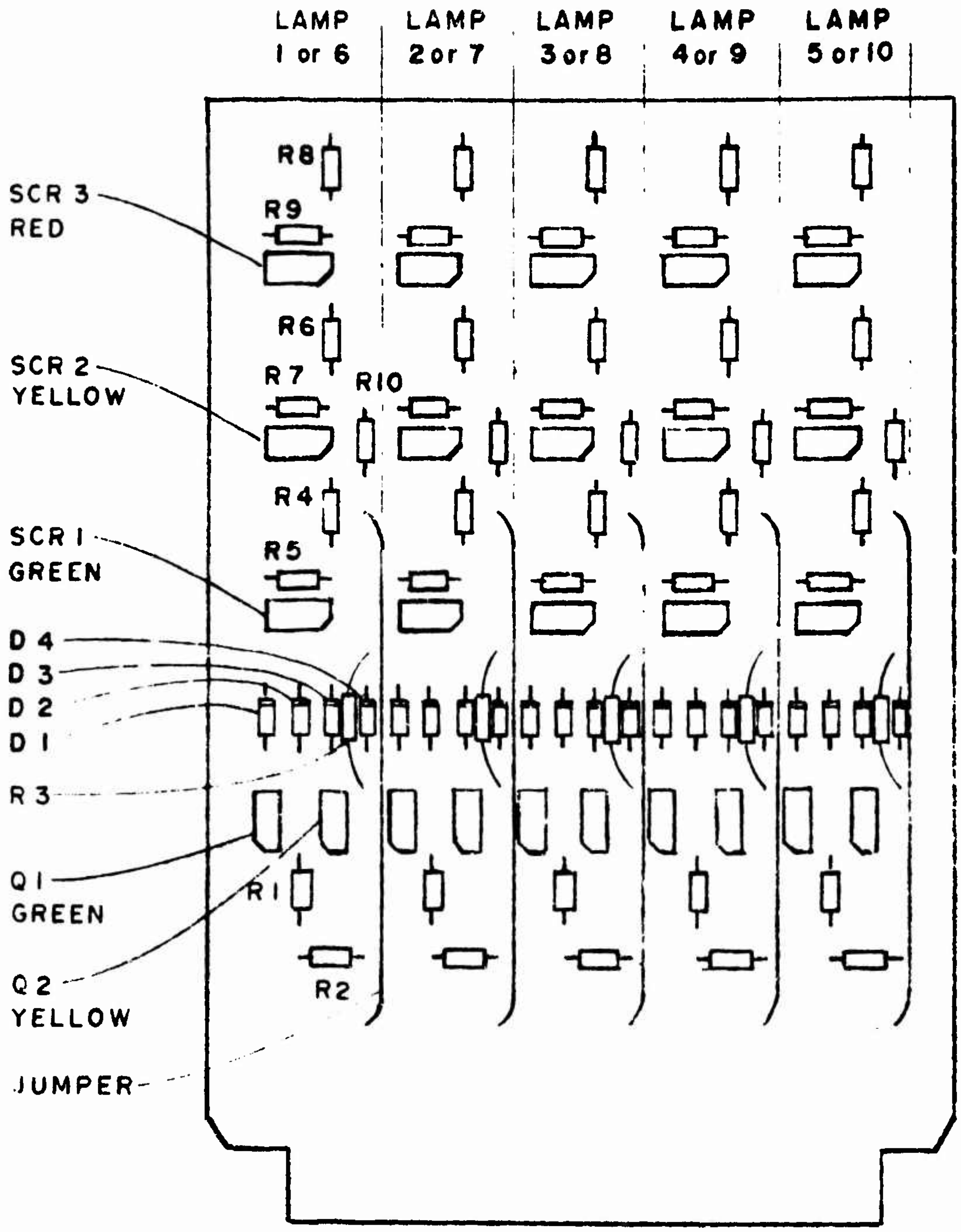


Figure 19 - Printed Circuit Card

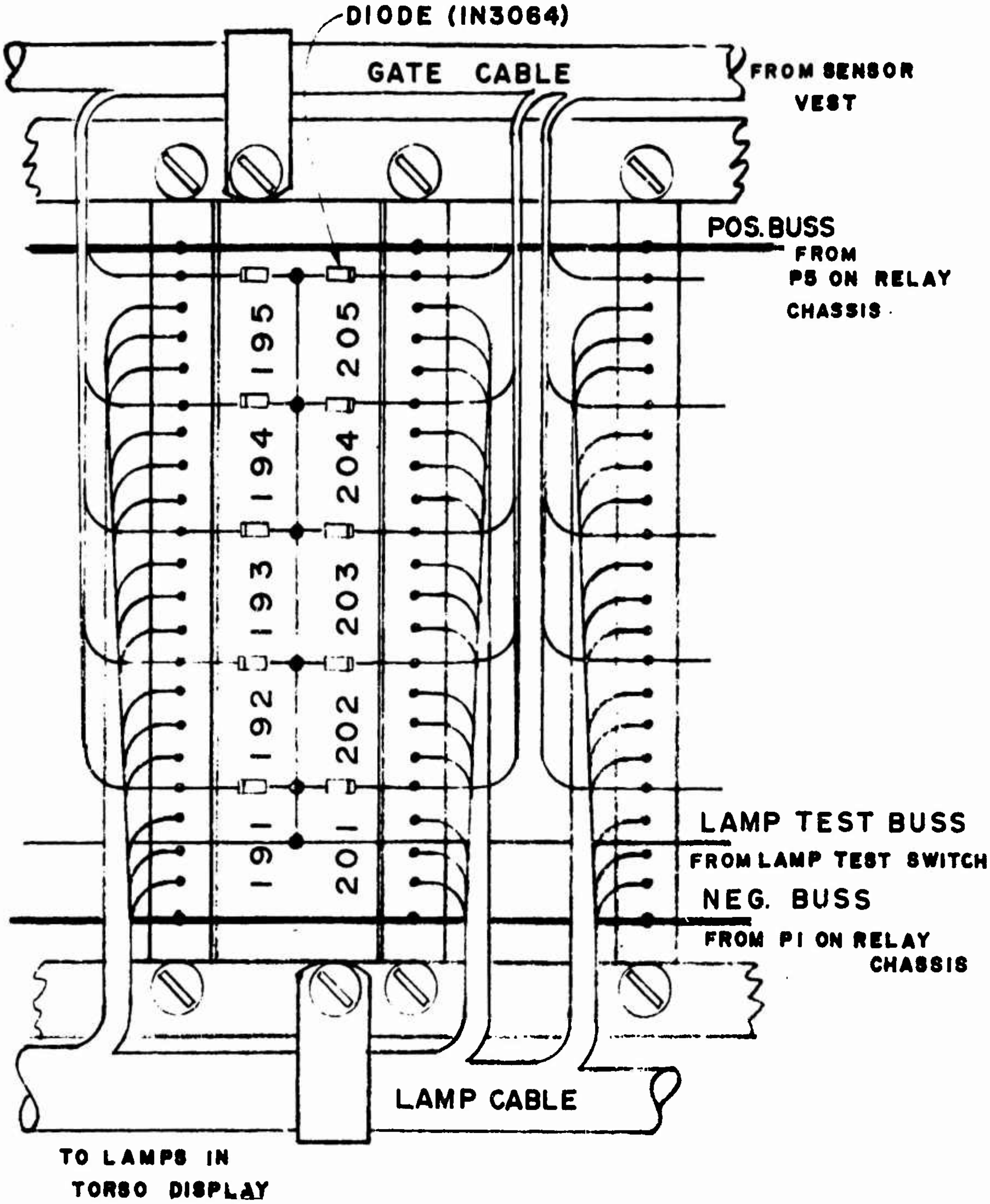


Figure 20 - Typical Card Rack Wiring

Since all three lamps are in a single housing, energizing more than one lamp at a time would make load level determination virtually impossible. Therefore, when the yellow lamp is turned on, the green lamp must be turned off. Transistor Q1 is used for this purpose. When the red lamp is on, both the green and yellow lamps must be shut off by transistors Q1 and Q2. The transistors used here are the NPN type.

If the base voltage is the same or higher than the collector voltage in this circuit, then the transistor is fully conductive, the current being limited only by the lamp resistance. If the base voltage is less than 0.5 v more positive than the emitter, the transistor is in the off condition and will not allow current to pass through the lamp.

If we assume the green lamp to be in the "on" condition, the emitter voltage of transistor Q1 will be about 1.5 v. If SCR2 is turned on causing the yellow lamp to come on, the voltage at the junction of D2, D3 and SCR2 will drop to the same value as that at the junction of D1 and SCR1. The voltage drop across D1 will be about the same as that across D2 effectively causing the emitter and base of Q1 to be at almost the same potential. Since the difference of potential is much less than the 0.5 v necessary to make Q1 start conducting, current flow through Q1 is stopped, extinguishing the green lamp. The same process occurs to extinguish the yellow lamp when the red lamp is on. When red is on, all three SCR's are on, but the green lamp is held off by Q1 and the yellow lamp by Q2.

2. Circuit Operation

It is possible to use the load profile analyzer in any one of three modes.

- Continuous Mode. The load at each sensor is read 120 times/sec. Any change in the load patterns may be observed instantly.

- Accumulate Mode. The load at each sensor is read continuously and the highest load reading obtained during the reading period is shown and retained on the display units.

- Hold Mode. The position is similar to the accumulate position except that load readings are obtained only when the hold button is depressed. Its primary purpose is to freeze the readings shown in either the continuous or accumulate modes for study or data recordings.

- <u>Clear Mode</u>. This position effectively erases all readings from the display units to allow the next readings to be taken. In operation, the unit can be switched from one mode to another if desired without using the clear button.

The schematic of the time control circuit is shown in Figure 21. The control box contains four illuminated push buttons to operate three relays located in the lower portion of the rear torso display console.

A lamp is located in each push button. Only the button that was last operated will be illuminated. The buttons are also color-coded, green for continuous, orange for accumulate, red for hold and white for clear. This enables the operator and observers to determine the mode of operation at a glance.

Silicon controlled rectifiers are used in the circuit to negate the effects of sensor contact resistance and also to provide a means of retaining the sensor readings in the display console.

An SCR is analogous to a relay with a built in holding contact. Once the gate signal starts conduction in an SCR, the conduction will continue until the anode voltage on the SCR drops to zero, regardless of whether a gate signal is present.

If a pure dc voltage or a dc voltage with a ripple that does not cause it to drop to zero is on the SCR anode, the SCR will conduct until that voltage is removed. When either the hold or accumulate modes of operation are chosen, the printed circuit cards are connected to the regulated filtered dc power supply.

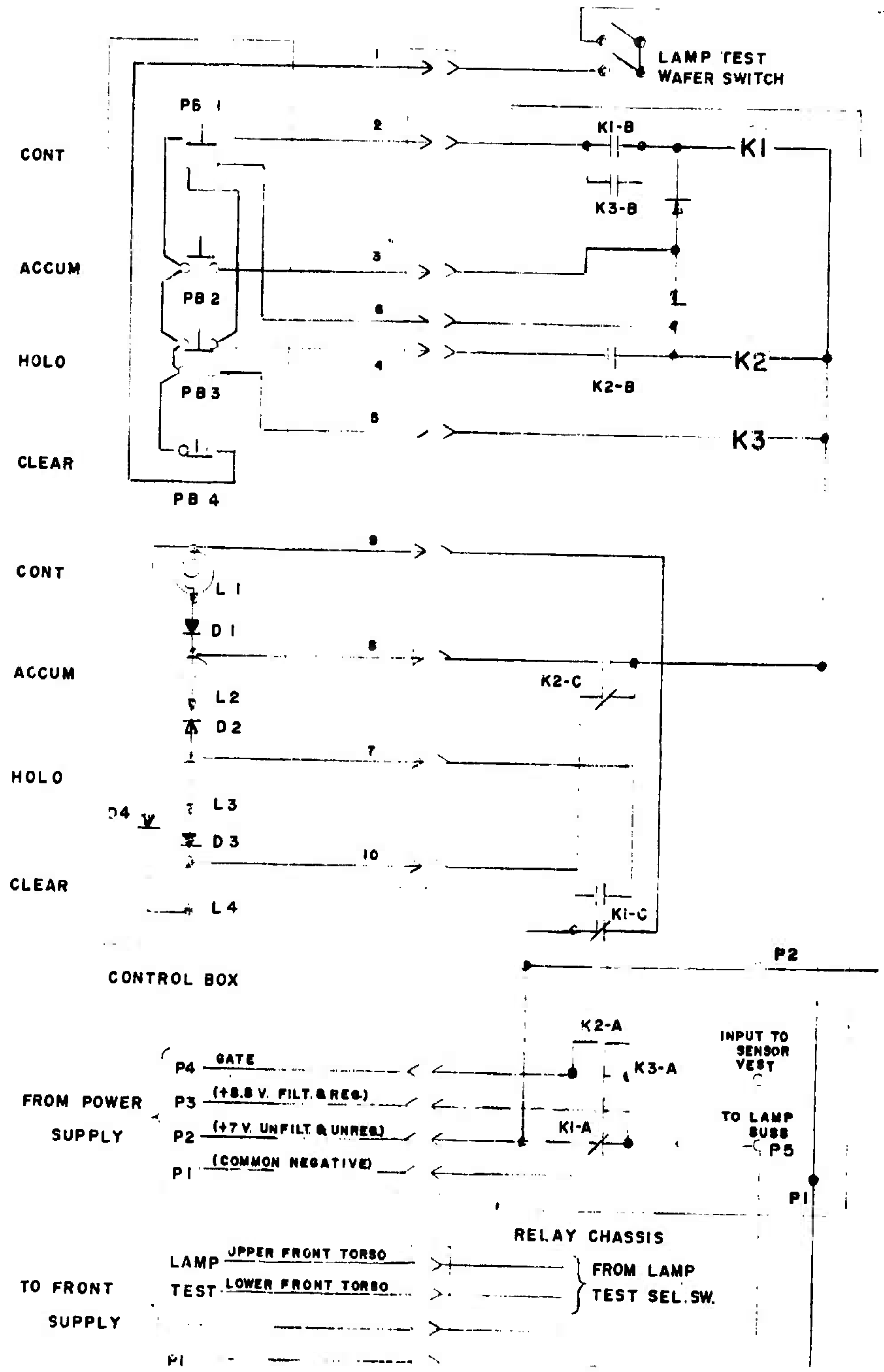


Figure 21 - Control Circuit Diagram

If 60 cycle ac is rectified into full wave dc and is connected to the SCR anode, the SCR will shut off at the end of each wave (120 times/sec) and will only start conduction when a signal is present on the gate. This unregulated unfiltered type power is used to supply the printed circuit cards when the continuous mode is selected.

a. Modes of Operation

- Continuous Mode. Relay K2 energized and holding (K2B N.O. contact). Unfiltered unregulated dc voltage is fed to lamp circuit (K1A N.C. contact). Regulated filtered dc voltage is fed to sensor vest (K2A N.O. contact). Lamp L1 is on (K1C and K2C N.O. contacts).

- Accumulate Mode. Relays K1 and K2 energized and holding (K1B and K2B N.O. contacts). Filtered regulated dc voltage is fed to lamp circuit (K1A N.O. contact). Filtered regulated dc voltage is fed to sensor vest (K2A N.O. contact). Lamp L2 is on (K1C and K2C N.O. contacts).

- Hold. Relay K1 energized and holding (K1B N.O. contact). Relay K3 energized only while hold button is depressed. Filtered and regulated voltage is fed to lamp circuit (K1A N.O. contact). Filtered and regulated voltage is fed to sensor vest (K3A N.O. contact). Lamp L3 is on (K1C N.O. contact - K2C N.C. contact).

- Clear. All relays open. No power to lamps or sensor vest. Lamp L4 is on (K1C and K2C N.C. contacts).

Note: the four diodes in the control box lamp circuits are used to eliminate extra relay contacts and three extra lines in the control cable. Diodes D5 and D6 are used to allow a single push button contact PB2 to operate relays K1 and K2 together eliminating the need for a fourth relay.

b. Lamp Test Circuit

A rotary switch on the back of the rear torso display unit allows all lamps in the display to be checked. The switch has 13 positions. The first is for normal operation of the system and the remaining positions test separately the green, yellow, and red lamps of the upper front, lower front, upper rear, and lower rear sections of the display. This is done by feeding three different voltages from the lamp test switch (Figure 22) through the lamp test bus lines shown leading to diode D5 in the basic sensor circuit (Figure 18). The diode is necessary to provide isolation when the sensor vest is in use. These voltages are applied to one card rack at a time (to prevent unnecessary heating of the power supply). The method of mounting these isolation diodes is shown in Figure 22. The three voltages used to perform the lamp test are obtained from resistors Rg and Ry (Figure 22).

3. Power Supply

The power supply module consists of two basic power supplies (Figure 23). The first is a commercial unit manufactured by the Wanlass Electric Company. It is their type 120-OEM-1 which is regulated, filtered, and adjusted for 6.8 v dc output (Figure 24). This supply furnishes the common voltage input to the sensor vest and must be regulated to enable the gate resistor networks to properly discriminate the signals from the sensors. It is also used to provide power for the lamps when the accumulate or hold modes are used.

The second part of the power supply consists of a transformer and a diode bridge which furnishes about 7 v dc of power that is unregulated and unfiltered. This supply furnishes power to the lamps in the display when in the continuous or clear mode. It also powers the relays and the pushbutton lamps in the control circuit.

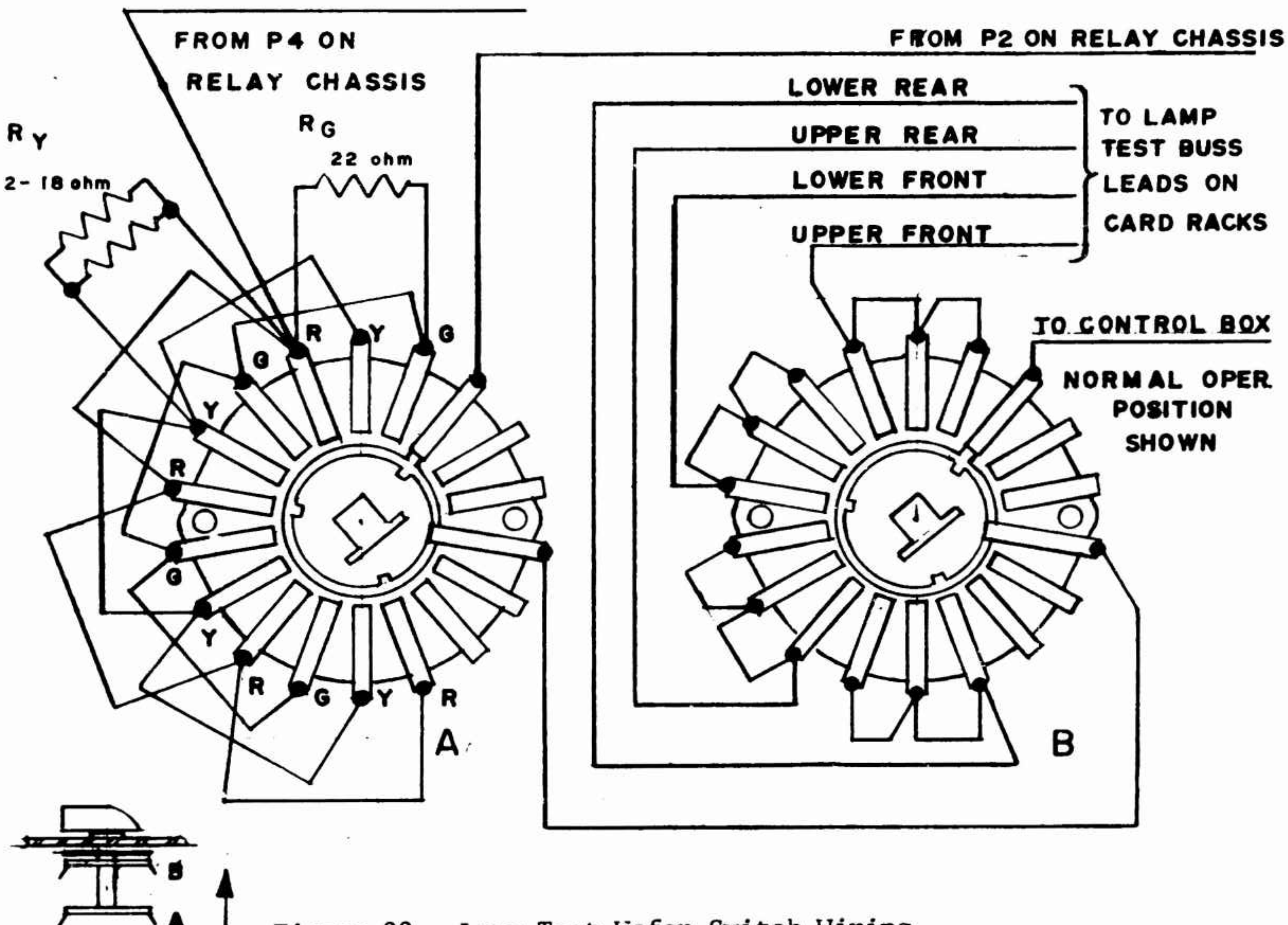


Figure 22 - Lamp Test Wafer Switch Wiring

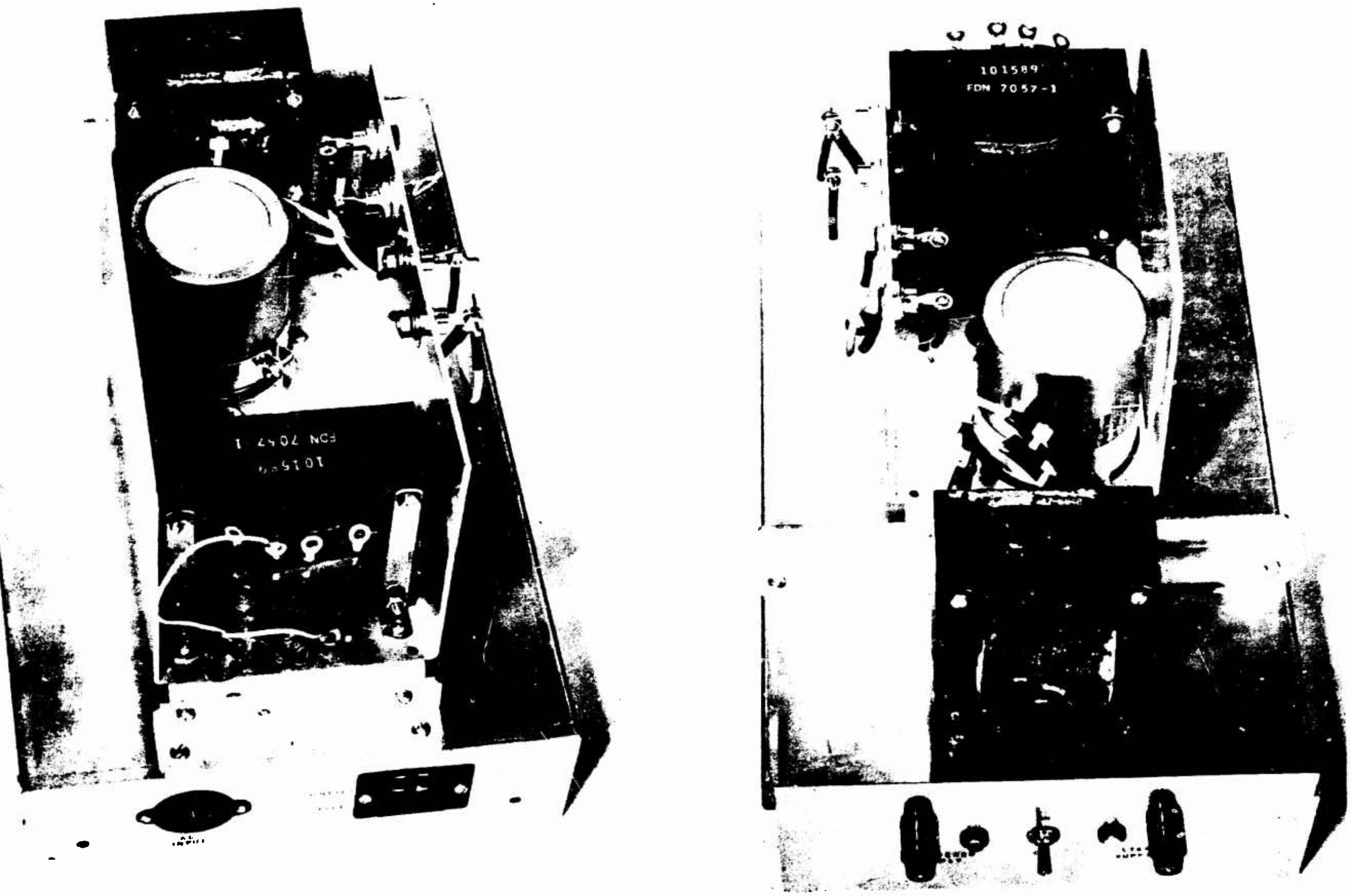


Figure 23 - The Power Supply Module

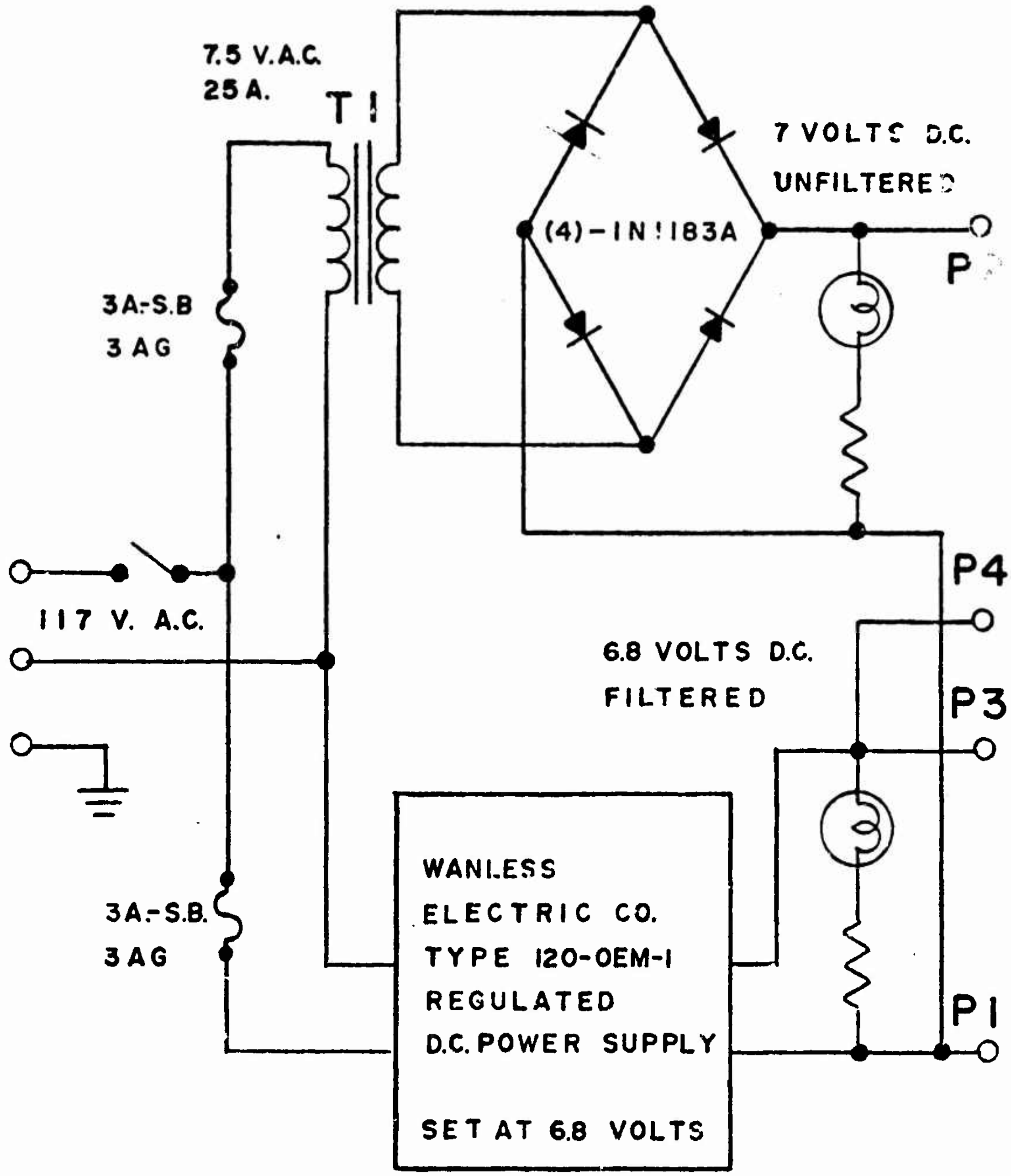


Figure 24 - Power Supply

PART III. LABORATORY TESTS AND LOAD BEARING EQUIPMENT EVALUATION

A. TEST ITEMS AND PROCEDURES

The full-scale anatomical load distribution analyzer system was functionally tested using six personnel protective armor or load bearing systems and one load carrying system as test items. They may be described as follows:

1. Experimental, infantry body armor, fragmentation protective 3/4 collar vest, lightweight, water repellent nylon 128, size medium (weight 6 lb, 8 oz).

2. Experimental, aircrew body armor, spall, fragment, small arms protective vest with front and back armor plates, size medium (weight 28 lb, 4 oz).

3. Experimental, aircrew body armor, spall, fragment, small arms protective vest with front plate and nomex raschel weave back unit, size medium.

4. Experimental, infantry body armor, fragmentation protective 3/4 collar vest, lightweight, XP, size medium (weight 6 lb, 4 oz).

5. Experimental, aircrew body armor, raschel knit, tension web suspension vest (Ref. 4) with anatomical front and back plates (weight 32 lb) (Ref. 5).

6. Experimental, aircrew body armor, raschel knit, tension web suspension vest with anatomical front and back plates with experimental waist augmentation belt (weight 58 lb, 5 oz) (Ref. 4).

7. Standard rucksack carrier with standard load carrying equipment (weight 58 lb).

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Two test participants were used to evaluate each of the six test items, based on the medium range of anthropometric dimensions for chest circumference, chest breadth, and torso length. One test participant could be classified as fleshy while the other was in the slender but muscular category. Test participant No. 1 had a chest circumference of 32 in. and that of test participant No. 2 was 34 in.

Each test parti pant wore test items 1 through 7 over the load sensing tment. They were asked to negotiate through the following chomotor tests:

1. Standing er
2. S ated erec
3. Seated leaning forward
4. Head movement, vertical to dorsal
5. Arm overlap
6. Finger touching

The tests were performed in the order listed above and were required as test movements under the program. In addition to these required movements, IITRI performed the following psychomotor tests:

7. Shoulder flexion
8. Shoulder abduction
9. Figure eight, duck
10. Combat crawl

A "goniometer" supplied by NLABS was used to measure angular movement of the head, limbs, and torso (Figure 25). These data were recorded on IBM data cards used to document the load distribution and magnitude information collected from a particular test movement. Sample data cards are presented in the following sections of this report and as a separate submission which includes data cards for each psychomotor test movement (total of nine) for each test item (total of seven) for each test participant (total of two). In many cases, tests were repeated to verify questionable data or to check the repeatability characteristics of the full anatomical load distribution analyzer. Evaluation of the device was the purpose of the above testing procedure

Figure 25 - Goniometer, Head Flexion Test

and not the evaluation of load carrying or suspension systems. However, from the data collected it is possible to evaluate and make comparisons between different systems. Because of the limited test program, and limited data collected with a prototype instrument, it is not recommended that such data be considered as conclusive.

B. DATA RECORDING, INTERPRETATION, AND APPLICATION

1. Data Recording

Data recording was accomplished on specially printed IBM cards which depicted sensor location on the torso garment. A separate card was used for the front and rear torso sensor array (Figures 6 and 26) for each test item and test movement.

The data cards are coded to permit identification of a particular test sequence. The data cards are printed with a test number and blank space in the upper right hand corner of each card. A sequence of three numbers are recorded in this space and their significance may be defined as follows (Figure 26):

SAMPLE

Test No. $\underset{A}{1} - \underset{B}{1} - \underset{C}{1}$

A = The number of the item (load carrying or suspension system) being tested (see listing in Part III, Subsection A).

B = The number of the psychomotor test being negotiated by the test subject (see Part III, Subsection A).

C = The number of the test subject involved in the evaluation (only two subjects were used in our test series).

Therefore, the above test number indicates that test participant No. 1 wore armor system No. 1 listed as "infantry fragmentation vest" and negotiated psychomotor test No. 1, listed as "standing erect." The notation

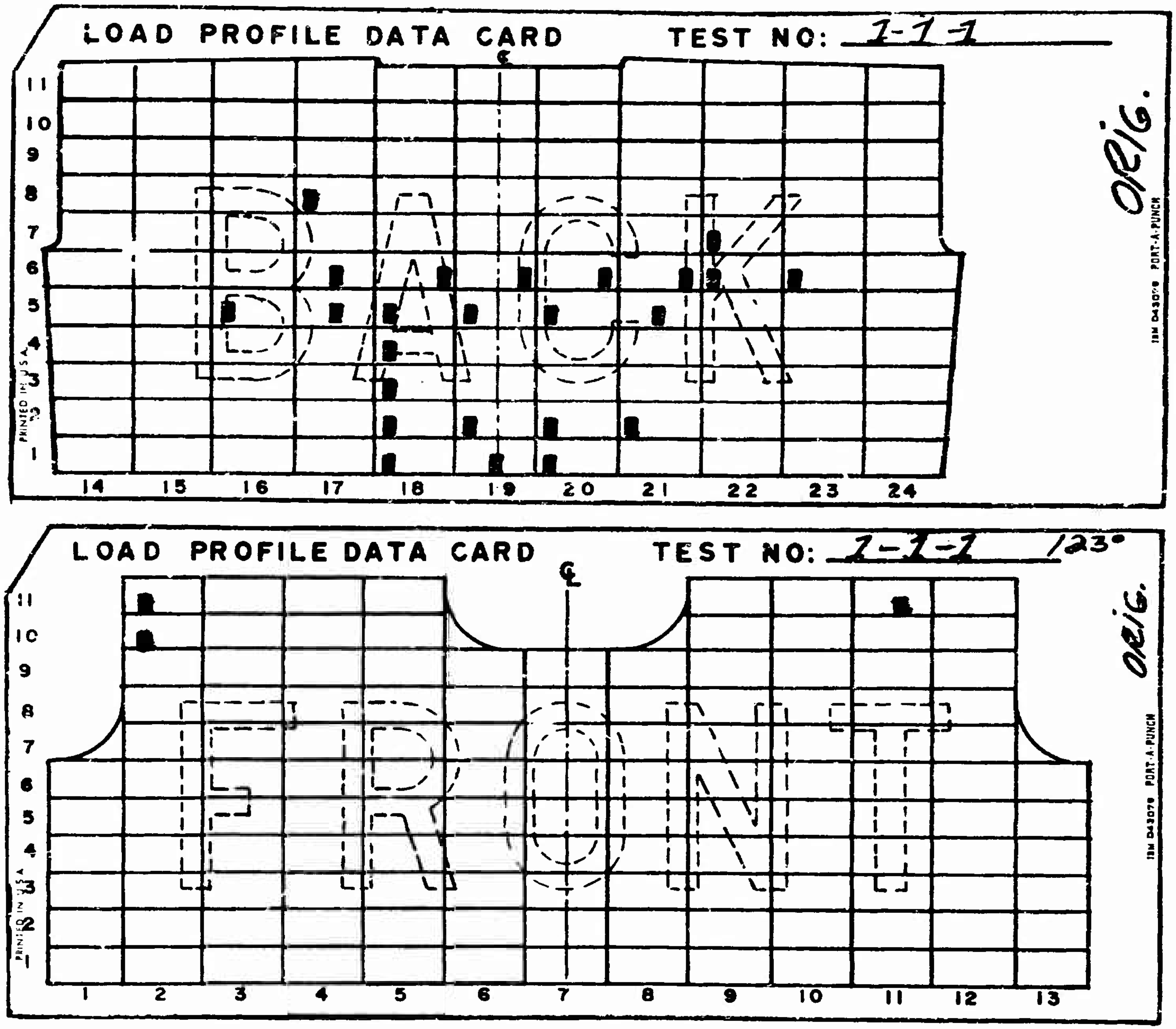

Figure 26 - IBM Cards for Sensor Data Recording

"orig" or no marking on the right-hand border of the card implies that this was the first test run (Figure 26). Where the work "repeat" and a number appears on other test cards, this indicates that the test was repeated the number of times indicated by the number. For example, "repeat 3" means the same test series was repeated three times and this is the third data card.

Angular designations on the card indicate readings taken from the goniometer for a particular test movement as defined in the psychomotor test description. Numerical designations are linear measurements taken during a specific test movement to indicate the degree of restriction or reduction in the articulation range induced by the wearing of protective clothing.

The data cards have three perforated vertical slots in each sensor position rectangle which may be punched to indicate load range, as described in earlier sections of this report (Part I, Subsection C). The "front" and "back" data cards shown in Figure 26 have been punched to record the load distribution and magnitude information presented on the full anatomical display on completion of the test sequence.

2. Data Interpretation

The data card format depicts the anatomical location of each sensor on the torso with the centerline of the torso clearly marked on the "front" and "back" data cards. This system permits a data card to be scanned by an investigator to instantly discern where loads are being distributed on the torso and their relative magnitude. It is therefore possible to rapidly define areas of high load concentration, uniform load distribution, or no load distribution. The investigator may also observe the shifting of these load patterns with movement.

The data cards in Figure 26 indicate that in a "standing position" the "lightweight fragmentation vest" weight is primarily distributed over the middle back area beginning slightly above the scapular bones and extending down to the waist. The loads shown are fairly evenly distributed and of low magnitude (green and yellow lights, indicating loads of 1/2 lb and over, or 1 lb and over). The "front" data card indicates that some load is distributed on the shoulder areas with no loads on the front torso area.

The data interpretation technique just described is used to analyze each data card and can be used to study shifts in load patterns with articulation for a specific load bearing system or to make comparisons in load distribution on the torso for different armor systems. Comparisons can also be made between various suspensions with dramatic results presented by use of the waist augmentation weight transfer distribution belt developed by IITRI for NLABS on an earlier program (Ref. 4). This unique suspension transferred load from the shoulders and torso to the hips as indicated by the data cards coded as test series, item 6.

3. Data Application

Data gathered on a particular load carrying or armor system can be studied and analyzed to interpret whether loads are being optimally distributed on the torso. The data will also indicate high load concentrations or load distribution on particularly sensitive areas of the torso as defined by these areas, even relatively light loads will eventually induce pain (Ref. 1).

The data collected may then be used as the basis for improving existing or experimental load carrying or protective armor systems. Improvements in comfort, endurance, and tolerance to loads are extremely important in wearer acceptance of personnel protective equipment.

C. ARMOR SYSTEMS EVALUATION

The data collected on six personnel armor systems and one fully equipped rucksack carrier permitted a comparison to be made between systems related to load and magnitude on the torso in static and dynamic modes.

The comparative evaluation of the seven armor systems was conducted by visually analyzing the data cards for a specific armor system, test subject, and test position by comparing the load magnitudes and distribution on the anterior and posterior areas of the torso. Changes in these parameters with articulation (other test positions), different test subjects and armor suspension were also visually compared, forming the basis for the evaluations which follow. The conclusions drawn are subjective based upon the experience of IITRI personnel. A more objective analytical approach should be taken in future studies. However, for the scope of the program, the conclusions derived provide an acceptable evaluation of the seven systems.

It must be emphasized that the full-scale anatomical load distribution analyzer was able to provide information related to induced loads and their transference to the torso by the various personnel armor and load carrying systems but that the interpretation of this data is not necessarily conclusive when comparing systems. A true evaluation should be conducted using a broad range of test subjects and a physiologist to plan, conduct and evaluate the results.

The evaluation and comparison of test items may be summarized as follows.

1. Test Items 1 and 4

Test Item 1, the lightweight nylon fragmentation vest, distributes loads primarily on the back with some minimal loads being absorbed by the shoulders. There are no loads on the chest except during articulation where some minor loads appear. The barrel shape of the vest causes it to stand away from the chest. These comments also apply to Item 4, the lightweight "XP" fragmentation vest. However, since this vest is stiffer by virtue of the "XP" material as compared to fabric, greater loads are induced on the spine when bending forward as compared to Item 1.

Both vests distribute loads uniformly on the body and in good load bearing areas. The nylon vest permits increased mobility as indicated by the "reach" measurements, but comfort appeared to be the same for both vests. Test results could not discern comfort levels between the two items since load distribution and load magnitude were similar. However, the stiffness of the"XP" vest was reflected in reduced mobility during dynamic movement which could cause discomfort during extensive wearing periods. Wearer endurance was not included in our evaluation.

2. Test Items 2, 3, and 5

A comparison between these test items can be made since they used combinations of rigid plates. Test Items 2 and 5 used front and back plates; Test Item 3 used just a front plate.

A simple carrier was used in Test Item 2 to support and position the armor plates on the torso. The data indicated the bulk of the loads to be carried on the back and shoulders in the standing position. Bending at the waist increased loads on the back and abdomen of the wearer with reduced loads on the shoulders. This was also true for reaching or cross-arm movements.

Test Item 3 with front plate only and raschel knit back, transferred armor loads primarily to the shoulders with some loads carried through the reinforcing webbing used to control the stretch of the raschel knit back. The force in this webbing was depicted on the light display card caused serious discomfort in a relatively short period of time. The device indicated that this reinforcing webbing should be removed or redesigned.

The tension web suspension developed by IITRI under a contract with NLABS distributed loads well and reduced load magnitudes on the torso as indicated by the data cards for this test item (Ref. 4). However, it was not possible to establish whether this item was superior to Item 2 without raschel knit.

3. Test Item 6 Compared to Items 5, 3, and 2

The waist augmentation belt's effectiveness was dramatically demonstrated by use of the test device. Load transference off the shoulders and to the waist when activating the waist augmentation belt was shown by the shifting load pattern indicated by the display lights. Test Item 6 is only compatible with Test Item 5 but it may be presumed that its effectiveness with Test Items 3 and 2 would be equally dramatic if properly designed to integrate into these suspensions.

4. Test Item 7

The rucksack carrier was tested cautiously because of possible damage to the sensor vest. It weighed 58-1/2 lb, fully loaded with water in the canteen. Sensor loadings were high as might be expected and were transmitted through the rucksack carrier suspension system as indicated by the light patterns on the display. Surprisingly enough, some green lights were in the loading pattern indicating good load distribution with moderate loads in these areas. In total, however, most loads were in the red light or high load range, resulting in discomfort and fatigue in a relatively short period of time (Ref. 6). A fair comparison between Test Item 7 and the previous test items could not be made because of the basic difference in design and total distributed weight.

PART IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The full-scale anatomical load distribution analyzer has demonstrated the feasibility of measuring, displaying and recording loads transmitted to the surface of the body by force inducing systems such as protective clothing, personnel armor or load carrying systems.

This capability opens up and permits the evaluation of past, current, and future designs eliminating dependence solely on the user's subjective reports regarding personnel systems and permitting an objective evaluation based on analytical data.

The purpose of this program was to design, develop, and fabricate a full-scale anatomical load distribution analyzer. Preceding this program, such a device was non-existent. It was necessary to develop sensors which could be integrated into a garment and worn on the body. A technique had to be devised to display, record and interpret large quantities of data provided by the device. All of these goals were accomplished with varying degrees of success. Since it was a first "prototype" device, certain areas could be improved in future designs.

The evaluation conducted was primarily to test device function and performance. The following conclusions are based on the evaluation results:

- The anatomical load distribution analyzer demonstrated the potential of being a valuable research instrument in evaluating and improving personnel protective equipment, clothing and load carrying systems.

- The anatomical load distribution analyzer front and rear torso manikins provide a clear, concise and rapid interpretation of load distribution and magnitude and shifting load patterns with test subject articulation for a particular test item. The concept of "sampling loads" using a step type sensor has the distinct advantages of: (1) simplicity of sensor design; (2) elimination of the need to recalibrate each sensor before conducting a test sequence; (3) special signal conditioning equipment is not necessary; and (4) generation of digital data which can be easily presented visually and/or stored for manual or automatic data recording.

The entire system is transportable, easy to operate, and may be serviced by technician type personnel.

Sensor vest durability can be improved in future models by redesigning the sensor vest interconnecting wiring system. The printed circuit mylar tape concept had to be replaced by point-to-point wiring using stranded wire; however, the concept could be made more durable through the application of advanced technology in this field.

B. RECOMMENDATIONS

Automate the output, obtaining continuous readings from each sensor. Recording on punch cards for magnetic tape for computer programming would significantly accelerate the laborious process of data collection. The manual technique currently used is subject to human error and is tedious and time-consuming.

Sensor versatility should be expanded through the addition of extra load ranges to include a system which transfers greater loads to the torso (such as the rucksack carrier). A sensor with a 15 to 20 lb upper load limit may be desirable.

Conduct studies to determine what the output of the sensors (force loads) means in terms of human performance and comfort.

The application of special load sensing garments or sensor arrays appropriate to other parts of the human anatomy (such as the head, neck, legs, hands, buttocks or parts of the torso in contact with restraint systems) should be considered with the eventual development of dynamic load sensing concepts which will permit rapid analysis of the following:

1. Effects of vibration
2. Vehicle crash impact studies
3. Helmet shapes, sizing and suspensions
4. Aircraft and automotive seat restraint systems
5. Athletic equipment for all contact sports
6. Prosthetic and orthopedic devices
7. Body support garments (braces, girdles, etc.)
8. Seat shapes and materials
9. Footwe[illegible]d footwear fitting
10. Parac[illegible] harnesses
11. Effects of clothing and equipment (weight, bulk, rigidity, design) on human performance
12. Load carrying systems
13. Pressure suits

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