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ABSTRACT

An independent engineering evaluation was conducted of the Optical to Tactile Converter (Optacon), a reading aid for the blind which senses the contrast of printed text and converts the information into a tactile presentation. Tasks performed included: user evaluation, optical, electrical, mechanical, production costs, life tests, reliability, and field trips. The study concludes that the Optacon is a viable tool for motivated individuals with unimpaired tactile capabilities and is basically sound in its design. Recommendations for improvements were made. (EMH)

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Technical

Report

Final Report
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ENGINEERING EVALUATION OF THE OPTACON

(OPtical to TActile CONverter)

By

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September 1973

Prepared for

Department of Health, Education and Welfare
Office of Education
Contracts and Grants Division
400 Maryland Ave., S.W. Room 1077
Washington, D.C. 20202

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THE FRANKLIN INSTITUTE RESEARCH LABORATORIES
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Harry Bassler:	Computer Programmer Colonial Penn
Charles Groom:	X-ray Developer Frankford Arsenal
John Falter:	Computer Programmer Univac
Charles Morgenstern:	Computer Programmer Mack Truck
Theodore Young:	Manager, Bureau of Visually Handicapped State of Pennsylvania
Stephanie Conrad:	Student Albright College
Richard Snipas:	Computer Programmer Bradford Computer & Systems
Bernice Reilly:	Psychiatrist Phila. General Hospital
William Kennedy:	Systems Analyst National Forge

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Martha Osborne:	Braille Teacher Overbrook School for the Blind
John Covici:	Computer Programmer Information Engineering
Steve Dubin:	Salesman Not currently employed

In addition, Mr. Harry Bassler, President of SIGCAPH made Optacons available to fourteen other potential users during the summer months when Overbrook and Logan schools were not using the equipment. Antionette Whaley, Secretary of SIGCAPH made a comprehensive Optacon report available for this evaluation. Gale W. Lutz (San Diego City Schools) kindly submitted his manuals and "Optacon Project" reports for consideration. Psychologist, Dr. Maryanne Sullivan, Programs Director of the Tactile Vision Substitution System at Overbrook was very instrumental in the development of our user questionnaires and very helpful in diagnosing potential classroom problems.

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User Evaluation	- E. J. Dougherty
Optical Evaluation	- J. W. Woestman
Electrical Evaluation	- Dr. S. T. Fisher
Mechanical Evaluation	- B. F. Shelley
Production Cost	- D. F. DeCleene
Laboratory Life Test	- B. K. Thron
Reliability Evaluation	- R. C. Pitman

Miss Mary Hargens demonstrated the Optacon to the staff of Childrens Hospital in Philadelphia on behalf of FIRL. Visitors to FIRL for the purposes of becomming acquainted with the Optacon included Theresa Demanop, Jane Hill, Marcia Bhatti and J. A. Leitch of the Overbrook Alumni Association.

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ABSTRACT

The Franklin Institute Research Laboratories (FIRL) conducted an engineering evaluation of the Optacon (OPtical to TActile CONverter), a a reading aid for the blind which senses the contrast of printed text with a hand (right) held camera and converts the information to a one to one tactile presentation via a 6 x 24 array of tiny piezoelectric reeds monitored by the left index finger. The study was conducted for the Office of Education, Department of Health, Education and Welfare under contract number OEC-0-72-5181. Tasks performed included: user evaluation, optical, electrical, mechanical, production costs, life test, reliability and field trips (to support a parallel education evaluation conducted by the American Institutes for Research and to gain hum factor use data). This study concludes that the Optacon is a viable tool for motivated individuals with unimpaired tactile capabilities and is basically sound in its design. A host of recommendations are presented for optimization of future generations. Future research should be directed at freeing one hand for holding material to be read, elimination of noise generated by the bimorph stimulators and conversion of the output to Grade 1 Braille.

SUMMARY

This report is the culmination of a fifteen month study designed to evaluate the Optacon from an engineering point of view. Tasks were divided into a user study, an optical evaluation, electrical evaluation, mechanical evaluation (including affects of environmental parameter's), a production cost study, reliability calculations, laboratory life tests and periodic field trips to monitor equipment status used in an education evaluation conducted by the American Institutes for Research. The field trips also offered an opportunity to gain valuable insights from students, teachers, administrators and the facilities available for the project.

Key personnel reviewed Stanford University's (developers of the Optacon) progress reports and publications and then visited Telesensory Systems Incorporated (manufacturer of the Optacon) for a comprehensive tour of their facilities and detailed discussions which were aimed at making FIRL aware of experiences gained by the manufacturers which might prove germane to our studies. Close rapport was maintained with the education evaluators to generate forms and questionnaires which would yield data useful to both studies.

Teams of personnel were organized for specific studies under the direction and coordination of the principal investigator. The Optacon itself received most attention because the peripheral equipment is used for training purposes only. The following is a brief summary of the methodology employed and the results generated by each team.

USER STUDY: Data was generated by the students, teachers and administrators at the 14 education evaluation sites around the country as well as from approximately 40 blind adult volunteers recruited by FIRL. This task force integrated this data with their experiences gained through the conducting of the study, on site observations and their professional

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backgrounds. Major problems noted included the fact that the Optacon requires two hands for operation (therefore, anything that has to be held cannot be read), the camera and camera cable are difficult to store and are subject to damage, the Optacon is a right handed instrument and the noise generated by the bimorph stimulators is objectable. In addition, a potential user must be motivated to learn the techniques, must have unimpaired tactile abilities and must have significant resources available for both the equipment and training. A host of suggestions for improvements in controls and carrying case designs are presented in detail in Section 2. Future research should be aimed at a one hand model (would not only free one hand but would eliminate problems of left handed users), alternate methods of tactile presentation (to eliminate noise, or possibly minimize it with lower frequencies) and the advisability of multiple finger reading. The Optacon was almost unanimously judged by the users to be a system useful to them in their daily lives. Requiring them to return Optacons they borrowed for their evaluation was not a pleasant task.

OPTICAL EVALUATION: This study looked at each element of the camera individually and at its function in the overall system. Emphasis was placed on environmental affects, maintainability, reliability and cost factors. Overall, the optical system is considered well designed. Recommendations include suggestions for easier assembly and maintainence (See Section 3). In addition, the scanning head is not properly keyed to avoid improper connection. This problem is easily alleviated by relocating a slot on the mating connector.

ELECTRICAL EVALUATION: A detailed study of the schematic diagrams was conducted to evaluate the soundness of design. Choice of components and fabrication techniques were evaluated and the circuit layout was studied. The Optacon was judged to be soundly designed. Some minor problems were noted. Recommendations included shockproof bimorph pins, better yields on retina chips and a field maintenance kit including extender cables. Other suggestions are aimed at reducing cost of manufacture and increasing reliability by better manufacturing techniques. (See

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Section 4). Future studies should be to develop a self scanned camera to minimize the number of wires required in the connecting cable and to reduce the voltage requirement and complexity of the bimorph array.

MECHANICAL EVALUATION: This study looked at the Optacon's ability to withstand normal use and anticipated misuse including expected environmental extreme conditions. Some specific notes are reported in Section 5 to eliminate nuisance repairs (stripped screws, bent pins, loose parts) and to enhance the capability of the components to withstand abuse. Environmental testing included negative pressure environment (simulated aircraft transportation), high and low temperature extremes including humidity control (storage in vehicles under extremes), temperature shock tests (quick changes), vibration tests and mechanical shock tests. The Optacon withstood all anticipated misuse extremes with no noticeable affects on performance.

PRODUCTION COSTS: This study addressed all phases of the production process with emphasis on cost saving techniques. It looked at each individual part and offered suggestions to reduce cost and increase reliability by adjusting specifications and better material selection. Recommendations include the use of molded plastic parts, further design changes to minimize the number of parts and efforts to increase production rates. See Section 6 for details.

LABORATORY LIFE TESTS: Four Optacons, four Visual Displays and one Casette Trainer were subjected to life tests designed to simulate extended usage and to exercise all subsystems in a realistic manner. Daily tests were conducted to pinpoint failures. Some minor nuisance failures are noted in Section 7. Battery failure was frequently noted but subsequent calculations proved the battery to have a very acceptable life time. Users should be cautioned that extended shelf storage will deplete the battery voltage but that state does not indicate failure as the batteries readily respond to recharging.

RELIABILITY: This study consisted of an experimental determination of the mean-time-between-failure (MTBF) of the Optacon, Visual Display and

Casette Trainer. Lack of failures in the lab life tests made meaningful calculations difficult. Contradictory information from field tests (numerous failures) indicated a poor MTBF (41 hours). It is conjectured that equipment use reporting was not complete. Therefore, the results of this study (Section 8) has to be considered to be a first approximation to "reliable" reliability data. Further data inputs will tend to maximize confidence in the results.

FIELD TRIPS: FIRL personnel visited all field sites (14) at the beginning, at the midpoint and at the conclusion of the education evaluation. These trips were made to ensure that equipment was operating properly. It also afforded FIRL scientists the opportunity to interview and observe program participants and their facilities. This information was extremely valuable in making all the subtasks more meaningful. (See Section 9).

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I. INTRODUCTION

The Franklin Institute Research Laboratories (FIRL), under contract No. OEC-0-72-5181, has conducted an engineering evaluation of a reading aid for the blind called the Optacon, a name taken from its functional description as an OPtical to TActile CONverter. The systems employs a hand guided camera which is capable of sensing printed text (typical typing). The camera employs a photo array and transmits the information over a flexible cable to an electronics processing package (about the size of a tape recorder) which is either battery or AC operated. The information, in the form of the printed text, is presented to the user via a 6 x 24 array of piezoelectric reeds which he monitors with the distal phalanges of his left index finger. Equipment includes a camera tracking aid for beginners, Visual Display for teaching purposes and a Cassette Trainer for presenting lesson material. The study was conducted for the Department of Health Education and Welfare's (DHEW) Office of Education (OE). OE also supported Stanford University's basic developmental research in reading aids for the blind which resulted in the Optacon (Grant No. 0-8-071112-2995 [607]). Telesensory Systems Incorporated (TSI) is currently manufacturing the devices to make them available to the public. In addition to our engineering study, the American Institutes for Research (AIR) conducted a parallel human factors evaluation and training program by enlisting the aid of fourteen schools around the country. This report is the result of a cooperative effort with TSI, AIR and OE. TSI manufactured all equipment, distributed it to the schools, conducted follow-up seminars, performed all maintenance, supplied all technical support data and cooperated in every manner. AIR selected school sites, developed training manuals, trained teachers on site and evaluated results. AIR also worked closely with FIRL in gathering reliability data and solving problems as they developed. Our study of the Optacon and its support equipment included a user study, an optical evaluation, electrical evaluation, mechanical evaluation, study of production costs, laboratory life tests, development of reliability data and periodic field trips to the fourteen field sites to ensure that the equipment was operating properly. Emphasis of our study was placed on reducing the cost of the Optacon and increasing its reliability, usability and maintainability.

This report is designed to present detailed information on the procedures used by each team of evaluators, their results and their recommendations. There exists some overlapping of effort between groups because problems are related. Each section concludes with a "Summary of Recommendations" for those readers interested in specific conclusions of individual teams. The overall summary suffices for those readers interested in general conclusions.

2. USER EVALUATION

2.1 STUDY RATIONALE

FIRL conducted a thorough human factors systems analysis of the Optacon and the user context. This analysis involved the user/control interface as well as safety and what might be termed "first echelon maintenance." In addition, operational effectiveness and versatility is reported upon.

These analyses were conducted with the aid of approximately forty blind users, both adult and school age. These people were recruited by FIRL for the purposes of this evaluation. In general they did not receive formal training on the use of the Optacon. Their special insights in respect to general handling and use of the unit proved most useful.

In addition, the blind children, teachers and school administrators who participated in the Office of Education's Education Evaluation (conducted by the American Institutes for Research) were interviewed by FIRL. The interviewers were guided by, although not restricted to, the questionnaire outlines developed for that specific purpose. The blind adults in the FIRL study were loaned Optacons. In most cases, they did receive lessons on the Optacon from those who had training. It was not the intent of this study to monitor reading prowess; however, general information in that regard was of interest. A written report containing comments on the soundness of design, safety, maintainability and other pertinent observations were requested of each user. In most cases, the blind adults were technically oriented (computer programming, engineering, short wave radio operation, etc.) and therefore were accustomed to handling and evaluating electronic equipment. The two "non-technical" evaluators provided invaluable information from different standpoints; one of the evaluators was a Braille instructor, the other a recently blinded salesman.

Virtually all evaluators concluded that the Optacon is a viable tool which opens many avenues for the blind. Their comments for improvement are summarized in the following text.

Finally, FIRL staff contributed many suggestions and observations as a result of experiences gained through their involvement with this project.

2.2 OVERALL DESIGN AND USER CONTEXT

This analysis was concerned specifically with the user/instrument interface. In regard to convenience and ease of operation, we first looked at the control knobs (threshold, intensity). The control knobs are located on the front right hand side of the Optacon. This placement permits the user to adjust the controls with the thumb of the left hand, allowing the reading finger (left index) to remain on the vibrator array to "observe" the effects of control adjustment. This method also frees the right hand for camera operation (scanning print, etc.). In essence, this creates a human closed loop control system which allows the individual Optacon user to act and react to the reading situation at hand.

Most users have no complaints about control knob location, although some find their thumb's position awkward and fatiguing. The size of the user's hand is probably a factor in determining comfort and efficiency in this case, as it is for many of the other minor operational problems. One of the most common complaints was that the Optacon user could mistakenly bump one or both of the control knobs with the thumb. This problem was considered an annoyance, but many believed that the fault was in the inexperience of the user and not the machine design.

Extending the range of the intensity control was suggested by two students, but most felt the range and sensitivity of this control was sufficient.

The range of the threshold control drew no complaints, although the sensitivity was considered by some as "too touchy." This problem would be solved by replacing the single turn threshold potentiometer with a multiturn potentiometer of the same value. This modification would allow the same range of threshold adjustment, but would reduce the rate of threshold change with knob rotation. A multiturn adjustment knob, however, may remove a subtle feature of the existing Optacon noted by many of the Optacon readers. They suggest that if the reader has a variety of materials that are commonly read (i.e. newspapers, magazines, computer printouts), he may save adjustment time in jumping from one type to another if he remembers the position of the adjustment knobs for the particular material he intends to read (e.g. newspaper threshold ~1 o'clock, intensity ~12 o'clock). It has also been suggested that as an aid to this method, the manufacturer should place tactile indicator dots around the adjustment knobs and on the zoom slide, to help the reader accurately and quickly set the controls. Or perhaps, one could incorporate a step-wise adjusting system, that is; grooved steps for incremental changes instead of a smooth transition.

The majority opinion of those questioned was that the operation, resolution and placement of the vibrator array was good. Several felt the Optacon should come in both right handed and left handed models. Comments were made about insufficient resolution, a problem particularly noticeable with characters containing diagonal features. A few individuals suggested that the field of view presented by the vibrators was too confining. It was felt that the tracking task in particular and reading in general would be improved with the additional information a wider field of view would provide.

One individual suggested that the hand cavity on the Optacon be deepened for persons with hands too large to seat properly.

The cables for the visual display, the cassette trainer and the Optacon were too short. The problems created by the short cables were simple though numerous. The short AC cord from the Optacon could be used with an extension cord, but this would reduce the safety benefits of transforming the voltage (from 110 VAC to ~5 VDC) at the AC source. The short cable from the visual display to the Optacon created a space problem (Optacon reading material and visual display had to fit on a single desk) and an inconvenience to the teacher (the teacher was unable to set the visual displays together to provide an efficient view of all the students' work. The teacher had to scan the room, looking from one visual display to another.) The shortness of the master/slave cables and the cassette trainer cables forced the students to work in elbow bumping proximity.

The cable connectors for the visual display and the cassette trainer are difficult to connect (for the sighted teacher as well as the student). The connectors are "force fit," which means that the connection is maintained by friction and has no locking mechanism.

The camera cable tends to become tangled and twisted with use. This is an inconvenience to the user and a strain on the cable wiring. While storing the camera cable in the Optacon, the user must fold the cable and place it in the camera storage well while attaching the camera to its holder; this is a difficult task, and modifications should be made for simplification. TSI has recently studied a housing box for the camera which allows the cord to be wrapped around the box for storage.

The on-off switch and the invert switch drew no complaints and were judged convenient and easy to operate. The on-off switch for the visual display drew many comments from the Optacon teachers. The switch is prone to damage during transportation of the visual display. TSI has been replacing the damaged switches with a new "low-profile" version which will solve the problem.

The battery condition button is rarely used and, therefore, drew no significant comments or suggestions. The charge condition of the battery is indicated by changes in pitch of the vibrator buzz while the battery condition button is being operated.

The size and shape of the camera module was judged, nearly unanimously, as satisfactory. However, when asked if improvements could be made to the size and shape, nearly all those questioned answered "yes" and made specific comments. Many of the smaller children suggested that the size of the camera be reduced for easier handling. While a majority felt that holding the camera while reading was not fatiguing, most said the task was awkward and felt this was due to the shape of the camera. A difficulty relating to camera shape is the tendency of many to tilt the camera, resulting in the improper alignment of the characters on the vibrator display. The amount of difficulty encountered varies among users and is a function of the user's particular grip of the camera. This tilt tendency is the greatest among those who grip the camera fully on the cable end, the grip that is nurtured by use of the tracking aid, therefore learned early in training. Those who grip the camera between their thumb and middle finger have the least amount of difficulty. In order to reduce the awkwardness and difficulty in aligning the camera, a standard grip should be recommended for use early in Optacon training. The "thumb, middle finger" grip seems to be the most acceptable. This method also frees the first finger for operation of the zoom lens.

The retina module, as pointed out by one adult user, can be removed from the camera housing, reversed and replaced. The result of this operation is to invert (geometrically) the retina, causing the characters to be displayed upside down. This is a minor problem, and no actual damage is done. Keying the retina module so that it cannot be replaced incorrectly would be a minor modification.

The camera aperture is located about 1/2 inch from the top of the camera module. A few of the users commented that the camera should have tactile markings on it to indicate the location of the aperture. The manufacturer apparently believed that the user should be aware of the aperture, for he did engrave the camera to indicate the location, but the engraving either is not mentioned in the training or is too weak a tactile signal for the user. The most probable reason is the former and should be easily corrected for the future.

Difficulty has been expressed in reading near the binding in certain books, particularly paperbacks. Two types of problems have been mentioned by the users. In books with small margins, the characters nearest to the binding are often unreadable because the camera module is physically blocked and, therefore, unable to cover the characters. The second problem is the difficulty in keeping the camera coupled to the curved portion of the page which leads to the binding. This problem is usually an inconvenience because the characters nearest the binding can be read, but in these cases it is an inconvenience for every line of the book and will probably slow down the reading speed and certainly add a bit of frustration to the reading. Both of these problems are considered by FIRL as serious. Solutions are possible but would seem to require a major change in the camera's optical design, which would surely be more complex and, therefore, increase the manufacturer's cost. For the present, this situation must be regarded as a design limitation.

The camera's zoom adjustment, located on the far side parallel to the reading surface, is conveniently situated. It is also easily adjusted. The users realized that the zoom lens and the threshold adjustment were interactive but felt this was only a slight complication. A few readers bump the adjustment occasionally, but most have no difficulty in readjusting. Notched step-wise movement would alleviate this problem also. The range of the zoom is unsatisfactory to many. The complaints were usually that the users could not read larger type (book titles, labels, newspapers, etc.). An adapter to effectively increase the zoom range would be most welcome.

Although, in general, the leather carrying case rarely generated meaningful comments, a few important suggestions and comments were made. The carrying case should be designed to allow the Optacon to be protected from damage under all possible weather conditions. The present design does not satisfy this need.

The cover flap, when unbuttoned for Optacon use, falls towards the user and is an obstacle to free hand movement. Common field solutions are either to remove the carrying case or to fold the flap under the Optacon. Neither is a satisfactory solution. The former is not popular because the users feel that the carrying case provides protection for the costly instrument. In addition, the cycle of taking the case off and putting it on is both a difficult task and dangerous to the instrument. The common technique of removing the Optacon from its case is as follows. First, the cover must be unsnapped from the Optacon and all cables detached. Then a finger has to enter the back of the case and push out the Optacon, while the other hand must try to obtain a secure grip and then pull the Optacon from the case. The latter field solution is not ideal because it requires that the flap be folded under the Optacon, thus creating an unstable base. A suggested solution is to design the cover flap so that it could fold back and fasten on to the top of the Optacon. This would require fairly minor changes to the existing design.

The range of adjustment for the carrying case strap is said to be too small.

A pouch in order to carry the battery charger and other accessories would be a welcome modification to the carrying case design.

An important manufacturing criterion is the production of items so that the quality and characteristics of the individual items are closely matched. This relates to the Optacon in that a person who has learned and developed skills in reading while using a particular Optacon should be able to use that ability at the same level on other Optacons.

While most users, now and in the future, may have access to only one Optacon, the present program has allowed a situation to exist where several people have each used different Optacons. In general the manufacturer's quality control has been judged satisfactory. A person reading with one Optacon can read with another. The effects of the adjustments have approximately the same sensitivity and range. Many readers, however, did have a preference and felt that, while all the Optacons were satisfactory, some were better than others. The descriptive term used most often was "clearer." It is believed that this problem is due to a lack of quality control in the length of the vibrators. On many units the vibrators extend above the finger plate when no video is present. This produces "noise" in the vibrator's character display.

2.3 EXPOSURE TO HAZARD OR INSTRUMENT DAMAGE

2.3.1 Electrical Hazards

The general design was judged safe. The battery charger is such that the 110 V AC is converted to a lower voltage (≈5 V DC) at the AC source and, therefore, eliminates the higher voltage on the power line to the Optacon.

Plugging the charger into a 110 V wall socket is potentially hazardous. The hazard is greater than plugging in typical appliances (lamps, tape recorders, etc.) because of the large size of the plug-transformer (approximately a 2-inch cube).

Several users have received shocks from the Optacon. While these shocks were possibly not harmful (see Electrical Evaluation—Bimorph Stimulators), they certainly discouraged use of the Optacon.

2.3.2 Other Hazards

The Optacons are relatively free of sharp edges, rough spots or other potential hazards. Few areas have been found that may even be classified as fairly sharp or mildly rough, etc. The possibility of any type of injury is small and serious injury improbable.

2.3.3 Exposure to Instrument Damage

The Optacon's exposure to instrument damage, as far as the user is concerned, is mainly in handling (see Mechanical Evaluation and Optical Evaluation for comments on packaging). As in most instruments, there is a direct relationship between an item's possibility of damage and its handling time. The more an item is used and handled, the greater the possibility of damage. In the Optacon the most handled item is also, unfortunately, one of the most delicate; this is the camera. The camera is very light and about 3" X 1/2" X 1/2"; it is attached to a cable feeding into the main Optacon housing. The users have often dropped or bumped the camera (often the camera needs repair after such a bump or drop) and are likely to continue to do so in the future. The situation is not ideal. In normal operation both hands are occupied. The left hand is constrained somewhat, resting on the vibrator array; the right hand is continuously moving the camera. The camera is small and fairly light. The reading is usually performed while seated at a table or desk. Therefore, the scanning activity gives a high probability of occasionally dropping the camera. The left hand is not in a position to catch the camera. The camera is light, small and easy to move and the camera is high off the ground. While the twisting cable and the difficulty of replacing the camera for storage (both design inadequacies mentioned previously) may have compounded the problem slightly. This problem seems to be an intrinsic characteristic of the system and could not be easily designed out, although slight improvements could be made (for example, the camera could be made sturdier and therefore able to withstand the abuse to which it is bound to be subjected).

Other possible conditions in which the Optacon is exposed to damage are unnecessary and can be solved with design modifications of the carrying case. For instance, the leather carrying case is difficult to remove and subjects the Optacon to the possibility of damage due to dropping. In addition, the leather carrying case should be replaced with one that will protect the Optacon in all types of weather conditions.

One of the great fears among the users involves theft. The Optacons are expensive pieces of equipment. Their portability and compactness allows them to be conveniently moved about. This feature makes theft fairly easy. The fear of theft is so strong that in some cases the portability feature is not used. It is believed that the methods used in prevention of theft of electronic pocket calculators could be easily applied in manufacturing the Optacon (locking to desk, mini-alarm, etc.).

2.4 EASE AND SAFETY OF FIRST ECHELON MAINTENANCE

2.4.1 User Repairs or Replacement

The Optacon has not been designed to allow the user to make repairs or replacements. This is justifiable because of the sophistication of the system and the difficulty of failure analysis. Any repairs should be made by a qualified technician.

The page-illuminator lamps and the battery, which many of the users feel should be easily replaceable, are actually intended to be permanent components. The lamps should live over 40 years (see Optical Evaluation—Page Illuminator) and the batteries are rechargeable (the batteries do have a limited life expectancy, but the estimated time between replacement is one to two years, based on a battery charge cycle life of 300 → 500 cycles and an average daily usage of about three hours). The user should be given additional data concerning battery storage and charging. For instance, most users are not aware of the fact that the battery will self-discharge when left unused. In fact the battery could self-discharge as low as 50% of rated capacity while stored six weeks. While the batteries are not harmed, the Optacon owner should be aware that this is to be expected and that it does not indicate failure. The users should also be aware of storage temperature limitations (usually ranging from a minimum allowable temperature of -40° F to the high of +140° F).

2.4.2 Cleaning

Since the Optacon is largely an optical device and since the optics operation is susceptible to dust and dirt, the Optacon should be easy for the user to keep clean. The following is a list of the camera components, whose location and construction are described in detail in the Optical Evaluation section. The list also contains comments on the ease and advisability of the user's attempt to clean the items. (Cleaning is defined as dusting or gently wiping with tissue paper.)

- Lamps—easy

- Rollers--easy
- White light diffuser--easy
- Retina glass cover--fairly simple; must remove retina module and replace correctly.
- Mirror--difficult; could be wiped with a cotton swab through the camera aperture, but alignment is fairly critical and cleaning is therefore not recommended.
- Lens--extremely difficult; exposed side could be wiped with cotton swab after removal of the retina module, but to clean the other exposed side would require removal and subsequent replacement of several miniature screws; cleaning not recommended.

The vibrator finger plate can be expected to collect dust or other foreign materials, but again the user cannot easily clean the cover, and any attempts to do so are not advised.

2.5 ORIENTATION

Locating a specific book, page, paragraph and line on a random access basis with the Optacon is a more difficult task than the same task using Braille. Probably the most difficult problems are book and page identification.

Most books cannot be identified by the cover alone. The problems here are cover layout, print size and print contrast ratio. In a typical search, the user would actually ignore the cover and turn to a page in the middle of the book. The user would then scan near the top of the left hand page, in hopes that the book title appears on every page. If unsuccessful, the user will turn to the first few pages of the book and scan, hoping to find the title. Unfortunately, in most books the title is too large to be picked up by the Optacon, and the user cannot determine the book title.

Finding a particular page is not too difficult since once the location of the page number is determined (by scanning any page at top and bottom), it is consistent throughout the book. However, finding a particular section of a book is fairly difficult since the task normally requires finding and reading the table of contents. If the table of contents cannot be found and read, occasionally the user can find a particular section by scanning through the book and reading the section heading often located on each right hand page at the top.

So, book and page locating with the Optacon is difficult compared with Braille where the cover is easily readable and the page numbers are in standard locations. Finding a paragraph and a line with the Optacon is in principle identical to searching in Braille. The page is simply scanned, usually from the top, and the reader skips lines or paragraphs as recognized until the particular paragraph or line is found or passed. In the latter case the reader would repeat the process by backtracking until the line or paragraph is finally located. Generally this process would take a longer time with the Optacon and would seem more tedious, but this is only because reading speeds with the Optacon are presently slower than with Braille. (Hopefully with experience, Optacon readers will approach and perhaps pass their Braille speeds, although the "shorthand" nature of Braille tends to make the latter possibility improbable.)

Several users feel that a larger field of view would aid in tracking and comprehension. The Optacon has been deliberately designed to present a single character to the reader. Whether readers can actually gain from additional information or whether the additional inputs would appear as noise was not determined under this contract. It is believed that a study such as this would, however, be valuable if undertaken by an independent organization. An experiment was tried with one of FIRL's adult users, a Braille teacher, to determine whether one could accept multiple inputs. FIRL presented the subject with a list of words in Braille that were arranged in a column. The words were justified to the left hand margin and were limited to no more than four Braille symbols per line. The Braille teacher was then asked to scan the column from top to bottom and to limit horizontal displacement so that each finger of her reading hand fell over a single character only. The teacher found that she could indeed read the words quite easily. While not related directly to Optacon reading, and while the teacher is certainly an above average reader, the experiment indicates that multiple tactile inputs can be accepted. Stanford University reported early in the Optacon development that multiple finger reading is not advantageous. These facts conflict.

2.6 EDUCATIONAL FACTORS EVALUATION

Despite the advantage of allowing the blind to read materials other than Braille, the Optacon presents quite a few problems to the classroom, the teacher and the school. Most of these problems are generally judged minor. In particular situations many of these problems are difficult to overcome.

2.6.1 Teacher Training

Except for a few special cases, the teachers had very little difficulty learning the operation of the Optacon. The difficulty rises steeply, however, if the training is not personal and "hands on." That is, those teachers not technically oriented, in order to obtain an adequate understanding, require that they are personnaly shown and allowed to operate the Optacon. Several of the teachers felt that a "What to do when the Optacon doesn't" manual of minor trouble shooting would be important and would render unnecessary many of their calls to the Optacon service organization. Another aid to education would be to have all the materials, especially the Optacon instruction manual, in Braille. This would not only aid any blind teachers or assistants, but would be useful to the Braille reading student.

2.6.2 Classroom Setup

When used in a classroom for the instruction of the Optacon (e.g. each student would have an Optacon located at his desk), wiring of the desks would be necessary to prolong the life of the battery and, therefore, minimize the time between replacement. The reason for this is that in such a classroom the Optacons would undergo nearly continuous usage and, therefore, justify the wiring. Wiring a classroom is not difficult nor is it unusual; take for example, a typing classroom. An Optacon in a normal classroom probably would not require special wiring. (If a large percentage of students had Optacons; wiring should be considered for convenience.) A normal classroom rarely requires continuous reading and therefore, the Optacon could be run from the battery assuming most classes for the day are similar and the Optacon could remain on charge most of the night.

A common concern among teachers is the lack of 3-Pronged Outlets (required by the Visual Display) in most schools. The Visual Display would not be used in a normal classroom but only in an Optacon classroom which should be rewired.

In a special Optacon classroom, oversized desks would probably be used. This again is not especially expensive or unusual. The Optacon classroom can be compared with a typing class which also use larger desks. A normal blind school or classroom will usually already have oversized desks as the norm because of the space needed to operate the Braille writter and it would be expected that at a mostly sighted school the blind student may already have been provided with a larger desk.

A major problem with the Optacon in both a normal classroom and an Optacon classroom is the high percentage of "downtime" as seen from the reliability tests. The Optacon cannot be expected to run continuously day in and day out. The school must either invest in the purchase of "back-up" units (to replace failed units awaiting repair) or to incorporate the expected downtime in the course program and provide the students with other educational activity while their Optacon is being repaired.

A serious concern among educators is the effect the noise of the Optacon will have on a classroom. It is pointed out that noise is already accepted in many classrooms. The typing class again provides an example, as does computer classes (using equipment such as a teletypewriter). Noise is accepted in other classrooms also as exemplified by the general acceptance of the Brailler. However, it should also be noted that these noises are usually all typing sounds. These random bursts of sounds are actually considered by some as soothing and compared to the pleasant sound of rain and surf. The sound of the Optacon however, is a high pitched buzz which would probably be annoying to many and surely not pleasant to anyone. One adult user states.....

> "I could not use the instrument in my present job setting. We have two person offices and my roommate did not think she could get used to the buzz. This is not to say that I would not isolate myself in some manner if I could use the Optacon."

The last sentence is a common field solution. Most blind people feel that they would isolate themselves in order to use the Optacon. This cannot, however, be a solution in the classroom (there is nowhere to hide.)

2.7 USER ECONOMICS

Besides the initial outlay of funds for the Optacon many other costs in time and money are involved. A collection of typical costs is outlined in the following sub-sections.

2.7.1 Costs of Optacon Training

Course Tuition is: $500 at TSI, $300 at New York Lighthouse and $700 at the Pittsburgh Guild. The training requires between one and two weeks on site. Of course, the cost of transportation and room and board is a concern and should be calculated by the prospective buyer. It should also be noted that the training gets the Optacon user on the right track, but the user must devote many hours of practice for efficient operation.

2.7.2 Warranty and Service Contract

Presently, TSI offers a warranty of one year from purchase. This warranty covers defective parts and offers a service contract for $100 per year. After the first year the contract is $200 to cover both parts and labor.

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2.7.3 Battery Cost

At present time a replacement nickel cadnium battery is priced at $12.96.

2.7.4 Maintenance Turn Around Time

The average number of days for repair of the Optacon is estimated at 3.5 days. This data was taken from the TSI reports based on data from September 1972 to June 1973 as contained in their "Service Record for OE Equipment." The time for shipment to and from the service center should be considered and is a function of an individual's location with respect to the service center.

2.8 SUMMARY AND RECOMMENDATIONS

a. The threshold, intensity and zoom lens controls should have notches to enable the user to readily locate his settings. This would enable presetting for frequently read material. This would also aid recovery from accidental movement.

b. Manufacture a model for left-handed operators by designing the front controls and case in a "mirror-image" of their present configurations.

c. Increase length of all interconnecting cabling, including master/slave cables and cassette trainer cable.

d. Obtain cable connectors for the Visual Display and Cassette Trainer for self-guide and alignment as well as locking in place.

e. Improve camera and camera cable storage. Retractable cord and a quick disconnect fastener (instead of screw type) should be considered.

f. Include instructions for gripping the camera while reading. Emphasize "thumb-middle finger" grip.

g. Key retina module so that it cannot be replaced upside-down.

h. Accentuate tactile indicator of camera aperture.

i. Supply adapter as optional accessory equipment to facilitate large print.

j. Supply all-weather carrying case.

k. Design case flap to open over top of Optacon and to snap toward the rear of the unit to facilitate reading while the unit is still in the case.

l. Increase range of adjustment of carrying strap.

m. Supply accessory pouch to house battery charger for portability.

n. Improve vibrator quality control to insure that all pins are uniformly high.

o. Design vibrators to eliminate possibility of shock (see Electrical Evaluation recommendations).

p. Ruggedize the camera case. (See Optical & Mechanical Evaluation Recommendations).

q. Design carrying case for easier removal of Optacon to avoid damage in handling.

r. Optional accessory equipment for locking unit to desk.

s. Emphasize to the user in operating instructions that he should expect battery depletion due to shelf storage. Also caution user regarding storage temperature limitations. Include optical element cleaning instructions.

t. Take a fresh look at the advisability of reading with more than one finger at a time. In addition, supply "what to do if Optacon Doesn't" manual for minor repairs. All material should be available in Braille.

u. Provide special classrooms with proper desk size and locations. Rewire Optacon classrooms to accommodate equipment in convenient locations. Especially, provide grounding lug for 110 VAC lines.

v. Program "downtime" into the course outline to accommodate repair time.

w. Noise elimination (from bimorph stimulators) is a formidable problem unless alternate forms of tactile stimulation prove feasible (electrical shock, air puffs etc) but the noise could be reduced if the frequency of vibration was reduced. A study to determine the minimum frequency acceptable for legible reading should be undertaken. Skilled readers use much less "intensity" than do learners. By the same token, they may be just as adept at perceiving less "frequency."

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3. OPTICAL EVALUATION

3.1 SCANNING CAMERA

3.1.1 Zoom Lens

The zoom lens consists of three elements, namely: a doublet lens, a filter and a biconvex lens. These elements are housed in a lens cell. The operation of the zoom consists of moving the lens cell close to the page for maximum magnification and further from the page for minimum magnification. As a zoom lens it is about the most simple design possible. The lens cell fits into a slotted piece to which the operating button is fastened through the camera housing with a screw. The opposite side of the lens cell has two channels which ride on lands. Clearance cuts are made in it to clear the wiring for the lamps. The slide in which the upper surface of the lens cell is fitted, and the lower surface of the lens cell are lubricated with a viscous lubricant. Operation of the zoom lens is very smooth.

3.1.2 Reading Retina

The reading retina is housed in a cylindrical container. At one end is a plain window and at the other end is the electrical cable permanently attached. The window serves to protect the retina chip from contamination by dust and foreign particles. The window is recessed into the housing so that its outer surface is not flush. This has the advantage of reducing the possibility of accidental contact and thereby avoids fingerprints during handling. On the other hand, it makes it more difficult to clean. Since removal of the reading retina housing from the rest of the scanning camera is a maintenance operation, the recessed arrangement is considered satisfactory.

The field of view on the page as determined by the retina is approximately as specified by the manufacturer and lies well within the perimeter of the optical aperture. Therefore there is no vignetting, and

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illumination uniformity in the image is good.

3.1.3 Page Illuminator

The illumination on the page is provided by two tiny lamps recessed in the head and located at either side of the rectangular aperture. The walls of the recess are coated with a white paint that serves as a diffuse reflector. The lamps are connected in parallel and the combination is in series with a 15-ohm resistor that is mounted on the back of the mirror bracket. Depending upon battery voltage the voltage on the lamp is in the neighborhood of 3.5 volts. The lamps (Chicago Miniature #6152) are rated at 5.0 volts and a life of 5000 hours. At 3.5 volts, life should be extended about 72 times, which equates to about 40 years. Hence, the bulbs should last the life of the unit unless physically damaged. Nevertheless, one of the bulbs was covered with opaque plastic in a test to determine whether the unit is still usable with only one lamp.

It was found that the operation with the illumination of only one lamp was essentially the same as with both lamps after readjustment of the threshold control.

3.1.4 Scanning Camera As a Unit

Some added description of the camera unit as assembled remains. The optical path includes a front-surfaced mirror, which is epoxied to a metal bracket. This mirror is located directly above the main aperture, and is protected from outside air by virtue of being behind the aperture. A protective glass cover over the aperture would protect both this front-surfaced mirror and the lamps. However, such a glass cover may have greater disadvantages. It would have to be recessed so as not to be scratched by rubbing on the paper being read; and, if it were recessed, it would be both a dirt-catcher and difficult to clean. If dust were to deposit on the mirror, it is likely it would deposit on the lens also. In such a case, the scanning camera should be disassembled for cleaning of all optical surfaces.

The reading retina housing disconnects from the rest of the scanning camera by a bayonet type of disconnect. The connector slots are symmetrical, and it is possible to make an inverted connection. If this is done, the display presentation is upsidedown and backwards. It would be better if the connection could only be made the normal way.

3.2 DURABILITY

Durability of the optical components of the system can be assessed on the basis of physical effects, optical effects and electrical effects.

3.2.1 Physical Effects

The main optical aperture of the scanning camera allows access to the interior, and through it dirt and moisture could be admitted. Dirt is not likely to be a problem unless the scanning camera is used in a very dusty atmosphere or on dusty paper. Even so, the mirror and lens are so far recessed that they are not likely to be contaminated by dust under ordinary usage.

Moisture may be a problem if the scanning head is, for example, used outdoors in very humid weather. Under conditions where eye glasses would fog, the mirror surface would also be liable to fog. Although complete sealing of the unit would reduce or eliminate this condition, such sealing would not only increase the cost but add another optical window which would also be susceptible to dirt and/or physical damage.

The possible damaging effects of sunlight on the reading retina can be considered. The optical aperture, being about 0.6 cm in diameter, has an area of about 0.28 cm. Sunlight at the earth's surface is 100 MW cm and the optical transmission of sunlight is probably less than 80% due to the filter. Thus the total power through the aperture into the reading retina housing is not more than 23 milliwatts if the scanning camera is directed towards the sun. This power should not cause any objectionable heat dissipation problem.

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Power density is a somewhat different consideration. Because the optics are not focused at infinity the sun will not be imaged on the retina; that is, it will be out of focus. Under the worst condition of minimum zoom, the energy bundle from the sun will fall in a spot of approximately 2.5 millimeter diameter. The energy density in this spot will be about 470 cm. This is still not an excessive level for short durations (minutes). However, intentional or prolonged exposure is not recommended.

Mechanical shock, such as dropping the scanning camera, could cause a problem. The lenses are held in the lens cell by an end ring which is press fitted to the inside circumference of the cell. Under severe mechanical shock this end ring could fall out, releasing the lenses.

A second possible effect of mechanical shock would be breakage of the lamps. Since these are epoxied into place, breakage is minimized. Direct physical contact with the lamp surface would probably be necessary to break a lamp.

Clearance between the roller and the main frame of the scanning camera is only a few mils. While it is not likely that the rollers would become clogged with dirt or lint, both rollers can be removed for cleaning by unscrewing a single flat-head screw.

Rollers are one piece and can be readily replaced if they become damaged or corroded. This is mentioned because one of the rollers of the unit examined had a pitted area. It is likely that periodic lubrication of the roller ends, which serve as bearings, will be required.

3.2.2 Optical Effects

The zoom action is continuous and there is no way of locking it to a fixed or predetermined setting. The zoom setting is adequately stable from the durability viewpoint. Since all of the optical elements are recessed or wholly internal, there is no probability of scratching the optical surfaces accidently. The white reflective surface around the lamp cavity may become less reflective with aging, but this can be renewed as a part of maintenance. It is not normally exposed to touch by the user.

3.2.3 Electrical Effects

Electrically, the scanning camera has adequate durability. The cable between it and the main unit is permanently attached at both ends and is resistive to bending without being too stiff. The internal electronics are adequately protected from the expected environment.

3.3 LIFE OF REPLACEABLE PARTS

There are actually no replaceable parts in the usual interpretation of the term except for the camera head itself. A bayonet-type of connector is used between the housing for the lenses and the reading retina assembly. Thus in the event of any problem with the camera head, it could be replaced as a unit. Thus, lamp burn out, soiled or abused optics including zoom action or roller troubles could be remedied by replacing the camera head.

3.4 EASE OF REPAIR

The scanning camera is easily disassembled with adequate tools. Once the sheet metal housing is removed the lens cell can be removed. With the removal of one screw both rollers can be removed. Lamp removal will require chipping away the epoxy that glues it to the frame. Repair of broken or burned out lamps is possible but somewhat difficult. Since it will be very infrequent, the method used to mount the lamp (in epoxy) is still considered a good method.

Mirror repair would consist of removing the mirror bracket by means of its single retaining screw. Because optical alignment of the mirror would be required, it would be preferable to replace the mirror and mirror bracket as an assembled unit.

Repair of the reading retina assembly will be difficult. The window disc has been epoxied into place and the unit would probably be severely damaged by attempting to open it. The interconnecting cable enters this unit and it appears that to repair the cable it would be necessary to replace the reading retina assembly as well. This would be much more costly than replacing a cable alone. This situation could be remedied by fabricating the case in two pieces instead of one. A suggested method is to make one piece of the casing a hollow cylinder and the other piece a removable end cap which attaches to the end of the cylinder. These two pieces would replace the drawn cylindrical cup used now. In this way, it would be possible to remove the end cap to get at the cable termination inside the reading retina assembly.

3.5 DESIGN ADEQUACY

The optics of the scanning head appear to have been well engineered with adequate consideration of all the usual optical tradeoffs. The zoom lens is one of the simplest that could be devised. The illumination level is adequate to activate the sensor. The lamps are powered at reduced voltage to provide long life. The color filter is reportedly designed to provide an overall spectral response at the detector that approximates the eye response. In this way, the contrast of printing on paper background will be close to what the average eye perceives. The detector array sensitivity allows this otherwise severe tradeoff, since the lamps emittance and detector response both peak in the near infrared.

Acceptable tradeoffs have been made between simple design, durable construction, protection from the environment and maintainability.

3.6 COST TO MANUFACTURE

To consider manufacturing costs we can delineate between materials, fabrication, assembly and test costs. The scanning camera appears to utilize readily available and inexpensive materials. There are no materials used which could obviously be replaced by less expensive ones to significantly reduce costs in quantity production.

With regard to fabrication costs, it is evident that several machining operations are required. Since several of the machined pieces are small they could be cheaply fabricated if the machining would be arranged to be done on several pieces at once. The lens cell, zoom slide, end plate, mirror bracket and roller end plates are examples of pieces that could be machined in this way. The main aperture appears costly to machine since it is milled out and has two holes for the lamps. Some saving in fabrication costs might be realized if this aperture were stamped out of sheet metal or molded from a tough plastic such as lexan or even nylon.

Practically all of the machined parts in the scanning camera are of a precision type; that is, they require close tolerances, fits and finishes. They all appear to be capable of production in quantity so that initial set up of the machining equipment will bear the brunt of the cost. No custom fits appear to be necessary and all machined parts can be produced on precision machine tools probably with a very low rejection rate. Black anodize finishes both inside and outside are an optimum choice for both aesthetic and optical reasons. Since the thickness of anodizing can be accurately controlled no unusual tolerance or fit problems should be encountered in assembly.

In consideration of assembly costs it is noted that for the most part pieces that require individual machining are attached by means of screws to the main frame. For economical assembly at least some of these machine screws should be replaced with "quick" fasteners or even eliminated. For example, four flat-head machine screws hold the housing cover on. By relocating, two might suffice.

As part of the assembly we consider the alignment of the optical system. Two critical areas exist, which are the mirror orientation and the reading retina orientation. Mirror orientation is likely controlled in three axes by gluing the mirror to the mirror bracket in a holding jig, by tolerances on the bracket fitted into the main frame and by bending the mirror bracket after assembly. The only post-assembly operation would be the bending of the bracket, and even this might not be necessary if mechanical tolerances are accurately controlled.

Orientation of the reading retina is probably more critical. The array must be rotated with respect to the connector bayonet studs so that its axes are alinged to the page when the scanning camera is mechanically aligned to the page. In addition, the window disc must also match the spring contacts for the lamps when connection is made. In both instances, it is likely that adequate orientation can be obtained by controlling mechanical tolerances, and making assembly in a jig.

For post-assembly testing, it should be possible to incorporate verification of the optics with the testing of the whole Optacon.

3.7 SUMMARY AND RECOMMENDATIONS

Recommendations fall into two categories; changes in fabrication, and important provisions for care and maintenance. In the first category are the following:

a. The bayonet-type disconnect between the scanning head and the reading retina assembly should be modified so that the reading retina cannot be connected in the wrong orientation. This might be simply accomplished by locating the bayonet slots and mating pins unsymmetrically rather than 180° apart.

b. Since the cable between the scanning head and the main Optacon unit is subject to considerable wear by flexing and rubbing, it is likely to require replacement. In the present manner of construction it appears that connection of a new cable at the end of the reading retina assembly would be a major operation involving the retina itself. The termination of the cable at the reading retina housing should be modified so that the risk of involving the retina in cable replacement is eliminated.

c. The lens cell consists of a hollow cylinder containing three optical elements held in place by a hollow end piece that is pressed into the end of the cell. It is recommended that this end piece be more positively attached to the lens cell. As a minimum a drop of Locktite or other adhesive agent should be applied at the flange to effect a bonding of these pieces.

d. The main aperture of the scanning head which contains the two illuminating lamps is milled out. For quantity production it is recommended that the design be modified so that this aperture can be stamped out of sheet material in order to effect a cost saving.

e. The sheet metal cover of the scanning head is attached to the scanning head frame by four flat head screws. It is recommended that assembly time might be saved by reducing the number of these screws to two or even eliminating them by using a different method of attachment.

In the area of care and maintenance, it is recommended that the two rollers under the scanning head be cleaned periodically and their ends be lightly lubricated.

Table 3.1 details the cost to manufacture the scanning camera (less reading retina, electronics and cable) per unit in lots of 1000.

Potential savings in this area are considered negligible percentage wise. If quantities significantly increase, incremental savings become significant.

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Table 3-1. Cost to Manufacture Per Unit in 1000 Quantity

MATERIAL:	
Aluminum 1/8 lb at $6.00 lb	$ .75
Steel 1/16 lb at $8.00 lb	.50
Stainless 1/16 lb at $32.00 lb	2.00
Hardware 12 @ .03 unit	.36
Lamps 2 @ $2.00 unit	4.00
Wire Insul. 1 ft at $0.12 ft	.12
Paint	.01
Anodize	.05
Lens, Doublet	.60
Filter	.50
Lens, Singlet	.35
Spring Contacts 2 @ $0.06 unit	.12
Epoxy	.06
Mirror	.40
Resistor	.05
Window	.10
Button Contacts 2 @ $0.12 unit	$ .24
	$10.21
FABRICATION:	
Main Frame	$5.00
End Plate	.50
Roller Plates (2)	1.00
Rollers (2)	.50
Cover	.16
Cylinder	.16
Cap	.16

Table 3-1. Cost to Manufacture Per Unit in 1000 Quantity (Cont.)

FABRICATION:

Mirror Bracket	$ .16
Lens Cell (2 pieces)	.16
Zoom Slide	.20
Zoom Button	.05
Window Disc	.16
Painting and Anodizing	1.00
	$9.21

ASSEMBLY AND TEST:

Screw Attachments (12)	$ 2.00
Wiring	3.00
Gluing	5.00
Rollers	.50
	$10.50

Total cost to manufacture scanning camera less reading retina, electronics and cable:	$10.21
	9.21
	10.50
	$29.92

4. ELECTRICAL EVALUATION

4.1 OPTACON PROPER

4.1.1 General Comments

The Optacon itself received the bulk of the evaluation effort since the display unit and the cassette trainer serve only for training purposes.

The design is basically sound; this is attested to by the continued satisfactory operation over long periods of time (see life tests). Several outstanding features were noted, as well as a few undesirable characteristics which can easily be corrected. These are summarized below and described in detail in later paragraphs.

The following desirable features were noted.

- a. Basically sound design;
- b. Maximum usage of custom bimorph driver chip so that development cost is widely spread;
- c. Low noise on power buses.

The following undesirable characteristics were also found:

- a. A "race" condition in the logic which could cause malfunction if the electrical characteristics of certain components fall near the extremes of their specified ranges;
- b. Possible mild electric shocks from the bimorph stimulator pins.

Recommended areas of improvement in a future design are:

- a. Self-scanning retina to reduce the number of wires in the camera cable;
- b. A further look at the mechanical design of the bimorph stimulator array and the electrical design of the drive circuits. The combination

> of complex mechanical design and high voltage requirement on the bimorph driver chip causes the stimulator subsystem to contribute approximately one-third of the total cost of the Optacon. (The other two-thirds is divided roughly equally between the camera and the rest of the Optacon excluding the stimulators.)

4.1.2 Electronic Design (Optacon)

The electronic design of the Optacon was evaluated mostly by examining the timing diagrams and the schematic diagrams. The object of the study was to reveal any basic design flaws rather than to seek ways to delete a component here or there; the latter course of action would have been tantamount to redesigning the Optacon, which is clearly beyond the scope of the task.

The only basic design flaw uncovered is one which could cause a reliability problem if certain components have electrical characteristics near the extremes of their ranges. This flaw is discussed in the following paragraphs.

Figure 4.1 shows a part of the logic used in the generation of the pulses which interrogate the rows of the silicon retina in the camera. Also shown are selected waveforms.

$\bar{Q}_1$ is the output of a flip-flop, and this is used to drive a second flip-flop whose output is Q_2. $\bar{Q}_1$ and Q_2 are NORed together to produce a positive pulse at X during the time that $\bar{Q}_1$ and Q_2 are both low. The waveform at Y is the same as at X except for a slightly lower "1" level (because of the diode drop) and a slower fall time. T_d is essentially an inverted and squared-up version of Y.

Ideally, the transitions of Q_2 would coincide with those of $\bar{Q}_1$. Since Q_1 drives Q_2, however, there is bound to be a small delay between the triggering of flip-flop 2 and the change of state of its output, Q_2.

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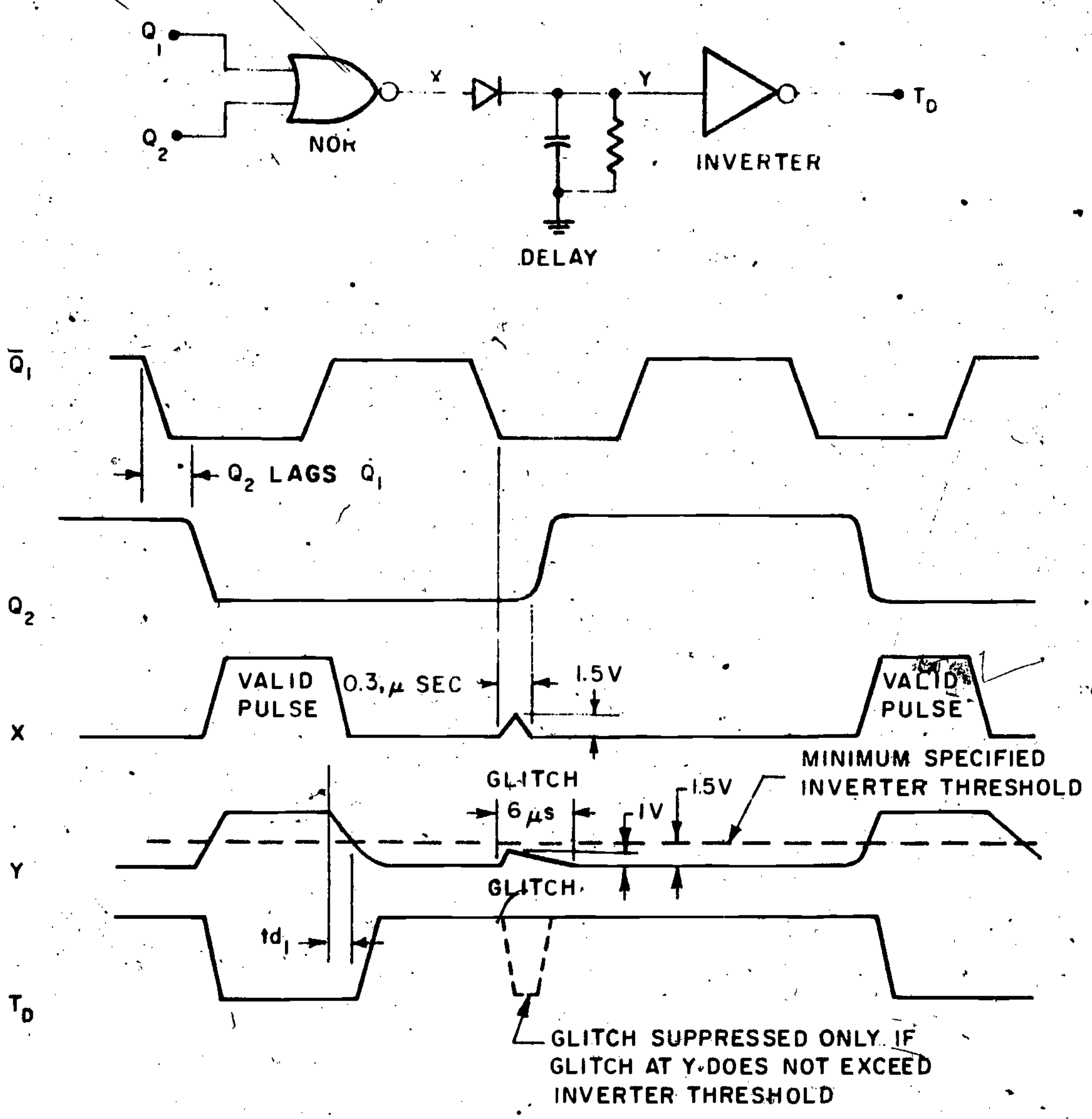

NOTE: TIME DELAYS ARE EXAGGERATED IN THIS FIGURE

Figure 4.1. Illustration of Potential Reliability Problem

Therefore, the transitions of Q_2 will always be slightly later than those of Q_1 and the delays are shown exaggerated in the figure. Because of this delay, there is a short time when Q_2 is still negative as $\bar{Q}_1$ goes negative for the second time as shown in the waveform. This causes a positive "glitch" to appear at X, and this was verified in an actual Optacon[1]. The glitch is spread in time and lowered in amplitude by the time it gets to Y, and is fortunately small enough that it does not cross the threshold of the inverter stage, and hence does not appear at T_d.

The "glitch" would propagate through the inverter and cause extra T_d pulses if one of two conditions were to occur:

a. The threshold of the inverter were low;

b. The delay between the transitions of $\bar{Q}_1$ and Q_2 is too long.

An extra negative-going T_d pulse would reset the comparator flip-flop[2] and then interrogate the retina a second time in the same row as did the previous, valid T_d pulse. Since the phototransistor would not have time to recharge in the short intervening time (the presence of light assumed), the "final" result of the interrogation would be "no light" whether there was light or not. In the NORMAL mode the bimorph stimulators would vibrate continuously; in the INVERT mode they would never vibrate. Since the T_d pulse scans all rows sequentially, all rows would fail, and all bimorphs would remain on (or off).

This potential reliability problem can be eliminated by eliminating the "race"[3] between Q_1 and Q_2, a race which Q_1 always wins, and therefore always produces the beginning of a "glitch."

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[1] Optacon serial No. R507-012

[2] The comparator flip-flop is always reset prior to an interrogation and then set if there is light on the retina element being scanned.

[3] A "race" is a condition in which two or more logic levels change state simultaneously and a spurious output could occur as a result of one changing ahead of the other.

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One approach which will alleviate the problem, but not completely eliminate it, is shown in Figure 4.2. Its advantage is that it does not require additional components. It consists of connecting the $\bar{Q}_1$ input of the NOR gate to the output of inverter A_5 instead of the $\bar{Q}_1$ output of flip-flop 1. A_5 inverts Q_1 and produces a waveform similar to $\bar{Q}_1$ except delayed by the time delay of the inverter. This would at least partially compensate for the delay between the original $\bar{Q}_1$ and Q_2, thereby alleviating the race problem, but not necessarily eliminating it.

Figure 4.3 shows an approach that eliminates the problem completely, but requires an additional flip-flop to produce the Q_3 signal, which changes state on the positive-going transitions of $\bar{Q}_1$, or the negative-going transitions of Q_1.

The rest of the Optacon logic was carefully checked for similar race conditions. None was found which could affect the proper operation of the Optacon.[4]

Another complaint about the design is, namely, the wide use of delay circuits to get rid of what otherwise would be severe "race" problems. In the case of the Optacon, this technique is permissible because the durations of the logic states are long compared to the transition times. The delays are therefore not critical, provided that they are long enough. In sophisticated, fast digital circuits, however, this technique could not be used; sufficient logic would have to be designed into the system to preclude all possibility of "races."

The wide use of complimentary symmetry MOS (CMOS) chips throughout the Optacon circuit is deserving of attention. CMOS has several advantages and drawbacks as compared with transistor-transistor logic (TTL), the advantages outweigh the drawbacks when power consumption is the

[4]One other potential "race" was found which could generate short, spurious $\emptyset_p$ pulses during the $\emptyset_2$ pulses. However, only the valid $\emptyset$ pulse, which signifies all "zeros" in the scanner shift register lasts through the $\emptyset_1$ pulse, at which time a "1" is shifted into the register. Therefore, spurious "1's" can never be shifted in.

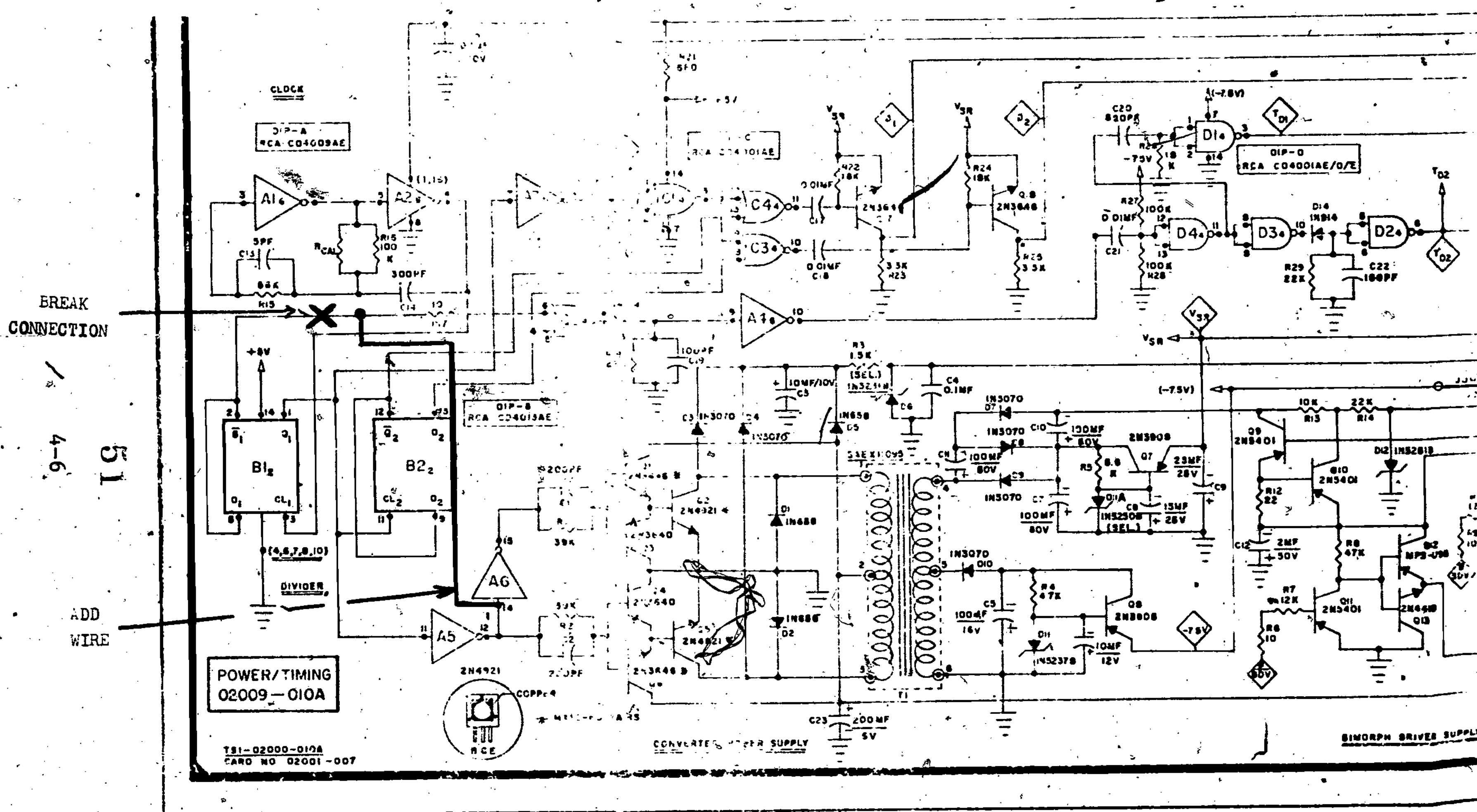


Figure 4.2. Elimination of Race Condition Requires Relocating One Lead

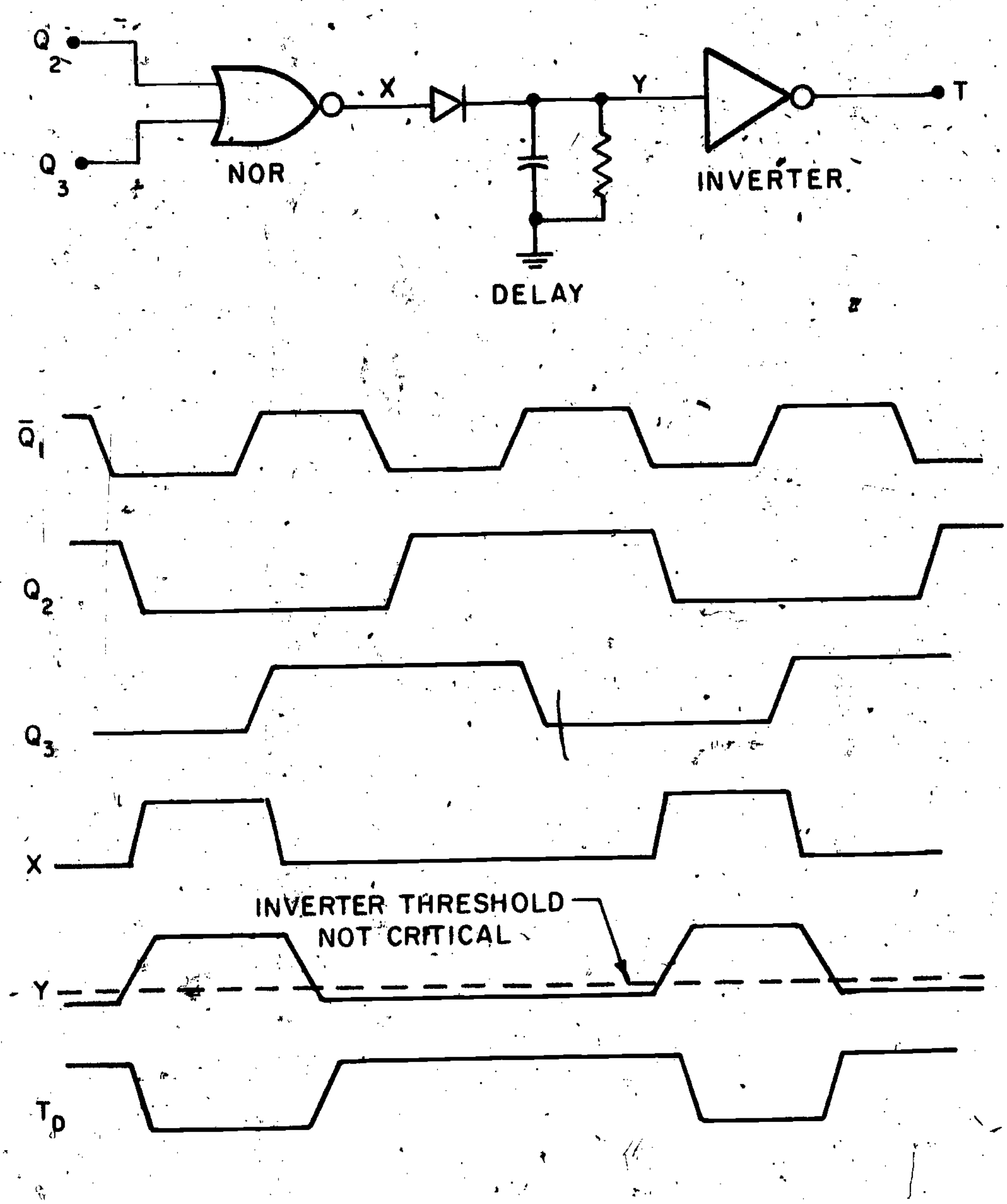


Figure 4.3. Elimination of Race Condition Requires One Additional Flip Flop (Q_3).

major design criteria. The chief advantage is low power consumption, of the order of 10^{-9} W for one CMOS logic "gate" driving another CMOS circuit. Another great advantage is high noise immunity. This is brought about because CMOS logic has a higher threshold than TTL, and is at least an order of magnitude slower than TTL, and is therefore less susceptible to, and less likely to generate, short noise transients. (In many digital applications, CMOS would be too slow, but this is not true of the Optacon.)

The drawbacks of CMOS are a greater number of components and the cost of the CMOS circuits themselves. The CMOS circuits cost three to four times as much as equivalent TTL circuits.[5] This would amount to roughly $30 per Optacon greater cost in purchased components than if TTL were used, which is not a large amount compared to the total cost of the Optacon.

Another sacrifice in cost arising from the use of CMOS comes about because of the larger number of packages required to be assembled onto the circuit boards. This is because there is currently a smaller choice of logic functions in CMOS than in TTL. Therefore, a large number of discrete components are used in the Optacon to perform functions which could have been performed by TTL integrated circuits. By using TTL, a saving in cost would be achieved through a smaller number of components, and therefore reduce assembly time. However, this drawback will tend to disappear as a wider variety of CMOS circuits are developed and the Optacon is redesigned accordingly.

[5] A hex inverter (six inverters in one package) costs $3.90 in RCA COS/MOS vs $1.04 in low power TTL.

4.1.3 Bimorph Stimulators

The bimorph stimulator array and its supporting circuitry constitute roughly one third of the cost of the Optacon. Besides being mechanically complex, the array requires about 40 volts to operate. This voltage imposes the requirement of special processing in the fabrication of the bimorph driver integrated circuits, processing that is not standard in the fabrication of most MOS integrated circuit chips.

While it is easy to complain about the complexity and voltage requirements of the bimorph array, no easy solution presents itself. One possibility is to make the bimorphs longer, so that less voltage is required to displace them a given distance. Another might be to drive the pins by means of pulsating air pressure. However, considerable research would be required to evolve a tactile stimulator system substantially better than the present one. It is, however, a recommended area of improvement in any new generation of Optacons.

One minor fault noted in the Optacon is residual vibration of stimulators when they should be turned off. One possible cause is mechanical coupling between adjacent stimulators through the common bar to which they are mounted. Another is stray capacitance to ground from the center conductor of the bimorphs and its connecting leads.

Because the bimorph capacitance is approximately 10,000 pF, and the stray capacitance to ground of leads, bonding pads and the bimorph driver switch can hardly be more than a few tens of picofarads, the residual vibration due to stray capacitance with the bimorph off should be less than 1% of the vibration with the bimorph on. Thus, stray capacitance should not be a problem.

The residual vibration situation has recently been investigated by TSI. They report that they have corrected it.

There have been user complaints of electric shock from the bimorph stimulators. It is noted that the stimulator pins are made of nickel and are attached to the bimorphs by means of RTV, a flexible adhesive. The pins may or may not be insulated from the bimorphs themselves, which carry a square-wave voltage of about 40 volts peak at full intensity. While 40 volts is not dangerous, it can cause considerable discomfort if the fingers are moist, (as with perspiration. This evaluator, using a variable source of alternating voltage, half-wave rectified to simulate the bimorph voltage, experienced moderate discomfort at 35 volts peak with moist fingers.

The suggested remedy is to use pins made of an insulator rather than metal to contact the user's finger. Or, insulating caps could be placed on the ends of the pins or over the bimorphs where the pins are attached. Stanford University tried a plastic sheet over the entire array. This "smeared out" the tactile image to an unsatisfactory extent.

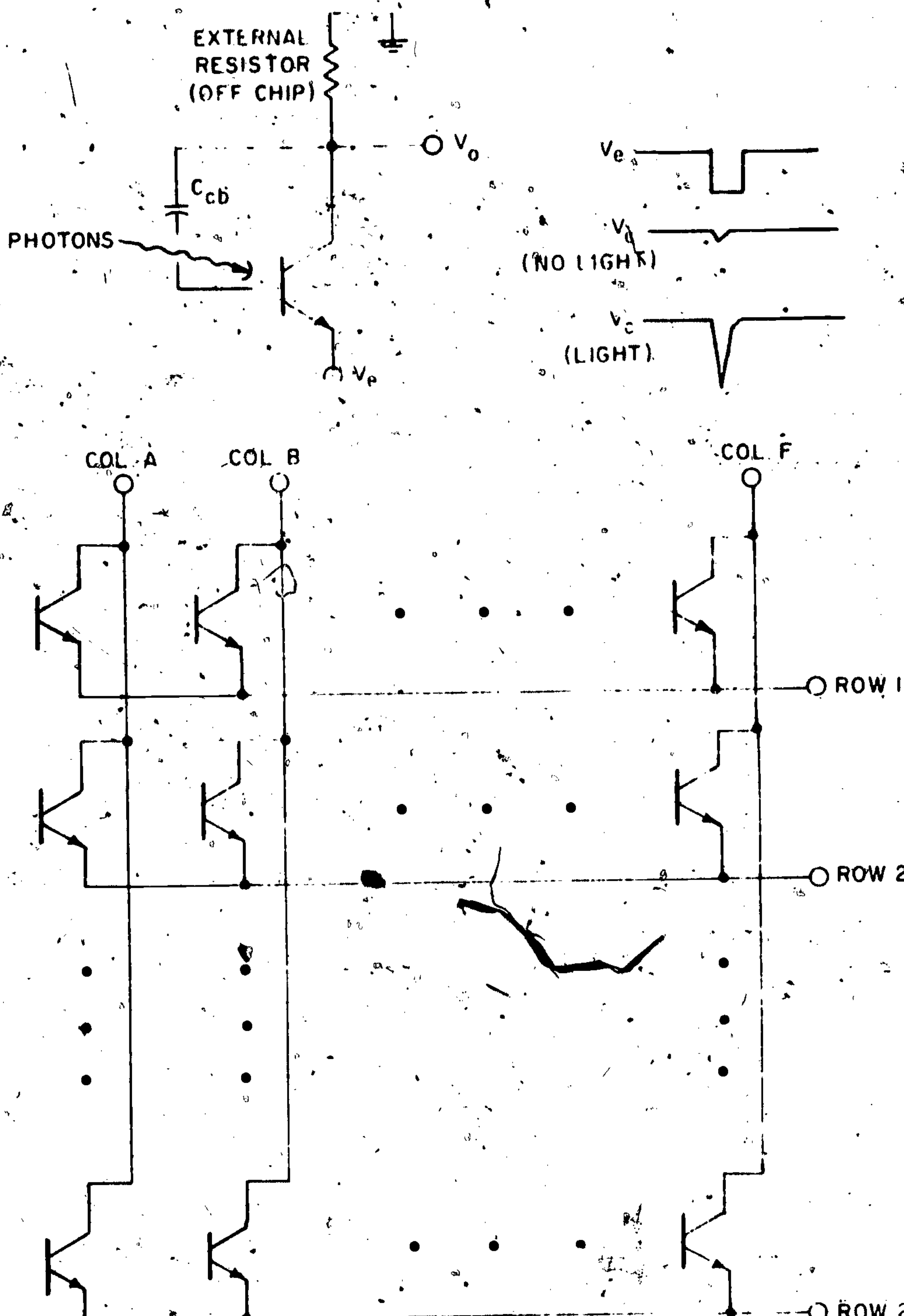
4.1.4 Custom Integrated Circuits

Two custom integrated circuits are used in the Optacon: the silicon retina and the bimorph driver. The silicon retina is used in the camera to convert the optical image into electrical signals. The bimorph driver is used 14 times throughout the Optacon: two to scan the 24 rows of the silicon retina and twelve to drive the 144 bimorph stimulators.

4.1.5 The Silicon Retina

The silicon retina consists of six columns and twenty-four rows of charge-storage phototransistors. Figure 4.4(a) shows an equivalent circuit of one transistor; Figure 4.4(b) shows how the transistors are interconnected on the chip. The transistors in each column have their collectors connected together. The transistors in each row have their emitters connected together.

Each transistor has a large, built-in capacitance from collector to base. The transistor is "interrogated" once per scan by a negative pulse at the emitter. If, during the intervening interval since the previous scan, there has been light on the transistor, the capacitance C_{cb} will have been partially or completely discharged, depending upon the amount of light. When a negative pulse is applied to the emitter, the capacitor recharges, and the current flow required to recharge the



(b) INTERCONNECTIONS

Figure 4.4. Silicon Retina

capacitor is amplified by the transistor, producing a pulse of current in the collector. If, on the other hand, there was no light since the previous scan, then the capacitor will have held its charge (except for a small amount of leakage), and therefore does not draw a charging current when the emitter is pulsed. Consequently, there is no (or negligible) pulse of current in the collector.

Only one row of emitters is pulsed at a time. Therefore, the presence or absence of a pulse on a particular column of collectors depends upon light or no light on the transistor at that column and that row. The rows are scanned in an interleaved fashion, i.e., 1, 3, 5..., 23, 2, 4, 6..., 24, 1, 3, 5..., etc. The scanning is accomplished by two bimorph driver chips in the main housing of the Optacon.

TSI has the retina chips manufactured by an outside firm. The cost per assembled retina is about $75. The most startling revelation concerning the cost is that the packaging yield is only about 50%; that is, a retina which tests good during die-sort[6] has only about a 50% chance of testing good after being packaged. The die-sort yield (percentage of good chips on a wafer) is about 10%, which is fairly reasonable for this array of phototransistors. If the packaging yield could be increased from 50% to 75%, the cost per packaged unit could be brought down to about $54.00; for 85% yield, $50.00; for 95% yield, $46.00[7]. Thus, beyond about 85% packaging yield, other things being equal, improving the packaging yield reaches a point of diminishing returns. (The data cited above was obtained from TSI in July, 1972.)

Figure 4.5(a) is a microphotograph of a part of a packaged retina. The large rectangles are the light-gathering base regions of the transistors with their large capacitance to the collector regions below (into

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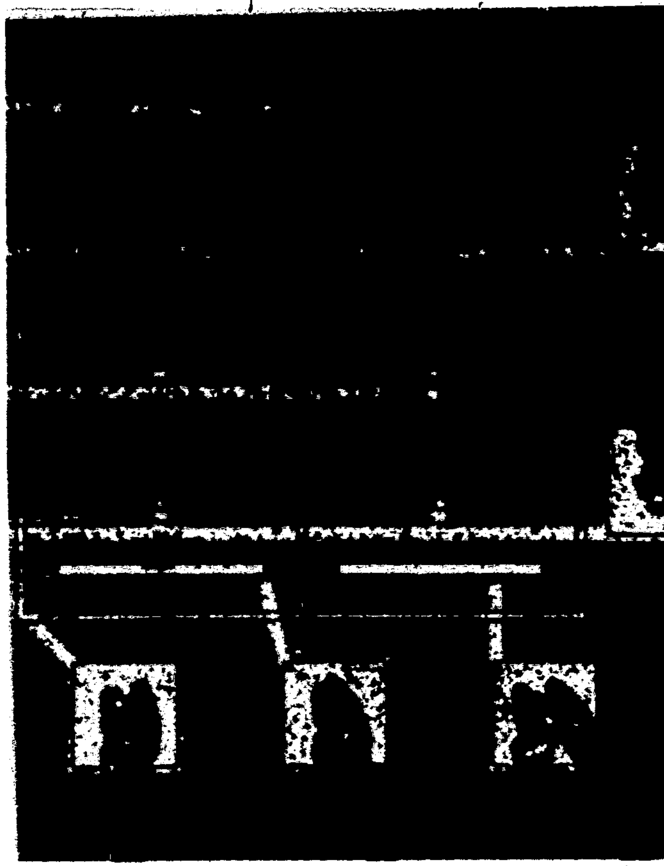
[6] Testing on the wafer with probes prior to scribing into separate chips and assembling the latter into packaged units.

[7] This ignores the cost of improving the packaging yield The packaging labor costs $4.50 per unit. If doubling the cost of packaging to $9.00 could lead to a 75% yield, the cost of the finished retina would be about $59.00 instead of the current $75.00.



(a)
PORTION OF PACKAGED SILICON RETINA CHIP

(b)
PORTION OF UNPACKAGED RETINA CHIP. NOTE MISREGISTRATION OF METAL PATTERN

Figure 4.5. Portion of Silicon Retina Chip

the paper). The "borders" between the columns of transistors are the isolation regions which prevent the collectors of adjacent columns of transistors from shorting together.

The small squares at the tops of the base rectangles are the emitters. These must be small to minimize blockage of light and to minimize emitter-to-base capacitance which, if too large, would cause feedthrough of the emitter pulse to the collector when there is no light. The long, narrow rectangle at the top of each column is the contact to the column of collectors. The squares at the edges of the chip are the bonding pads to which the package wires are bonded.

Figure 4.5(b) shows the same portion of an unpackaged chip from a wafer known to be bad, but otherwise selected at random. The entire metal pattern is misregistered low and to the left with respect to the rest of the circuit. Such misregistration would give zero yield on that particular wafer.

This gross an error is rare in an integrated circuit processing facility, although it does sometimes happen. It is due to misregistration of the photomask during photolithography, and is a human error. Good practice is to make a visual check of each wafer following each process step so that wafers bearing such obvious defects can be discarded without further processing. The cost of a raw wafer is approximately $15; it costs about $200 to process a wafer to completion. Each wafer contains about 130 chips, roughly 10% of which test good at die-sort.

4.1.6 The Bimorph Driver Chip

The design of the bimorph driver chip is highly praiseworthy. The same integrated circuit configuration performs a variety of different functions in the Optacon itself, in the display unit, and in the cassette trainer. Thus, the cost of developing the chip is spread over its several applications. The cost of developing a custom integrated circuit is typically tens of thousands of dollars. Therefore, the incorporation of a few "extras" in one chip to make it perform many different

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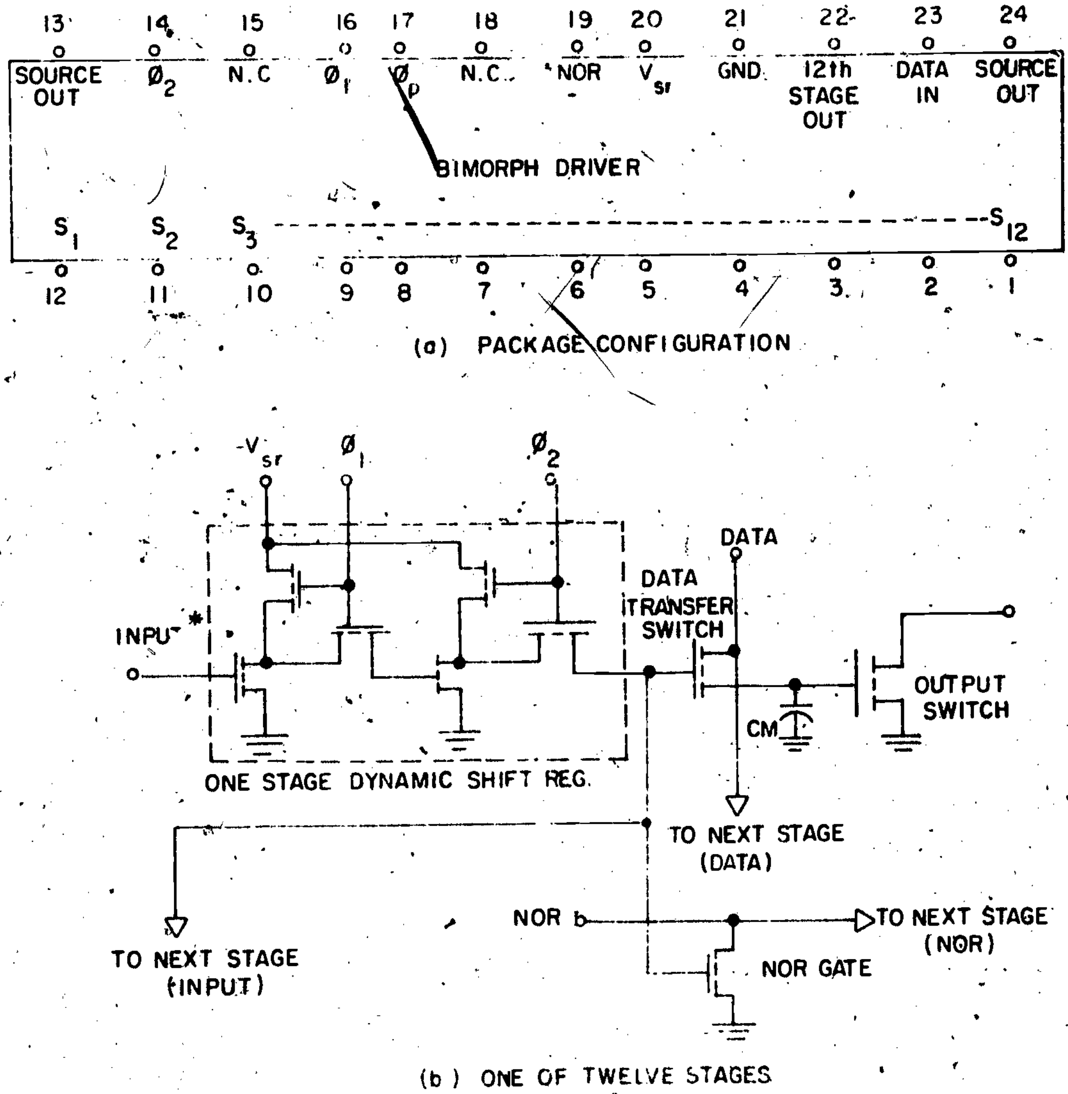
functions is far more economical than designing a separate chip to perform each function. The chip is a large-scale MOS integrated circuit.

Figure 4.6(a) shows the package configuration used by TSI for the chip; Figure 4.6(b) shows the schematic diagram for one of twelve stages. Each stage contains one stage of a two-phase dynamic shift register, a data transfer switch, an output switch, and one of twelve inputs of a NOR gate.

The chips are always used in pairs, one for odd rows, one for even. The 12th stage output of the "odd" chip is connected to the $\emptyset_p$ input of the "even" chip. The NOR connections on the chips used for scanning the camera are used together with some external logic to hold the $\emptyset_p$ input of the "odd" chip low ("0" level) whenever there is a "1" on any of the 24 stages of the shift register formed by the "odd" and "even" chips combined. When all 24 stages contain "0's", a "1" is developed at $\emptyset_p$. This causes a "1" to be shifted into the first stage of the "odd" register on the next clock cycle ($\emptyset_1$ followed by $\emptyset_2$). Thus, a single "1" is stepped along the 24 stages, advancing one stage with each clock cycle. Only one stage at a time contains a "1". The $\emptyset_p$ synchronizing signal, developed by the pair of bimorph drivers used to scan the camera, is connected to the $\emptyset_p$ input of the "odd" chip of each pair of bimorph driver chips used throughout the system, thereby ensuring synchronism among the camera scan, the bimorph stimulators, the visual display, and any "slave" Optacons connected to a "master" Optacon. In the cassette trainer, there are two bimorph driver chips which scan a simulated camera exactly as the camera scanners in the Optacon do to the real camera. When the cassette trainer is used, it generates the $\emptyset_p$ synchronizing signal to which as many as four Optacons can be slaved.

Let us consider what happens during the scanning of the i^{th} stage of the 24 stages formed by the combination of the "odd" and "even" chips. In the case of the camera scanners, a negative pulse ("1" level) is applied to DATA, i.e., to all twenty-four stages. However, this pulse can get to the gate terminal of the output switch only on the i^{th} stage, where the gate of the data transfer switch is high. The duration of the



*FIRST STAGE CONNECTED TO $\emptyset_p$

Figure 4.6. Bimorph Driver

DATA pulse is less than a clock cycle, so that the capacitor C_M is charged by the leading edge of the pulse and discharged by the trailing edge. Thus, the output switch of the i^{th} stage is "closed" only for the duration of the data pulse. An inverter (off the chip) converts the switch "closure" to a negative pulse which interrogates the appropriate row of the camera chip.

There are six pairs of bimorph drivers in the tactile stimulator array, one for each column of bimorphs. The signals applied to the DATA inputs for each column are derived from the signals generated at the collectors of the phototransistors in the appropriate column of the camera[8]. The signals depend upon whether or not there was light on the selected phototransistor. In what follows, we assume that the Optacon is in the NORMAL mode (dark text on a white background). In the INVERT mode, the operation is the opposite of what is described below.

Case 1: light *is* sensed as the i^{th} stage is scanned.

As soon as the data transfer switch is turned on by the appearance of a "1" in the i^{th} stage of the shift register, a negative pulse is applied to DATA. The presence of light on the appropriate phototransistor, however, causes the pulse to disappear after a few microseconds. If the "memory" capacitor, C_M, had been charged by the previous scan, it is discharged; if not, it may be charged momentarily and then discharged. In either event, it is left discharged, and the output switch is left "open." The drain of the output switch is connected to the bimorph center conductor; if the switch is open, the bimorph does not vibrate.

Case 2: light *is not* sensed as the i^{th} stage is scanned.

A negative signal appears at DATA as before, but it remains negative at least until the "1" level on the data transfer switch has shifted to the next stage[9]. The data transfer switch therefore "opens" while the DATA pulse is negative,

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[8] The "camera" may be the actual camera of the Optacon, the camera of another "master" Optacon, or the simulated camera in the cassette trainer.

[9] Actually, the DATA signal remains negative until a phototransistor which has been illuminated is scanned.

thereby trapping charge on C_M. The gate of the output switch therefore remains "high" *throughout the entire scan period*, and, in fact, until the appropriate phototransistor is once again illuminated. As long as C_M is charged, the bimorph vibrates. C_M thus acts as a memory element which is refreshed on each scan.

The bimorph driver chips in the display unit are used in the same manner as the camera scanner. The DATA signal is a short negative pulse which always "closes" the output switch of the i^{th} stage for a short interval. No charge is trapped on C_M since the DATA pulse disappears before the "1" level is shifted to the next stage.

This description of the operation of the bimorph driver chip was presented to demonstrate the versatility of the chip and to set the stage for a discussion of some of the special problems which had to be solved in the design of the chip. The chip must be fabricated by a process which is a modification of standard MOS integrated circuit processing.

There were two significant problems which had to be overcome in the development of the chip. One was due to the high voltage requirement of the bimorphs; the other was due to the application of a large square-wave voltage to the bimorphs to make them vibrate when the appropriate output switch devices on the chip are closed.

A detailed description of the problems is given in a Stanford Electronics Laboratories report[10]. A brief summary is presented here.

1. High Voltage

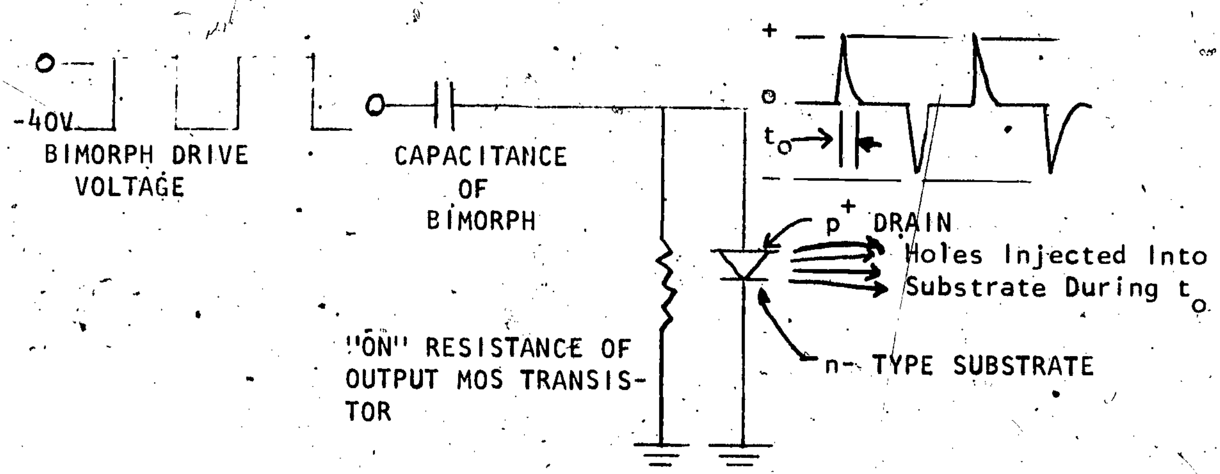
The fabrication of p-channel MOS circuits capable of withstanding high voltages (-40 volts) requires special techniques and greater chip area than is normal for standard p-channel MOS circuits. Deeper p^+-n junctions are needed to avoid surface breakdown. Long-channel devices, required to prevent punch-through, take up more real-estate. The n-type substrate must be heavily doped (n^+) in certain areas to prevent "field inversion," i.e., the creation of spurious MOS transistors where

[10] James D. Plummer, *MOS Electronics for a Reading Aid for the Blind*, Stanford Electronics Laboratories Technical Report No. 4828-6, August 1971, pp. 109-127.

metal carrying high voltages bridge two adjacent p^+ regions. The n^+ doping requires an extra photomask, extra processing and more real-estate.

2. Bimorph Voltage Waveform

The square-wave drive on the bimorph causes holes to be injected into the substrate on the positive-going transitions of the square-wave wherever the output switch is closed (bimorph on). This is illustrated in the following sketch.



These holes diffuse outward, away from the point of injection. If some of them reach the p^+ region forming the drain of the MOS device to which the capacitance C_M is connected, the holes will be collected by this p^+ region and discharge C_M, thereby turning off the bimorph. In effect, the p^+ region where the holes are injected forms the emitter of a spurious PNP transistor, the intervening n-type substrate forms the base, and the p^+ region connected to C_M forms the collector.

This "PNP problem" is solved by: (a) physically separating the "emitter" and "collector" as far as possible; (b) doping the intervening substrate to make it n^+, thereby reducing the surface lifetime of the holes; and (c) placing the grounded source of the output MOS transistor between the point of injection and C_M, thereby providing an intervening collector to intercept the holes before they can reach the p^+ region connected to C_M. As an added precaution, the risetime of the bimorph voltage waveform is slowed to reduce the transients which cause the injection of holes.

The n^+ doping requires the same extra photomask and processing steps as it does to avoid the "field inversion" mentioned above. Therefore, the n^+ step can be eliminated only if the bimorphs could be operated at lower voltage, and the excitation method could be redesigned to eliminate the massive injection of holes.

The PNP problem necessitates a chip layout which requires much more silicon real-estate than if the problem were not present. Large real-estate requirements lower yield and allow fewer chips per wafer thereby increasing the cost of each good chip. Because special processing is required for high-voltage operation, there are fewer manufacturers willing to gear up for relatively small production runs; consequently, the cost of processing a wafer is larger than if standard processing could be used.

Figures 4.7 through 4.10 are microphotographs of the bimorph driver chip taken with the aid of a scanning electron microscope. Figure 4.7 is an overall view of the chip. The top third of the chip is occupied by the 12-stage shift register. The top row of large rectangles midway down the chip are the memory capacitors, C_M. Just below these are large rectangles of metal which are presumed to be used to minimize the voltage drop along the long p^+ region which runs horizontally across the chip and forms the sources of the output MOS transistors. The source currents flow along this p^+ region and off the chip to an external ground via the SOURCE OUT connections. This p^+ region lies between the drain regions of the output switches and the memory capacitors to minimize spurious PNP transistor action as described above. The regions at the bottom of the chip and shaped like inverted U's are the gates of the output MOS transistors. Between the legs of the U's are the connections to the drains of the output devices; these are connected through the package leads and Optacon wiring to the bimorph center conductors. These drain regions are where the holes are injected which cause the spurious

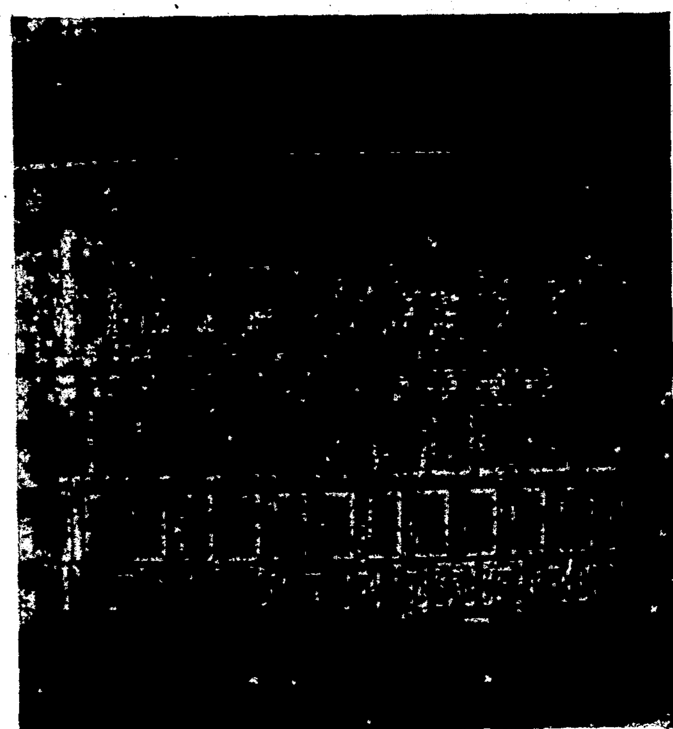


Figure 4.7. Bimorph Driver Chip

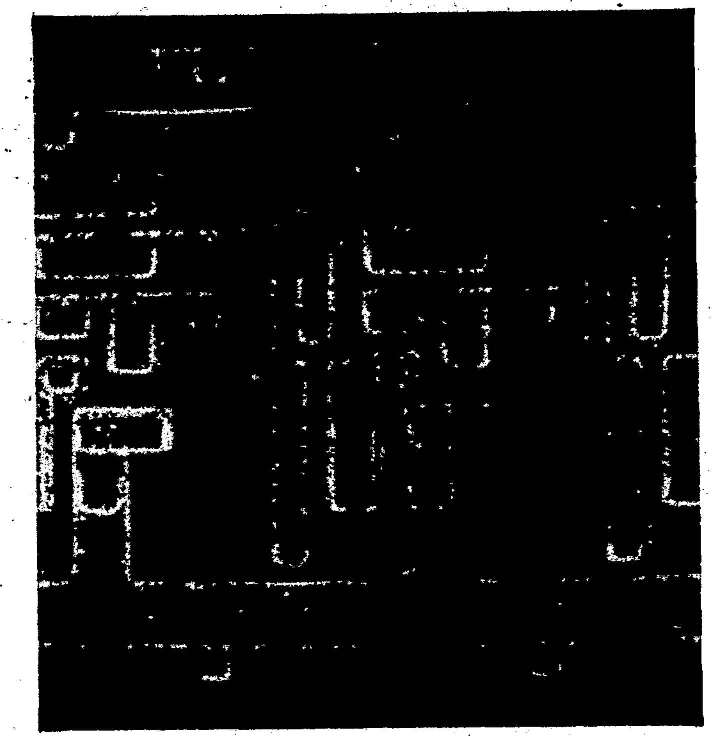


Figure 4.8. One Stage of Dynamic Shift Register (300X Magnification)

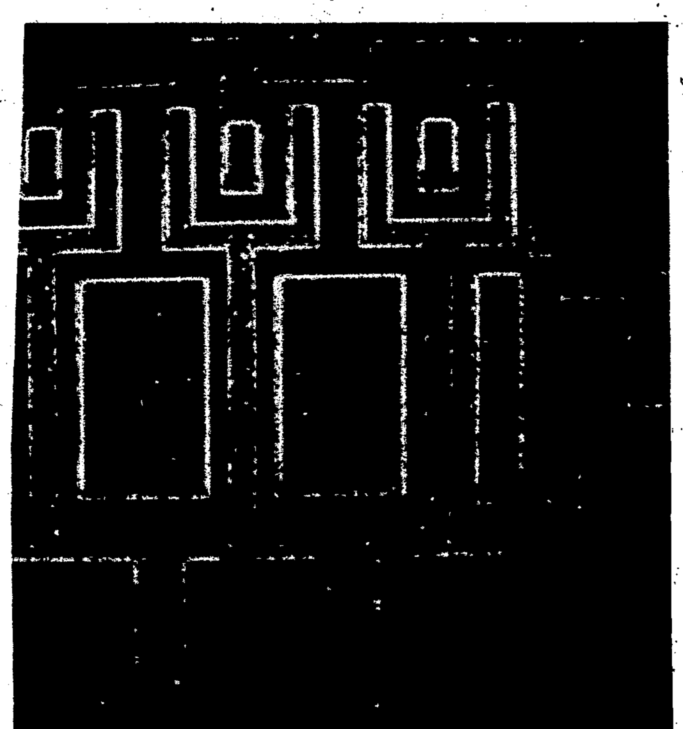


Figure 4.9. Memory Capacitors and Out-Put Switches (200X Magnification).

Figure 4.10. Adjacent Metal Runs Crossing Steps Formed by p^+ Regions (5000X Magnification).

PNP problem. Only through very careful layout and design of the process was this problem solved.

Figure 4.8 shows a view of one stage of the shift register. The small, roughly square depressions are the contacts between the metal interconnections and the p^+ source and drain regions. The large depressions are gate regions. The metal pattern is misregistered slightly high, but the dimensions used in the chip geometry are sufficiently conservative to allow for misregistration of this small a magnitude. It is impossible to obtain perfect registration of the various mask levels of an integrated circuit; the design of the patterns must allow for some misregistration.

Figure 4.9 shows a portion of the chip which includes parts of the memory capacitors, the large source region of the output switches, and the U-shaped output MOS transistors with the drain contacts between the legs of the U's. Figure 4.10 shows a highly-magnified region where two adjacent metal runs cross steps formed where p^+ regions adjoin n-type regions. The metal flows smoothly across the steps as it should. If the metal coating is too thin or the runs too narrow, opens may occur at the steps, causing functional failure. If the metal runs are too close together, filaments of metal may bridge the gap, causing short circuits. The lumps on the metal do not detract from the operation of the circuit. The microscopic examination of the chip indicates that its geometries were conservatively designed, so that yield problems should not arise from this quarter.

The cost of the bimorph driver chips is $15.35 per packaged circuit in lots of 1,000. Yield data were not available. Since the Optacon uses 14 drivers, the cost of the bimorph drivers is $215 per Optacon vs $75 per Optacon for the silicon retina chip. While yield figures are unavailable, it is reasonable to assume that if the bimorph system could be redesigned to lower voltages and to avoid massive injection of holes, the cost of the bimorph driver chips could be significantly reduced.

4.1.7 Circuit Layout

The printed circuit boards reveal several minor deficiencies.

4.1.7.1 Printed Circuits

While the printed conductors are separated sufficiently, many of the printed board notes are unacceptably close to the adjacent conductors and can be expected to short out many boards to bring down the PC board yield and therefore, force up the price (A case in point is the "2 NOR1" as shown).

Military specifications do not permit the sharp angles on conductors as used in the Optacon, but require rounded edges. The sharp angles require more stringent control in the etching process and are more susceptible to corrosion.

4.1.7.2 Soldering

Board design requires soldering on both sides of the printed circuit board. This fact prevents fully automatic soldering, thereby raising costs.

An unusual and costly method of interfacing one board to another is used for boards TSI-02001-007 and TSI-02001-001. The boards are connected by 18 metal "stilts" that are soldered to each board. This configuration not only takes costly manpower to assemble, but in order to repair most components on either board, the 18 stilts must be unsoldered and resoldered after the repair.

4.1.7.3 Component Layout

Sockets are used for the RCA CMOS Integrated Circuits (IC) and the Dual In-Line Packages (DIP), but not for the other DIP's or the transistors. The sockets were probably used for the CMOS because of that logic family's susceptibility to damage during installation. The use of sockets for the CMOS circuitry proves that sockets are acceptable; they should be used for the other DIP's and some of the transistors. Sockets allow I.C.'s to be placed into and removed from the circuit without soldering. This feature would add very little initial cost to the instrument and would reduce the maintenance costs involved in replacing components (a complicated process for some Optacon components as mentioned previously).

A standard practice involving socketed components has been violated in the Optacon in order to ease printed circuit layout. Normally, when a number of components are socketed in a group, they are referenced identically to prevent orientation confusion in replacing the IC (so it won't be plugged in backwards). Board TSI-02001-002 ignores this convention.

The 24 pin integrated circuit flat packs used on Board TSI-02001-001 are difficult to solder and would be simpler to install and replace if they were repackaged into a DIP configuration. The leads on both of the flat packs appear to be unreasonably close to the conductor plane below them. Again a DIP is suggested or a modification in the printed circuit.

Some of the dual inline packs on Board TSI-02001-005 are the ceramic packages (as opposed to the plastic packages used elsewhere). The ceramic packs have more rugged specifications and also have a higher price (up to twice the cost of the plastic packs). The ceramic packs are not needed in the Optacon but their elimination would only reduce the cost slightly.

On Board TSI-02001-005 a .1Mfd capacitor has been "tacked" onto the board by soldering to legitimate board components. The printed circuit should be modified to accommodate this component.

4.1.8 Power Bus Noise

It is very important in the design of a digital electronic circuit (as well as analog circuits) to provide adequate filtering and decoupling of the power buses to minimize spurious signals on these lines which could cause improper operation of the system. Such spurious signals are commonly referred to as "noise." This problem is critical in high-speed circuits where pulses a few nanoseconds long can cause spurious operation. Fortunately, the Optacon is a low-speed circuit and uses low-speed digital integrated circuits; consequently, the noise problem is less severe. Noise measurements were made on the power buses of the Optacon bearing Serial No. R507-012. The results are given in Table 4-1. These noise voltages are well below levels which would be likely to cause malfunction.

4.1.9 Maintainability

Field maintenance of the Optacon is very difficult because parts of the circuit are inaccessible for probing while the Optacon is in operation. It is suggested that extender cables be provided so that the circuit boards can be connected and operated while removed from the Optacon housing. TSI has special jigs for testing the circuit boards, but these would not reveal a fault in the Optacon wiring harness.

While it is conceded that certain major maintenance tasks, especially those involving the tactile stimulators, are best performed at the factory, minor electronic repairs could easily be performed by any competent electronics technician, given a kit of tools, spare parts, and the extender cables suggested above. If Optacons come into wide use and blind users become dependent upon them in their daily lives, these users will not be able to tolerate long periods of down time. The ability to perform minor maintenance locally should not be precluded simply because some of the components are inaccessible during normal operation.

Table 4-1. Measured Power Bus Noise on Optacon Serial No. R507-012

BUS	DESCRIPTION OF NOISE	WHERE MEASURED[11]
+5V	30 mV pk. to pk., rep. rate twice master clock frequency	Pin 1 of integrated circuit A
-7.5V	Positive pulse 110 mV x 160 μ sec once every 4 m sec, which is the timing of the $\emptyset_p$ pulse.	Pin 7 of integrated circuit D
-19V	Positive pulses alternately 50 mV and 25 mV high by 4 μ sec wide. Pulses are synchronous with the $\emptyset_1$ and $\emptyset_2$ shift register clock pulses.	Measured at test point V_s
-45V	General hash approximately 20 mV plus positive spikes of approximately 50 mV spaced at 80 μ sec.	Output end of R14, a 22 Kilohm resistor

[11] See TSI Inc., documentation, *Circuit Description of the Optacon Model R-1B*, 5 June 1972.

4.1.10 Documentation

The documentation of the Optacon is satisfactory. It includes detailed circuit and timing diagrams so that minor field maintenance and testing can be performed by qualified technicians. Major maintenance, such as replacement of a bimorph requires special jigs. This must be considered a factory repair.

4.2 VISUAL DISPLAY

4.2.1 General Comments

The design of the visual display is straightforward. The display is connected by a cable to the Optacon during training sessions to provide a visual display of the tactile image being presented to the blind user. Several Optacons and the display can be slaved to a master Optacon by means of interconnecting cables. The connecting cable and a.c. power line of the display are permanently attached and cannot be misplaced.

4.2.2 Electronic Design

The electronic design is straightforward, and can be thought of as a camera in reverse. The display itself can be visualized as a grid of 6 wires representing columns and 24 wires representing rows. A light-emitting diode (LED) is connected between a "column" wire and a "row" wire at each intersection of the grid so that when a "row" is connected to ground and a negative voltage is applied to a "column," the LED for that row and column is turned on. There are 144 such LED's.

The display contains its own power supply. The primary power comes from the commercial lines. Since the display is normally used in classrooms and demonstrations, battery operation is not required and was not designed into the unit. The unit draws a minimal amount of power from the Optacon into which it is plugged to drive two bimorph driver circuits which are used to scan the rows of the display. A small amount of power at -7.5 volts is also drawn from the Optacon to power a CMOS circuit in the display.

Two bimorph driver chips are used to scan the rows of the display, one for the odd rows, one for the even. A DATA IN signal, consisting of a negative pulse, is applied to the DATA IN pin of both circuits once every clock cycle. The pulse comes and goes while the "1" level remains on any particular stage of the circuit. The corresponding row of the display grid is consequently grounded for approximately 112 microseconds (through a pair of external buffer transistors). Any LED on that row for which the column wire is held high will light for 112 microseconds with a duty factor of slightly less than 1/25[12]. Column data are brought into the display via six wires. Each wire is coupled to a column grid wire by a pair of buffer transistors.

4.2.3 Integrated Circuits

The display uses two bimorph driver chips identical to the ones described in Section 4.1.6. It also uses one commercially available CMOS chip.

4.2.4 Documentation

The documentation is sufficient to permit field maintenance by qualified technicians.

4.3 CASSETTE TRAINER

The cassette trainer was not evaluated in detail because only relatively few of them are produced, and it is a training tool rather than a device to be used by trained users.

During a conference with TSI this evaluator pointed out the possibility of reducing circuit complexity in one part of the circuit. Most of the problems with the trainers have been mechanical or electromechanical rather than of an electronic nature.

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[12] The frame period is 25 clock cycles, 24 for shifting the "1" level through the shift registers plus one idle clock cycle used for synchronization.

4.4 RECOMMENDATIONS

4.4.1 Immediate Changes

The following changes are recommended in the present generation of Optacons:

a. Shockproof bimorph pins. Either make the pins of insulating material or put insulating sleeves on the bimorphs.

b. Seek a better packaging yield on the reti· hips. A 50% rejection rate due to packaging seems excessive.

c. Provide a field maintenance kit including extender cables.

d. Redesign printed circuit boards to eliminate proximity of notes to circuits and sharp bends in circuits in order to increase production yield of circuits and to minimize potential hazards of shorts.

e. Redesign boards so all soldering is accomplished on one side of the board in order to accommodate fully automatic soldering.

f. Eliminate 18 metal "stilts" connecting boards TSI-02001-001 and TSI-02001-007.

g. Use I.C. sockets throughout for ease of repair.

h. Replace 24 pin flat pack I.C's with DIP configuration. Replace ceramic packages with plastic packs.

i. Integrate the .1 Mfd capacitor "tacked" onto board TSI-02001-005 with printed circuit.

4.4.2 Future Changes

The following changes are recommended in any redesign of the Optacon which may be undertaken in the future:

a. Correct the "race" problem described in Section 4.1.4.

b. Use a self-scanned camera chip to reduce the number of wires in the cable. It is understood that such a chip is planned for the next generation of Optacons.

c. Expend further effort to reduce the voltage requirement and complexity of the bimorph array. This subsystem currently contributes approximately one-third of the cost of the Optacon.

5. OPTACON MECHANICAL EVALUATION

The Optacon has been evaluated for its ability to withstand normal use and anticipated misuse. Anticipated misuse includes anticipated environmental extremes.

5.1 NORMAL USE

Operation of the Optacon with respect to normal use was evaluated in the laboratory through life testing. The results of the life test are presented in Section 7.

Forty-six Optacon units were placed in various schools for the blind and operated by the teachers and students. The results of these field tests are presented in Sections 2, 8 and 9.

In general, the operation of the Optacon under laboratory life testing indicated that the units have a long life expectancy. However, in field testing, the failure rate (mean time between failure-MTBF) was approximately 41 hours (see Reliability-Section 8). These facts suggest that the Optacon is not "ruggedized" for careless handling.

Forty-one hours mean time between failure is not considered acceptable for this type of instrument. If this figure is realistic, some redesign is required to improve the reliability of the unit under normal use conditions.

A major problem in normal use is the sensitivity of the vibrating reed array to wear and to foreign matter introduced into the small reed openings. This is a result of normal contact with oily and dirty fingers of the users.

Another major problem associated with normal use has been stripped camera thumbscrews. A review of the thumbscrew design indicates not enough thread engagement for reliable operation. It is recommended that the thumbscrew be replaced by a commercial spring clip for increased reliability and lower cost.

A number of failures occurred during field testing. The service records indicate that the units had both mechanical and electronic failures. No one unit had the same recurring failure, but some units had more than one failure.

The mechanical failures listed below occurred during field testing. These failures were not attributed to abuse or misuse but were considered as failures during normal use. The failures listed in the field reports include:

- Stripped thumbscrew
- Bent stimulator pins
- Loose camera brackets
- Loose camera mirrors
- Loose control knobs
- Loose mirror brackets
- Loose camera zoom button.

5.2 ANTICIPATED MISUSE

The Optacon field tests indicate that the Optacon is not as rugged or durable as desired. Also, the unit is not adequately designed to withstand nuisance type failures.

Recommendations to improve the Optacon's ability to withstand anticipated misuse are as follows:

- Housing should be fabricated of a high impact, energy absorbing plastic.
- The present Optacon is heavy. Reducing the weight of the Optacon would improve its ability to withstand falls.

- The lens retainer should be redesigned to provide a positive lock on the lens elements to withstand shock loading.
- A stronger adhesive should be used to cement the mirror to its mount. The present epoxy is not strong enough to withstand shock loading.
- The camera cable should be reinforced. It should be spring-coiled to reduce its normal length and make it less prone to sharp bending and accidental snagging. A stronger cable strain relief at both the camera and Optacon ends is desired.
- A removable cover plate should be designed for the camera to seal the optics against dust and moisture during storage and carrying.
- Rubber feet should be added to the chassis to lessen chances of sliding off a table or other surface.
- The leather carrying case has protrusions that are susceptible to accidental snagging on foreign objects. A smooth surfaced carrying case should be provided.

5.3 ENVIRONMENTAL TESTING

The Optacon was tested under various environmental conditions to determine its ability to withstand extreme heat and cold, low pressure, mechanical shock, vibration and thermal shock. The test procedures outlined below cover the specific details of these tests. A summary of the test results and recommendations is presented in a latter section of this report.

Prior to proceeding with any of the test methods, the test item was operated under standard ambient conditions and a record made of factors necessary to determine compliance with the required performance. The test data include identification of test equipment and accessories as well as the actual test sequence. Test conditions were recorded periodically during the test period.

5.3.1 Altitude Test

5.3.1.1 Purpose

The altitude test was conducted to determine the effects of reduced pressure on the equipment such as would be encountered during shipment in airplanes or operation at high altitudes.

5.3.1.2 Procedure

The equipment was placed in an altitude chamber and the pressure lowered to -30m. Hg or 260,000 feet above sea level. The reduced pressure was held for one hour. The chamber was then returned to normal pressure and the Optacon operated and inspected for damage.

5.3.1.3 Results

N t mechanical or electrical failure occured and the Optacon was satisfactory performance after the test was concluded.

5.3.2 perature Test

5.3.2.1 Purpose

This test was conducted to determine the resistance of equipment to elevated temperatures as may be found either in storage or under severe service conditions.

5.3.2.2 Procedure

The Optacon was placed in the temperature chamber and the chamber temperature raised to 160° F and held for 48 hours while maintaining the humidity at 15%. After the elapsed time the chamber was cooled to ambient and the Optacon was allowed to cool. After cooling the Optacon was operated and inspected for damage.

5.3.2.3 Results

After 48 hours of exposure to 160°F, the Optacon suffered no apparent mechanical or electrical failures and was judged to be in satisfactory working order.

5.3.3 Low Temperature Test

5.3.3.1 Purpose

The purpose of the low temperature test was to determine the effects of low temperatures upon the equipment during storage or transportation.

5.3.3.2 Procedure

The Optacon was placed in the temperature chamber and the temperature lowered to -30° F and maintained for 24 hours. The chamber temperature was then allowed to rise to ambient and the Optacon was given sufficient time to reach ambient. The Optacon was then operated and inspected for damage.

5.3.3.3 Results

The Optacon experienced no failures during this test and was in perfect operational order afterwards.

5.3.4 Temperature Shock Tests

5.3.4.1 Purpose

This test was conducted to determine the effects upon the Optacon of sudden changes in temperature of the surrounding atmosphere.

5.3.4.2 Procedure

The Optacon was placed in the test chamber and the temperature raised to 75° F and held for two hours. Next the chamber temperature was reduced to -30° F and held for two hours. Finally the chamber temperature was again raised to 75° F and held for two hours. At the conclusion of the final test, the chamber temperature was returned to ambient and the Optacon given time to cool. After cooling, the Optacon was operated and inspected for damage.

5.3.4.3 Results

The Optacon suffered no failure as a result of the test and operated perfectly afterward.

5.3.5 Vibration Tests

5.3.5.1 Purpose

The purpose of this test was to simulate the vibration likely to be encountered during unit shipment and to determine its effects upon equipment operation.

5.3.5.2 Procedure

The Optacon was secured to a vibration table and the vibration level set to simulate the conditions onboard a propeller driven aircraft. This vibration level was maintained for four hours. At the test's conclusion the Optacon was operated and inspected for damage.

5.3.5.3 Results

The Optacon suffered no damage during this test and was in satisfactory operational order.

5.3.6 Mechanical Shock Tests

5.3.6.1 Purpose

The shock test simulated medium impact loading which may be imposed upon the Optacon during shipping and handling.

5.3.6.2 Procedure

The Optacon was placed in normal position on a bench, and using one edge as a pivot, the unit was tilted until the opposite edge was at 45° with the horizontal or four inches, whichever came first. The unit was then allowed to drop freely to the horizontal. The test was repeated using the other practicable edges of the same horizontal face as pivots for a total of four drops. Then the unit was turned upside down and the test procedure repeated. At the conclusion of the eight drops, the Optacon was operated and inspected for damage.

5.3.6.3 Results

The Optacon was not damaged by this test and operated perfectly afterwards.

5.3.7 Recommendations

The Optacon has withstood the various mechanical tests very well indicating all materials and components used are capable of withstanding anticipated environmental extremes. In view of these results we have no further recommendations for improved design features with regard to withstanding anticipated environmental extremes.

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6. PRODUCTION COSTS

6.1 GENERAL ANALYSIS

The principal sources of production costs are the product specifications and the manufacturing procedures. These items are interrelated. A change in specifications can affect the cost of production. Instruments such as the Optacon require a great deal of effort to minimize the production cost. The discussion below indicates potential areas of cost reduction.

6.1.1 Product Specification

Manufacturing costs related to product specifications are numerous. Specifications affecting costs include tolerance, finishes, materials, fasteners, surface embellishments and the use of standardized components.

6.1.1.1 Tolerances

Precision components can be difficult and expensive to manufacture. They require additional set-up time to machine, slower machining time and costly inspection procedures to determine whether the tolerances are being held. Tolerances on all dimensions should not be more restrictive than ±.01 for low cost machining. A tolerance of ±.005 is good practice for items that require dimensional control or lend themselves to machining in accurately controlled jigs, holding fixtures or numeric controlled equipment. The tolerances specified on the Optacon drawings are normally ±.010 and ±.005. These are considered good engineering practice and are not over-restrictive dimensional control. Examples of restrictive tolerances which can be opened up are noted as follows:

Drawing		Dimension
R11004-A	Contact Button	Headheight of .005 ± .001
R10019-A	Leaf Spring Contact	Radius .325 + .000 - .002

R11018-A	Slider Block	Slot Depth .035 ± .000 (impossible)
02040-P-A-B	Thumbscrew	Engagement Length .313 ± .002

6.1.1.2 Surface Finishes

Standard machining practices provide acceptable surface finishes on most items with the exception of such operations as shearing, stamping, saw cutting and rough machining. As a result, a surface finish of 63 microinches can be specified on any component used in the Optacon without incurring additional production cost. The specification of a 63 microinch surface finish is accepted as a cost and quality control optimization.

6.1.1.3 Materials

Optimization of production costs due to materials is based on the utilization of the most readily available material in a configuration of minimum acceptable weight. Materials used in the Optacon include aluminum, brass, nylon, glass, and acrylonitrile Butadiene Styrene (ABS). These are all readily obtainable, low cost, and easy to machine. The part configurations are such that a minimum weight is used. Production costs due to materials on the Optacon have been well optimized. The only further reduction in costs that could occur would be if some of the components such as the chassis base were molded out of a plastic instead of fabricated from aluminum. A slight savings in materials and fabrication costs would result.

6.1.1.4 Fasteners

Fasteners can add significantly to production costs. The most effective optimization of fastener costs is to reduce their number. Elimination of fasteners not only saves material costs but lessens fabrication costs by reducing the number of holes drilled and reduces assembly costs by reducing the time required to assemble components. The Optacon contains a number of fasteners that could be eliminated.

In particular the number of fasteners used in the camera could be significantly reduced by using molded camera components. In this way many parts could be combined into single elements. Likewise several of the chassis screws could be eliminated by molding the chassis and cover.

6.1.1.5 Surface Embellishments

Additional production costs are incurred when secondary surface treatment operations such as rounding corners, painting, anodizing, and polishing are performed. The Optacon has various parts which have been treated in the above manner. For example, the chassis and cover and the camera housing are all of anodized aluminum. The uses of such surface treatments in the case of the Optacon have not been found to be excessive. There is a definite need for all apparent surface embellishments on the Optacon parts and the additional production costs are not severe as none of these treatments is very costly and they are used only on a minimum number of parts.

6.1.1.6 Commercial Parts

Substantial savings in fabrication costs can be realized if off-the-shelf commercial parts are substituted whenever possible for in-house fabrication. Commercial vendors can produce cheaper parts because of their large volume production and specialized tooling and machining techniques. The Optacon possesses numerous commercial parts, such as the majority of electronics components. Aside from fasteners, the mechanical components are all custom fabrications, and there are only a few places where commercial parts could be used. These include the control knobs, the camera thumbscrew and the battery clamps.

6.1.2 Manufacturing

Manufacturing costs are dependent upon the type of tooling and fabrication techniques used. Tooling and fabrication techniques are in turn dependent upon the production volume. Small volume production cannot justify elaborate tooling or the use of specialized fabrication techniques such as a stamping process. The Optacon production, with its projected volume of only 25 units per month and its involved assembly procedures, does not lend itself to low-cost production procedures. However, cost savings can be realized by using special purpose tooling and assembly fixtures and by reducing the number of component parts.

6.1.2.1 Tooling

Special jigs and fixtures can be used to rapidly load and unload parts during machining and to provide automatic dimensional control. The Optacon, even with a production rate of 25 a month, can make use of such tooling to lower production costs. The use of jigs and fixtures can be justified for fabricating the chassis and cover, the camera parts, the electronic PC boards, and especially the stimulator array. Special dies could also be justified to cut out the leather case and to stamp out light metal parts such as the contact springs in the camera housing.

6.1.2.2 Castings and Moldings

Cast and molded parts are generally cheaper than machined parts because many pieces can be produced at one time and practically no material is wasted. Production volume does not have to be large as the tooling can be made to accommodate a minimum number of parts. The Optacon contains several parts which could be produced more economically by such processes. For example, the chassis and cover could be of molded high impact plastic. Likewise the camera housing could be made of molded plastic and perhaps the optical lenses could be of molded acrylic instead of glass. Finally the stimulator finger plate could be of molded ABS.

6.1.2.3 Stampings

Moderate numbers of thin metal parts can be economically produced by using a stamping process. Parts can be produced complete with holes in one operation. Even specially shaped holes can be stamped. Several components of the Optacon are amenable to this process. They include many of the stimulator pieces and the front and rear cover plates and the contact springs in the camera.

6.1.2.4 Special Machines

The use of specialized production machinery can be justified. Such equipment as automatic screw machines, Numeric Controlled (NC) milling machines, and turret lathes are valuable in reducing costs on production volume as low as 25 per month. The advantage of these machines lies in their ability to provide rapid metal removal and dimensional control of parts. Several of the Optacon parts can be produced by an automatic screw machine and the holes in the cover and the chassis can be gang drilled. Likewise, the various standoffs for the PC boards and several of the control knobs can also be produced by such equipment. Since the Optacon has only a few parts amenable to such production techniques, the production cost savings will be small but still worth going after for ultimate cost optimization.

6.1.3 Assembly

The major contribution to production cost is the assembly labor. The amount of labor involved depends upon the following factors:

- The type of production line used;
- The use of special assembly machines and tooling;
- The number of pieces to assemble per unit;
- The difficulty of assembly;
- The amount of testing required.

Examination of the assembly procedures of the Optacon can result in cost savings as this device lends itself to several cost saving procedures.

6.1.3.1 Production Line

With the production rate of 25 a month, an automated production line would not be economically feasible. However, a multiple station assembly line would be feasible. Various sub-assemblies like the PC boards, stimulator array and camera could be individually assembled and then all parts brought together for final assembly and testing at the appropriate time. With a multiple station arrangement, workers could be trained to assemble each component in the most efficient manner with a resulting cost savings.

6.1.3.2 Assembly Machines and Tooling

The use of specialized assembly machines, fixtures, and tooling can save considerable costs. These devices make assembly much easier for the worker and consequently increases his productivity. The Optacon has several sub-assemblies which would be amenable to specialized tooling. These include the PC boards, the electronics and especially the stimulator array. If specialized tooling can be found for the stimulator array, production costs could be substantially reduced. A large part of the total production costs of the Optacon lies in the assembly of the electronics and stimulator. The use of special solder tools, jigs and miniature tools can provide significant cost reduction in the assembly of these components.

6.1.3.3 Number of Pieces

The Optacon consists of a large number of individual components which must be carefully assembled for reliable operation. A reduction of the number of pieces would be economically advantageous and would provide greater reliability. Much of the electronics can be reduced by using integrated circuit technology with minature, specially designed, circuit chips that replace numerous standard components. The stimulator array also consists of a large number of tiny and delicate parts which are difficult to assemble. Reduction of the pieces in the stimulator array is not easily accomplished. A complete redesign would have to be done, requiring an extensive development program.

6.1.3.4 Assembly Difficulty

Production costs are greatly influenced by the difficulty of assembly. Parts which are difficult to mate because of poor design, or are small and delicate, require more time to assemble than larger parts. The Optacon contains many parts which present difficulty in assembly. The stimulator array is a good example. Not only are there many parts but each one is rather small and difficult to put together with ordinary tools. The use of special jigs and assembly tools should aid immeasurably in simplifying assembly.

Other areas in which assembly is difficult are the camera and the electronic wiring. Assembly of the camera can be simplified. Consolidating the number of pieces by using plastic moldings will reduce the number of fasteners and will simplify optical alignment.

6.1.3.5 Testing

As an instrument becomes more complex, the amount of testing to ensure reliability increases. The added cost due to testing can be reduced by more reliable assembly techniques, requiring tighter quality control on commercial parts, and by simplifying assembly. The Optacon requires significant amounts of testing to ensure reliability. The use of assembly jigs and machines can increase reliability over manual techniques of assembly and tighter requirements on some of the electronic parts supplied by vendors can also increase reliability. At the present time, many of the electronic components do not meet specifications and must be tested before assembly. Fewer assembly mistakes such as incorrect wire connections can be expected if the assembly were simplified by reducing the number of parts.

6.2 DETAILED ANALYSIS

A detailed review of the mechanical hardware of the Optacon has been made. Cost saving recommendations for each part are given below, and they should be used as a guide in the production of future units.

6.2.1 Detailed Part Review

The following is a part by part analysis of the Optacon with specific recommendations to lower production costs.

Part	
1. R-1 Chassis Base (R10011-A)	The tolerances on some of the switch mounting holes should be loosened. The entire housing could be molded of high impact plastic, saving fabrication costs, eliminating some fasteners and consolidating the chassis bulkhead into the chassis base.
2. R-1 Chassis Cover (R10010-A)	The cover should be made of molded high impact plastic without overlapping sides to simplify design.
3. R-1 Chassis Bulkhead (R10012-A)	This piece should be molded integrally with the chassis base, saving assembly and fabrication labor.
4. Clamp, Battery—Mod (R11023-A)	No change recommended.
5. Nameplate—Front (R10007-A)	The front nameplate should be molded integrally into the plastic chassis with raised lettering. If a metal nameplate is desired, a cutting die should be used to punch out the plate.
6. Rear Panel (R10008-A)	No change recommended.

7.	Thumbscrew Anchor (R12002-A)	This part should be replaced with a commercial spring clamp.
8.	Thumbscrew Holdown (02040-P-A-B)	This part should also be replaced with a commercial spring clamp. Machining, a spring pin and a threaded hold in the camera housing would be eliminated. A more mechanically reliable system would result.
9.	Clamp, Array (R10009-A)	A stamping should be used to lower costs over manual cutting methods.
10.	Stimulator Control Knob (R11001-A)	This custom fabrication should be replaced by a cheaper molded plastic commercial pointer knob. A custom molded knob would also be cheaper than a machined knob. The new knob should have a keyed hole to fit over a keyed shaft. Only one setscrew is needed and the knob will operate even with the setscrew loose. The setscrew should be coated with a sealant like "Locklite" to prevent loosening.
11.	Casing (R10018-A)	A cheaper plastic molding should be used for this part. This would allow consolidation with the bayonet sleeve.
12.	Leaf Spring Contact (R10019-A)	The leaf springs should be economically produced by using the stamping process.
13.	Receptor Case (R11002-A)	This part should be of molded plastic with integral locking elements, saving fabrication and assembly costs.

14.	Sensor Mount (R11003-A)	A plastic molding should be used to save fabrication costs.
15.	Contact Button (R11004-A)	The tight tolerance on the head-height should be eliminated as the mating contacts are spring loaded.
16.	24.9 MM Achromat Lens (.02079-P-A-A)	No change recommended.
17.	Locating Lug (R11005-A)	This part can be eliminated by molding locking elements into the Receptor Case.
18.	Retina Cover Glass (R11007-A)	No change recommended.
19.	Mirror Mount (R11009-A)	The mount should be integrally molded with the base block to reduce fabrication costs and to eliminate fasteners and alignment problems.
20.	Roller (R11011-A)	No design changes are recommended, but this part should be produced on automatic screw machines to lower fabrication costs.
21.	Bayonet Type Sleeve (R11012-A)	This part should be integrally molded into the plastic casing to reduce fabrication cost by eliminating fasteners and assembly time.
22.	Leaf Spring Mount (R11014-A)	Again this part should be molded integrally with the plastic casing and bayonet sleeve to reduce fabrication costs by eliminating two fasteners and assembly time.
23.	First Surface Mirror (R11017-A)	No change is recommended for the

mirror, but a stronger shock and heat resistant epoxy should be used to fix the mirror to its support.

24.	Zoom Slider (R11018-A)	A molded nylon piece is recommended.
25.	Zoom Button (R11019-A)	The button should be made of molded nylon to reduce costs.
26.	Schott Filter (R11020-A)	No change recommended.
27.	Lens Retainer (R11021-A)	This part should be redesigned of molded plastic to snap solidly into the lens mount to reduce fabrication costs and increase reliability.
28.	Lens Mount (R12003-A)	The lens mount should be molded integrally with the same slider.
29.	Front Roller Bearing Block (R12004-A)	No change recommended.
30.	Rear Roller Bearing Block (R12005-A)	No change recommended.
31.	Lens Spacer (02061-P-A-A)	A molding or stamping is recommended.
32.	Base Block (02063-A-A-A)	A plastic molding integral with the mirror mount is recommended. Some of the tolerances must be loosened for a molded part.
33.	Strain Relief Clamp (02101-R-B-A)	A plastic molded part is recommended.
34.	Front End Block (R11013-A)	The front end block should be molded integrally with the base block to save costs. The tapped hole for the thumbscrew should be eliminated by using a commercial

spring clamp to hold the camera.

35.	Dust Cover (02031-P-B-A)	A stamped metal cover would be ideal and should be used to save on fabrication costs.
36.	Vinyl Cover (R10013-A)	The Polyvinyl Chloride(PVC) should be die-stamped to exact specifications in one operation, saving fabrication costs.
37.	Top Plate (R1001-A)	A molded plastic plate should be used to lower fabrication costs. Tolerances on the rectangular hole appear over-specified.
38.	Spacer (R1002-A)	A stamped spacer is recommended.
39.	Stimulator Mount (02032 P-A-A)	A stamped part is recommended.
40.	Finger Plate (R12001-A)	A molded ABS part is recommended to eliminate the extensive machining cost involved in the drilling of the 144 holes.
41.	Bimorph (R14002-A)	A redesign of this element is desirable to eliminate the delicate fabrication and assembly procedures presently required. Advances in the state-of-the-art are required.

6.3 PRODUCTION COST ESTIMATE

A reliable cost estimate for the Optacon could not be obtained by FIRL. The principal reason is that prices on specific electronic hardware could not be obtained. Also, a detailed estimate of the assembly time, assembly procedures, and quality control procedures is necessary to develop a reliable estimate. This information was not available to FIRL.

Acceptable cost estimates on some of the components were achieved. However, these items do not constitute a significant portion of the total cost. Approximately 2/3 of the production cost is attributed to the cost of special electronic components and assembly of the stimulator array. Without reliable cost estimates of these two major items, a reliable cost estimate cannot be obtained.

A field trip was made to the production facilities for the Optacon. A review of the available drawings was also undertaken. In general it is estimated that a cost of $3500 to $4000 per unit is reasonable and reflects to a large extent man hours required to assemble the unit. Any effort to lower production costs must concentrate on redesign of the component parts to simplify assembly.

6.4 CONCLUSIONS AND RECOMMENDATIONS

In reviewing the mechanical design of the Optacon, we feel that extensive effort has been made to minimize production costs. Production costs can be lowered by using molded plastic parts in the camera and housing and by using stamped metal parts whenever possible. The savings resulting from such procedures will be no more than 10% of the production costs. Fully 2/3 of the production costs lie in the assembly of the stimulator and in the electronics. Any effort to substantially reduce production costs will have to deal with these areas.

As a result of our analysis of production costs, the following recommendations are made to reduce costs.

- Molded plastic parts should be used in the camera and housing and metal stampings used wherever possible.
- A major development effort to simplify circuitry and the stimulator array should be started.
- The production rate should be increased to allow the use of more sophisticated tooling, fixturing and automated assembly devices.

7. LABORATORY LIFE TESTS

Laboratory life tests were conducted on four Optacons, four Visual Displays and one Cassette Trainer. These tests were designed to simulate actual use patterns and to compress the time scale in such a manner as to realistically simulate extended usage in a manageable period of time. Steps were taken to ensure that critical components were vigorously exercised under user conditions.

7.1 TEST RATIONALE AND PROCEDURES

A special jig was designed to hold and maneuver all four Optacon cameras in a manner similar to actual use. The jig caused the cameras to continuously move back and forth across a sample page of printed material with a downward pressure designed to emulate a human operator. This meant that the rollers were properly operated and the camera was presented with actual letters which in turn operated the electronics in a real sense. Sample paper was periodically changed so that different electrical pathways were excited. Figure 7.1 shows the test set-up. Note the "finger" placed over the bimorph stimulator. Figure 7.2 shows the casting used to make the simulated finger. The material (RTV) was chosen for its reasonable representation of the texture of human flesh and the weight of a finger.

Detailed records of operation were generated daily. Weekday schedules included shelf storage with no charging from 9:00 AM to 1:00 PM, Tracking Life Test from 1:00 PM to 5:00 PM with no charging and Tracking Life Test with charging from 5:00 PM to 9:00 AM. The Weekend schedule was a continuous operation with charging. Daily, weekly and monthly test procedures were carried out. Daily Tests, were performed Monday through Friday at 9:00 AM. When weekly and/or monthly inspections were due, they were also performed at 9:00 AM. Hours of operation in various modes with

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Figure 7.1. Casting and "Finger" for Loading Bimorph Stimulators

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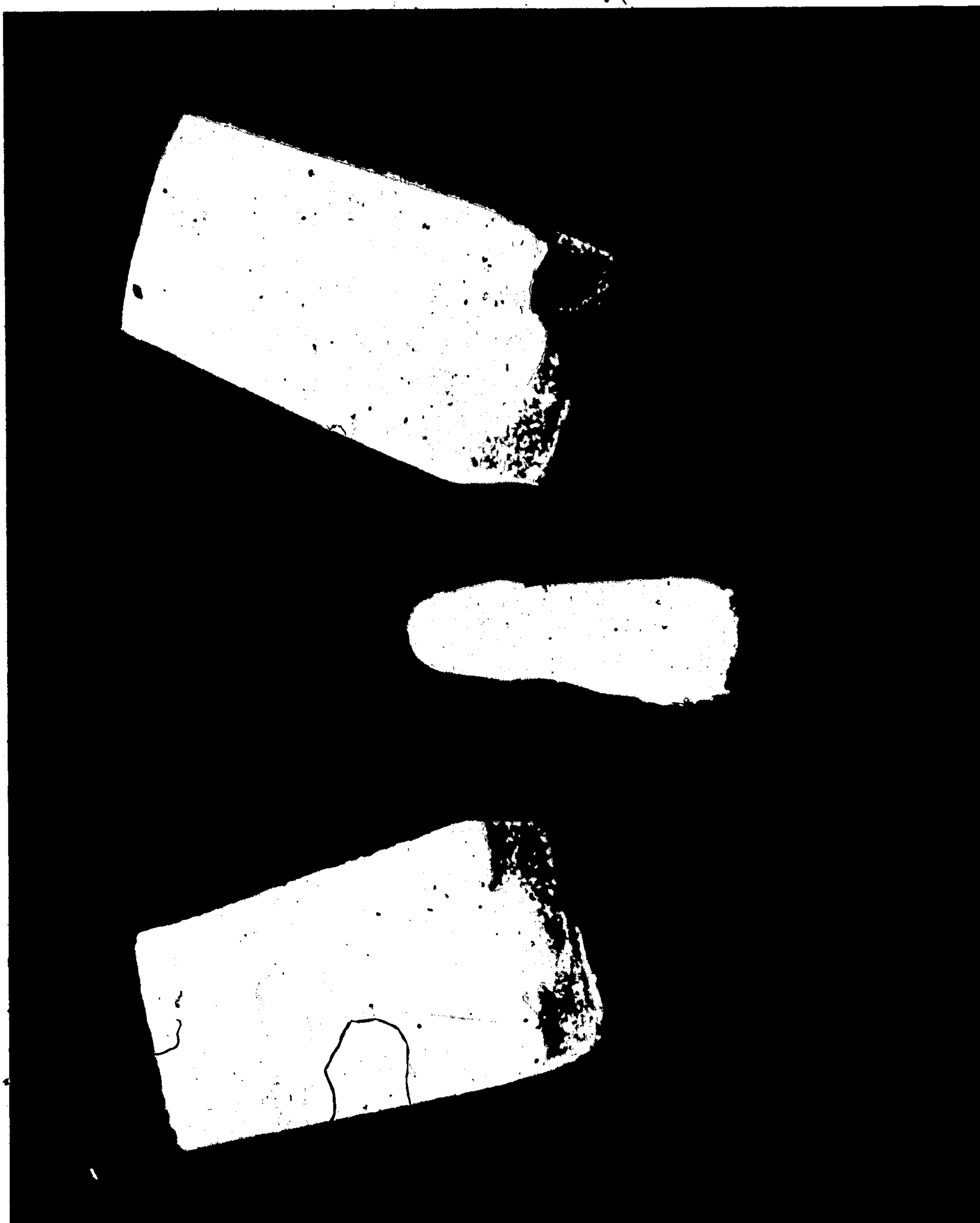

Figure 7.2. Life Tests

comments was recorded. Records were kept of comments directed at specific units.

7.2 LIFE TEST RESULTS

The Optacon and Visual Display life tests were continued for approximately 100 days. The Optacons were operated on battery power for a total of 274 hours and on the charger/AC adapter for 1899 hours. The cameras were scanned across the printed page at a rate of 6 inches every 5 seconds for a total of 209.5 miles.

A special electronic bench test unit was purchased from TSI for testing individual stimulators to determine whether coupling exists between adjacent bimorphs. Coupling did in fact exist; however, TSI had already isolated the problem and subsequently recalled all units for repair. Tighter quality control has minimized the problem.

The Cassette Trainer was operated for a total of 913.5 hours. Failure was the result of the tape cartridge's stretching to the point where it no longer wound tight. It eventually "looped" around itself and bound up.

When units ceased operating, the battery voltage had dropped to 3.0 ±.2 VDC. Normal operation was possible at voltages above this level. All batteries, after extended usage, failed during the 4 hour period when the Optacon was tracking on battery. As calculated in Section 2 (User Evaluation) of this report, the batteries can be expected to last 1 to 2 years under normal usage and proper recharging.

7.3 SUMMARY OF RECOMMENDATIONS

Laboratory Life Tests reflected an excellent performance record for the Optacon. The lone problem encountered was battery failure. As further study shows in this report, battery performance is acceptable. Nuisance problems such as an occasional "squeaky" roller are deemed minor. However, it should be noted that the Laboratory Life Tests did not

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subject the equipment to the mechanical shocks it receives in the field. Other sections in this report highlight field reliability problems. This implies that although the equipment is highly reliable when operated under ideal conditions and with careful handling, service calls are necessitated as a result of the relatively rough field handling.

8. RELIABILITY

8.1 METHODOLOGY

This evaluation consisted of an experimental determination of the mean-time-between failures (MTBF), based on data received from the life test and from the education evaluation contractor equipment.

A thorough reliability engineering evaluation was to be performed on the Optacon. This was to consist of a statistical study of data collected on the life test performed on four samples and of experimental data collected from the education evaluation contractor (AIR) performed on forty-six samples. The Laboratory life tests of the Optacon (see Section 7-Life Tests) did not provide sufficient information to form a realistic statistical data base; and, therefore, no conclusions can be drawn for the laboratory MTBF. However, adequate field data was accumulated from the experiment logs supplied by the education evaluation contractor.

In the usual reliability tests, there is a large number of initial failures due to defective parts and workmanship. This evaluation, however, is based upon the knowledge that sufficient burn in time has been performed at the TSI factory so that the infant mortality rate has decreased to the point where the unit exhibits a constant failure rate while in use under testing. This statistical evaluation assumes that the units possess identical characteristics and that they were operated under identical circumstances.

8.2 RESULTS

The Optacon field logs supplied each unit's total operating time for each reporting period. Table 8-1 shows the total operating time (in minutes) and total number of failures for each Optacon unit occuring during the project. An estimation of MTBF can be arrived at by dividing the cumulative operating time of all the Optacons by the cumulative number of failures as shown:

Table 8-1. Total Operating Time (In Hours) And Total Number of Failures for Each Optacon Unit During This Project

R-	T	F
12	4445	0
13	1770	1
14	60	0
15	5685	3
16	3840	1
17	0	0
18	1565	1
19	4350	1
20	2240	2
21	3375	2
22	2370	2
23	955	0
24	5210	0
25	4000	2
26	1840	1
27	3260	4
28	4875	2
29	2525	0
30	2300	0
31	1910	0
32	3030	0
33	2370	0
34	6350	0
35	3140	3
36	3255	2
37	6220	3
40	0	1
41	2500	2
42	2390	0
43	2235	1
44	5430	0
45	4210	4

R-	T	F
46	3665	1
47	1580	1
48	1760	2
49	2050	2
50	4455	2
51	3480	1
52	3755	0
53	4765	1
54	4255	1
55	555	1
56	4950	1
57	540	2
58	1850	2

Cumulative Operating Time = 135345 min 55

" " " = 2255.75 hours

Cumulative Number of Failures = 55

T = Operating Time (in min) During Project

F = Total Number of Failures " "

R = AIR Serial Numbers

Optacon MTBF = Total Hours/Total Failures
= 2255.75/55

Optacon Operating MTBE = 41 hours of Operating between failures.

Similar calculations can be made for the visual display and the tracking aid. Table 8-2 gives the total amount of minutes each visual display was in operation and the total number of failures occuring. Table 8-3 shows the same information as applied to the tracking aids under test. Their estimated MTBF are shown below:

Visual Display Operating MTBF = 376 hrs.
Tracking Aid Operating MTBF = 155 hrs.

Verification of the estimated operating MTBF was made using standard reliability mathematical techniques. The field data is described as resulting from a time-truncated test. The test assumed immediate replacement of failed units with the same constant failure rate. A 90% confidence interval can be determined for the MTBF for each of the units involved. A sample calculation for the Optacon units follows below:

$$\frac{2T}{\chi_4^2} < \mu < \frac{2T}{\chi_3^2} \qquad 1-\alpha \text{ confidence interval}$$

where χ_4^2 cuts off a right-hand tail of area $\alpha/2$ under the chi-square distribution with 2K+2 degrees of freedom, while χ_3^2 cuts off a left-hand tail of area $\alpha/2$ with 2K degrees of freedom.

T = 2255.75, K = 55, 0.90 confidence interval

$$\frac{2\ (2255.75)}{137.701} < \mu < \frac{2\ (2255.75)}{86.792}$$

Therefore, Optacon Operation MTBF falls within the following range:

33 hr <MTBF< 52 hr.

The above MTBF calculations reflect actual operation time. A (more applicable) reliability figure can be drawn from the actual (calendar) time between failures. This figure takes into account not only the periods in which the Optacons were operating, but also accounts for storage,

Table 8-2. Total Operating Time (In Hours) And Total Number of Failures For Each Visual Display Unit During This Project

V	T	F
1	1065	0
2	7425	1
3	4765	0
4	4130	0
6	5095	0
7	1850	0
8	6935	0
9	3535	0
10	7145	0
11	3055	0
12	4865	0
13	5900	1
14	4085	0
15	3775	0
16	4080	1
	67705	3

Cumulative Operating Time = 1128.43 Hours

Cumulative Number of Failures = 3

Table 8-3. Total Operating Time (In Hours) And Total Number of Failures for Each Tracking Aid Unit During This Project

T-	T	F
1	3815	0
2	1870	0
3	6650	2
4	2540	0
6	1850	0
7	1045	0
8	3140	0
9	555	0
10	2430	0
11	1760	0
12	1170	0
13	1260	0
14	3095	1
15	670	1
16	505	0
17	3790	0
18	1070	0
	37215	4

≅ 620.25 Hours

handling repair time, and shelf life. This figure is more realistic because it accounts for the damaging aspects of storage and handling. Since the field test period was approximately 178 days (until 27 June) the accumulated operating time for the 46 Optacons was 8,010 days. The estimated MTBF is therefore:

Optacon calendar MTBF = Total Days/Total Failures
= 8,010/55
= 146 days between.

Similar calculations for the Visual Displays and the Tracking Aids are as follows:

Visual Display Calendar MTBF = 890 days
Tracking Aid Calendar MTBF = 756 days

Again a 90% confidence interval can be established for the MTBF of the units, as defined above. The calendar MTBF for the Optacon is bounded by the interval calculated below.

$$\frac{2\ (8010)}{137.701} < \mu < \frac{2\ (8010)}{86.792}$$

$$116 \text{ days} < \mu < 185 \text{ days}$$

A further breakdown of the MTBF for the Optacon can be illustrated by examining the calendar MTBF for individual important sections of the Optacon itself. Results tabulated below were calculated with the same technique as that used for determining the calendar MTBF for the whole Optacon unit.

Array MTBF	= 8010/13 failures	=	616 days between failures
Battery MTBF	= 8010/4	=	2002 days
Power Timing Board MTBF	= 8010/8	=	1001 days
Comparator/Output Board MTBF	= 8010/4	=	2002 days
Camera MTBF	= 8010/11	=	728 days
Charger MTBF	= 8010/8	=	1001 days

8.3 SUMMARY OF RECOMMENDATIONS

- Results generated by this reliability study are questionable at best. Although sound engineering principles were employed to develop a usable model, the results are inconsistent and suggest that undefined factors were not taken into account. For instance, the laboratory life tests proved that the Optacon withstood extended use extremely well while the field results indicated that with the addition of real life handling, repairs were necessitated quite frequently. This suggests that the equipment does not have sufficient safeguards against handling and environmental parametes. However, our mechanical evaluation subjected the Optacon to simulated handling and environmental extremes designed to uncover specific faults. No faults were apparent. The rationale for conclusions is limited to conjecture. The most logical and probable explanation is that the equipment was used much more often in the field than was reported. It seems quite possible that the equipment use was not limited to the classroom. Oversights in reporting extra use could account for the discrepencies noted. Based upon our controlled lab results, we are inclined to conclude that the reliability of the Optacon is good to excellent. Much more field data is needed for verification of this conclusion.

9. FIELD TRIPS

9.1 OBJECTIVES

FIRL personnel visited each school site three times. The objective was to ascertain that all equipment was in perfect operating order before the program began, that midway through the program all equipment was still operating properly and that at the end of the program, all equipment had continued to operate properly. In addition, FIRL personnel interviewed administrators, teachers and students to gain insights into user problems. Those results are reported in Section 2 of this document. Sites visited were:

Logan School, Philadelphia, Pennsylvania
Overbrook School for the Blind, Philadelphia, Pennsylvania
Berkeley Unified School District, Berkeley, California
Campbell Union High School District, Campbell, California
Campbell Union Elementary School District, Campbell, California
Salem Public Schools, Salem, Oregon
Azusa Unified School District, Azusa, California
Visalia Unified School District, Visalia, California
San Diego City Schools, San Diego, California
Chula Vista City School District, Chula Vista, California
Houston Independent School District, Houston, Texas
Cincinnati Public Schools, Cincinnati, Ohio
Florida School for the Deaf and Blind, St. Augustine, Florida
Perkins School for the Blind, Watertown, Massachusetts

The field trips enabled FIRL personnel to identify real problems, observe classroom usage, advise teachers and students as needed, avoid potential problems, alert TSI as to service requirements and to supply background information for all FIRL task forces. Sites visited offered a variety of economic and classroom structure settings.

9.2 RECOMMENDATIONS

Recommendations based upon information gathered during the field trips are interspersed among the appropriate sections of this report.

10. CONCLUSIONS

Potential users, virtually unanimously, reported that the Optacon would be very useful in their daily lives. Engineering studies have proven that the design is basically sound and indications suggest that it is a reliable system although further data is needed to render this a firm conclusion.

A host of minor improvements are recommended by this report which would optimize user convenience and minimize cost in its present configuration. However, basic flaws not easily correctable include the fact that the Optacon requires two hands for operation, it requires motivated subjects with fairly sizeable resources available and unimpaired tactile senses, and it has an inherent noise problem. These basic flaws suggest that further research should be aimed at developing a one hand Optacon with an alternate form of information transfer such as air puffs or electrical stimulation.

These improvements will require advances in the state-of-the-art and cannot be expected to be available in the near future. Consequently, the present Optacon should be optimized in conformance with the recommendations of this report and concurrently, basic research should be undertaken to produce a one hand unit with either an alternate form of information transfer or at least a reduction in noise level by reducing the amplitude and/or frequency of the bimorph stimulator.