TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

IDEA Innovations Deserving Exploratory Analysis Project

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report of Investigation

IDEA PROJECT FINAL REPORT

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CONSERVATION TRAFFIC CONTROL LOAD SWITCH

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

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CONSERVATION TRAFFIC CONTROL LOAD SWITCH

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Through the National Academy of Sciences, the National Cooperative Highway Research Program's Transportation Research Board's IDEA Program, and Conservation Load Switch, Inc. (CLS) of Westerville, Ohio, a new conservation traffic control load switch (CTCLS) was developed.

CTCLS has been designed to extend the life of the incandescent lamps used in traffic signals by four times (conservative estimate) and, depending on the voltage set point selected by the U.S. Department of Transportation (DOT), CTCLS can extend lamp life as much as eight to ten times. CTCLS also has the potential to conserve energy, will significantly reduce maintenance personnel's exposure to hazardous situations, and will significantly reduce traffic lamp maintenance expenditures. This would be accomplished by regulating the input voltage from the controller to the signal head and soft-starting or ramping-up voltage and current for each lamp, thus eliminating the initial surge of current for each cycle.

CTCLS has a built-in microprocessor fail-safe to revert the unit to a conventional load switch, which is the most critical aspect of the unit. This technology could have applications in temporary traffic signals, flashers, railroad crossings, arrow panels, and changeable message signs. CTCLS meets all pertinent National Electrical Manufacturers Association (NEMA), model 170, model 200, and Institute of Transportation Engineers (ITE) specifications and is fully programmable to meet other regional requirements (depending on the voltage regulation set point selected by DOT, a higher minimum rated lumens output lamp or bulb may be required). CTCLS works in harmony with conflict and approach monitoring. CTCLS's microprocessor is also readily adaptable to Intelligent Vehicle Highway System (IVHS) without the need for retrofitting. Figure 1 shows a photograph of a CTCLS Model 20867 Solid State Load Switch.

CTCLS DESCRIPTION AND METHOD OF OPERATION

CTCLS will gradually increase voltage to the lamp over 80 milliseconds (soft start). This gradual increase will eliminate the high surge of current (in-rush current) that a cold filament coil is subjected to when the lamp is turned on. The load switch will also regulate voltage to lamps, maintaining a preset level that is lower than the maximum design voltage of the lamps. These two functions, soft start and voltage regulation, extend the life of the lamps and are undetectable to the human eye.

Figure 1 shows the block diagram of the CTCLS load switch. CTCLS routes the initial alternating current (AC) 120 V line into a micro-computer containing a complex series of software algorithms to slow the current surge. The micro-computer monitors the line voltage so that when the incoming AC voltage is above 102 V, the triac circuit delays firing for a short period to allow a regulated 102 V rms to be sent to the lamp. The microcomputer accomplishes this by controlling the triac triggering to cut the sinusoidal wave input in both the positive and negative halves.

Figure 2 shows the regulated output waveform. If the line voltage is below 102 V, no regulation is needed and the circuitry conducts for the full AC cycle time. Since the ITE standard for lumen output is specified at 1750 lumens, CTCLS requires that a 2450 minimum luminous output lamp be used to allow for margin to meet ITE specifications.

The input isolation circuits and triac drivers are almost identical to existing standard NEMA 170 and model 200 traffic control load switches. The microprocessor with an eight-bit analog-to-digital converter controls all CTCLS advanced technological functions, including a redundant fail-safe circuit that will convert CTCLS to a standard traffic control load switch in case of microprocessor failure. When an input is detected from the isolation circuits, the microprocessor starts a slow voltage ramp signal to the triac driver circuits.

Each AC cycle is programmed to have no direct current (DC) offset to eliminate the presence of any direct current imbalance on the AC output line. The exact number of cycles of the soft start will be controlled in the microprocessor's memory. As the soft start process is ending, the program calculates the final phase angle from the AC line input. In all cases the voltage to the lamp provides enough power to meet the ITE lumens standard. Also, the radio frequency interference filters reduce the switching harmonics to an acceptable level that does not interfere with radio reception.

The mechanical packaging is the standard NEMA 170 and model 200 traffic control load switches. All electronics are conformally coated with CONAP CE1170 using multiple thin coats to obtain a final coating thickness of 0.0089 to 0.0114 cm (0.0035 to 0.0045 in.) in a similar manner to existing units,. per ANSI/IPC SN-782-1987 class 2 standards for acceptability of circuit board assemblies. The connector and housing are exactly the same as existing units to ensure that no retrofit will be required.

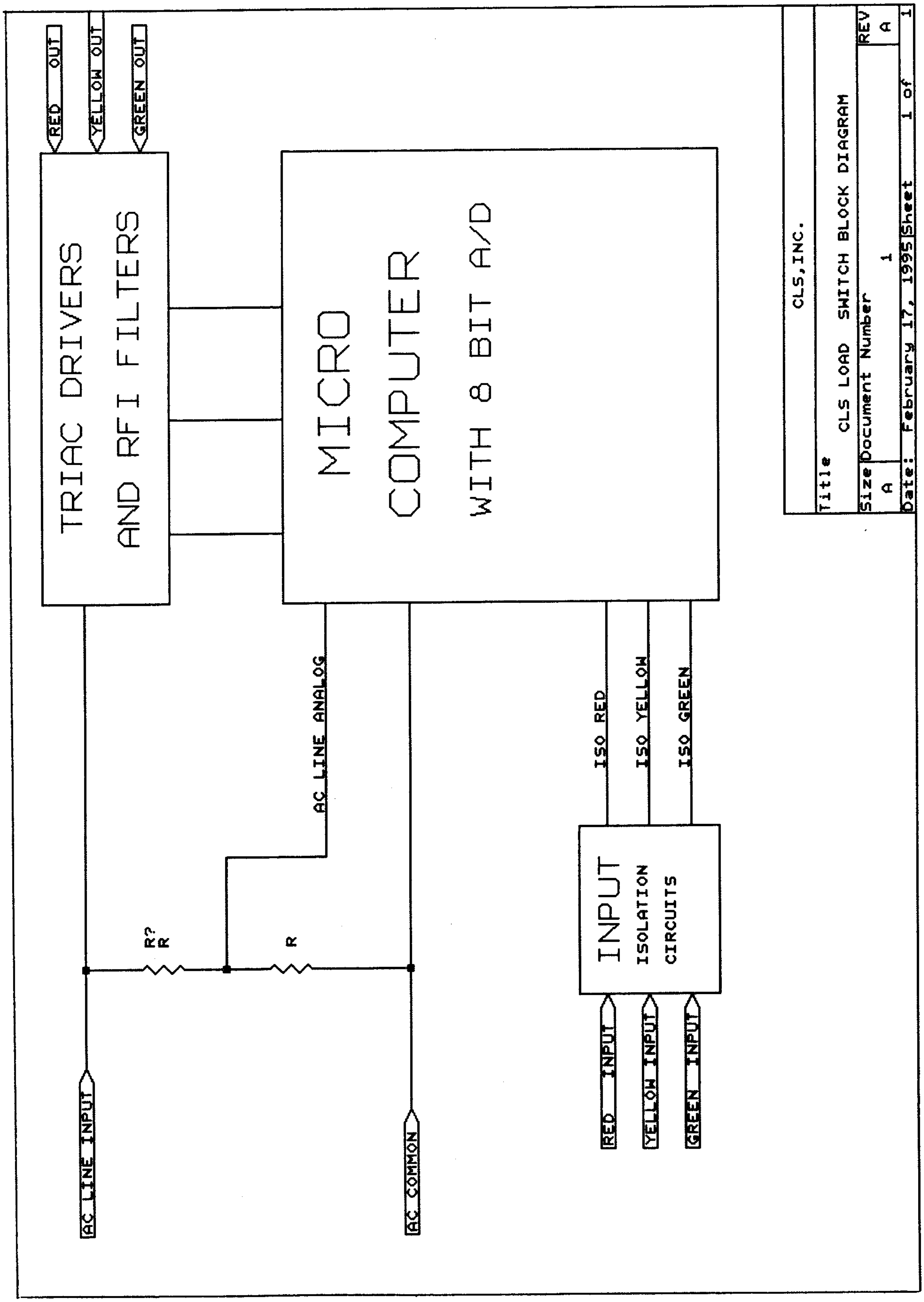
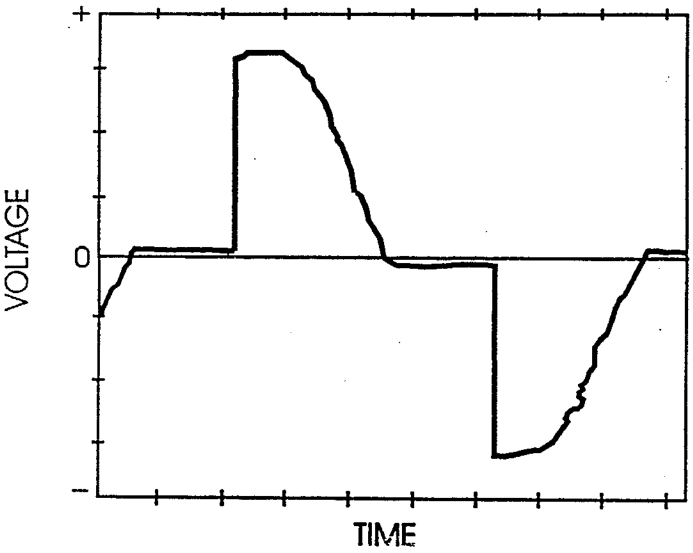
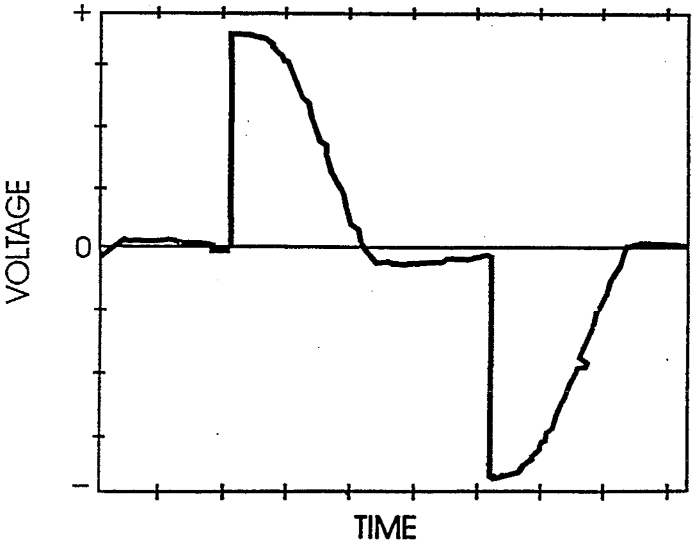


FIGURE 1 CTLS block diagram.



REGULATED
OUTPUT WITH
INPUT SET AT
120vrms



REGULATED
OUTPUT WITH
INPUT SET AT
135vrms

FIGURE 2 Regulated output waveform.

ACCOMPLISHMENTS

During the course of this investigation, CTCLS developed from a concept to working units distributed to various DOT labs throughout the country. Project accomplishments include

1. Printed circuit board design,
2. Software design and development of microprocessor code,
3. Printed circuit board layout and prototyping,
4. Extensive lab testing to include
    - *a*. Fail-safe circuit performance,
    - *b*. Operation at temperatures from -34° C to +74 °C,
    - *c*. Confirmation of soft start and voltage regulation,
    - *d*. Load testing;
5. Production of 100 test units, and
6. Distribution of test units to participating DOT signal labs.

RESEARCH PROGRESS

PROBLEM STATEMENT

Burned-out traffic lamps can be more than just an inconvenience to motorists. Their replacement is a considerable expense to state and regional DOTs. In addition, maintenance personnel are exposed to unnecessary dangers in order to perform replacements. The members of CLS recognized the need for a device or technology that would extend the life of traffic lamps, thus reducing maintenance expenditures and the exposure of personnel to dangerous situations. CLS found that for the device to be useful, it would have to be compatible with existing hardware and meet all applicable standards for traffic controlling equipment; and it would have to be cost-effective for users.

RESEARCH APPROACH

Why Lamps Fail

CLS found two primary reasons for lamp burn out. First, the burning temperature of the tungsten filament coil used inside the incandescent lamp is so high that its molecules continuously and unevenly evaporate and deposit inside the lamp. As the evaporation continues, it makes portions of the filament thinner and weaker. Second, the heavy surge of current used when the lamp is first turned on is due to the low resistance of the tungsten filament when cold. As the lamp heats up, the filament's resistance increases, thereby reducing the current to its rated value. The initial surge exerts a heavy stress on the weak portions of the filament causing it to break.

After the problems were identified, it was determined that an electronic circuit added to existing signal head controlling equipment could alleviate both reasons for lamp failure. The circuit would have to regulate the output voltage to the signal lamps, regardless of line fluctuations, which would reduce the burning temperature of the filaments and decrease the effects of tungsten evaporation. Also, the circuit would have to gradually increase voltage to each lamp in order to reduce the effects of surge current when lamp is turned on.

TWO STAGES OF RESEARCH

STAGE ONE: DESIGN OF PROTOTYPE AND MICROPROCESSOR CODE

Planning

All pertinent data were collected concerning load switches, cabinets and load bays, and the industry standards applicable to these devices. A NEMA load-bay cabinet and traffic light were also procured to provide a test bed for controller prototypes. In addition, a number of regional DOTs were asked to participate in the study and to provide valuable information and feedback on their needs concerning load switches.

Circuit Design

A Motorola MC68HC7805P9 microcontroller and state-of-the-art CAD/CAM equipment served as the basic hardware electrical design. This microprocessor was selected because it possesses an internal fail-safe circuit that will shut down the device if any error in its operation is detected. The actual switching portion of the circuit was designed so that if a microprocessor error did occur, the device would continue to operate as a normal load switch. Also, special care was taken in the selection of components that would meet the demands of NEMA testing and provide long life and rugged operation. Figures 3 and 4 show the circuit schematics. Note that the three switching circuits are identical between Phases A, B, and C and are represented by the schematic, Figure 4.

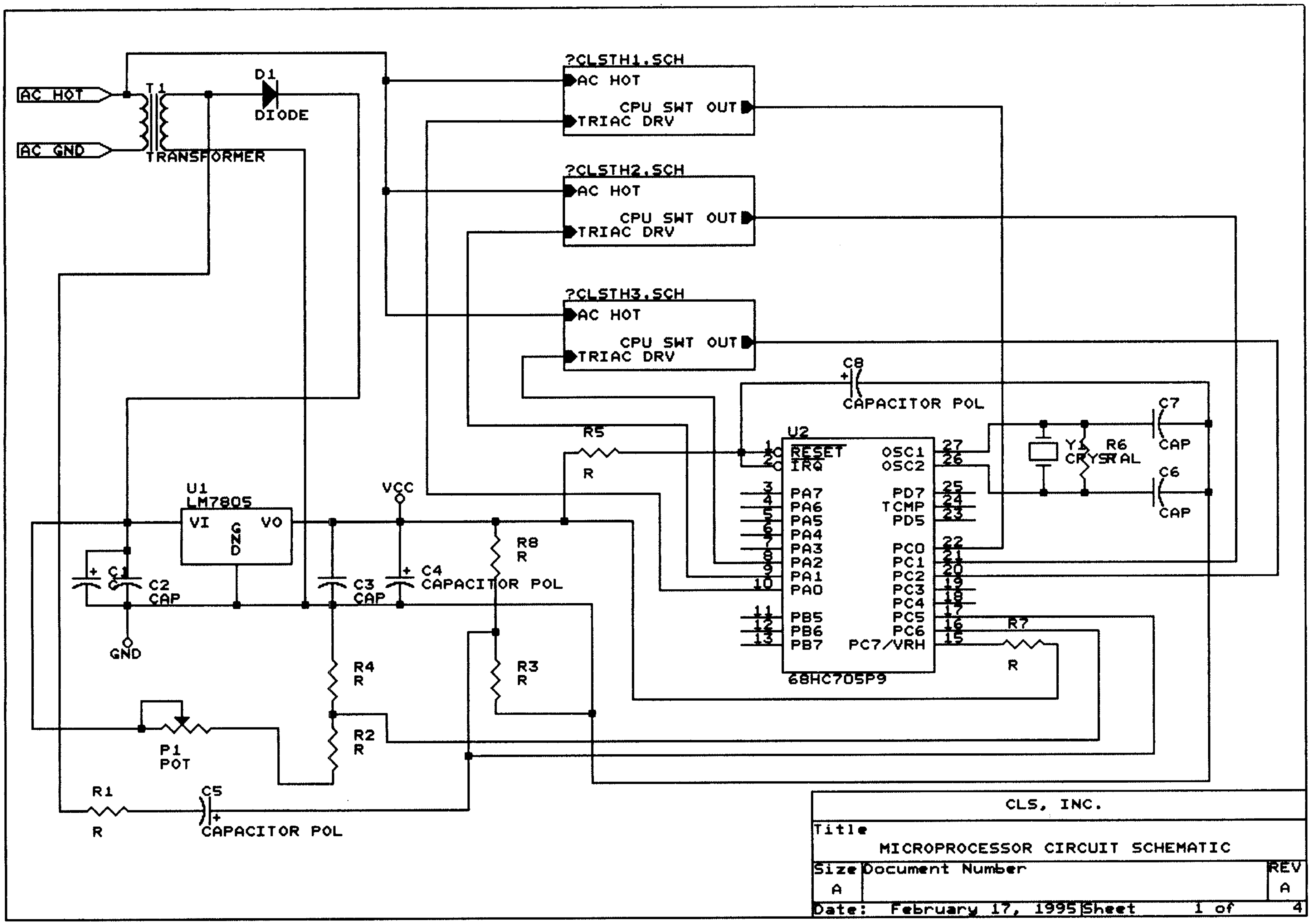


FIGURE 3 Microprocessor circuit schematic.

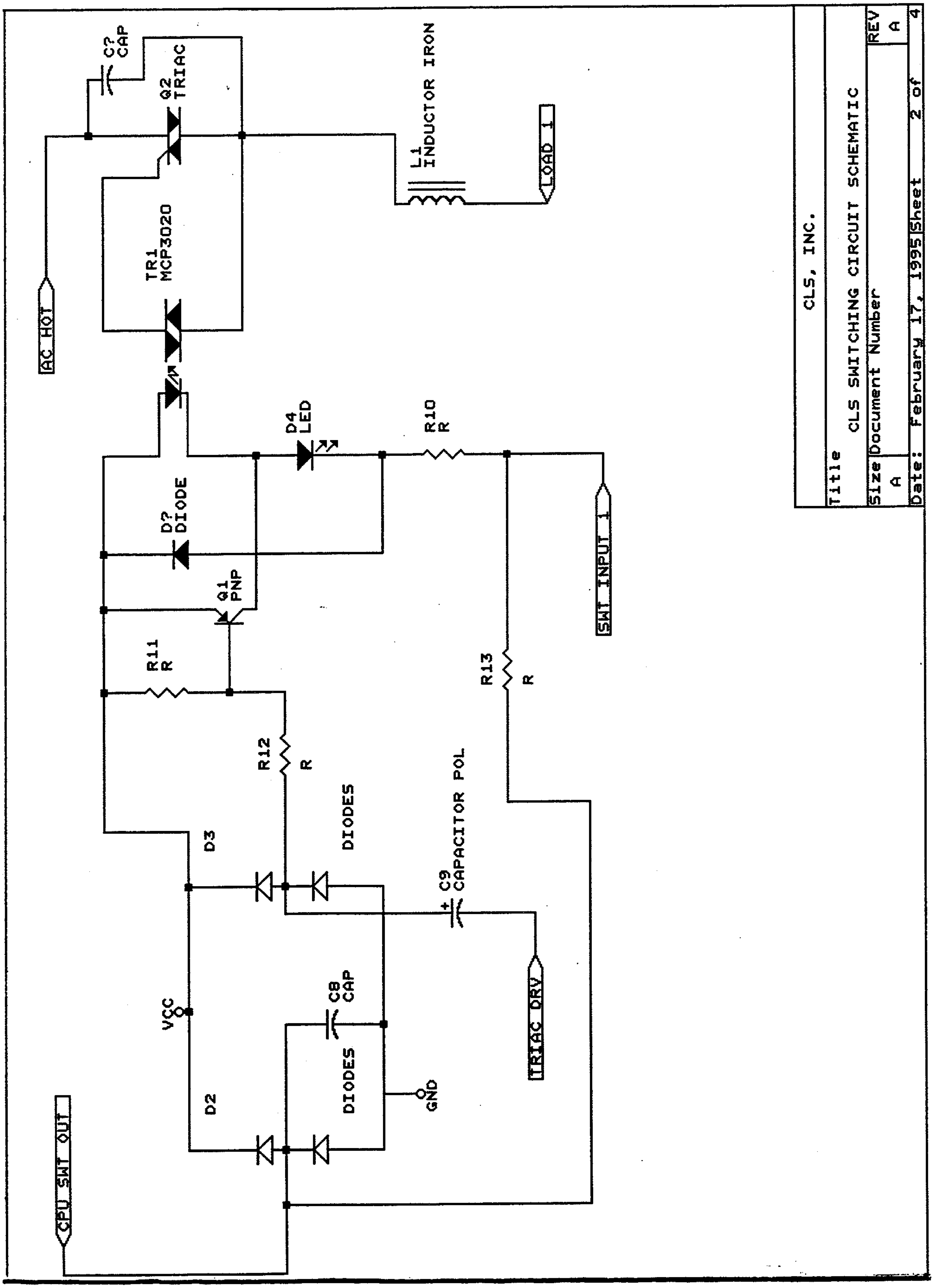


FIGURE 4 Switching circuit schematic.

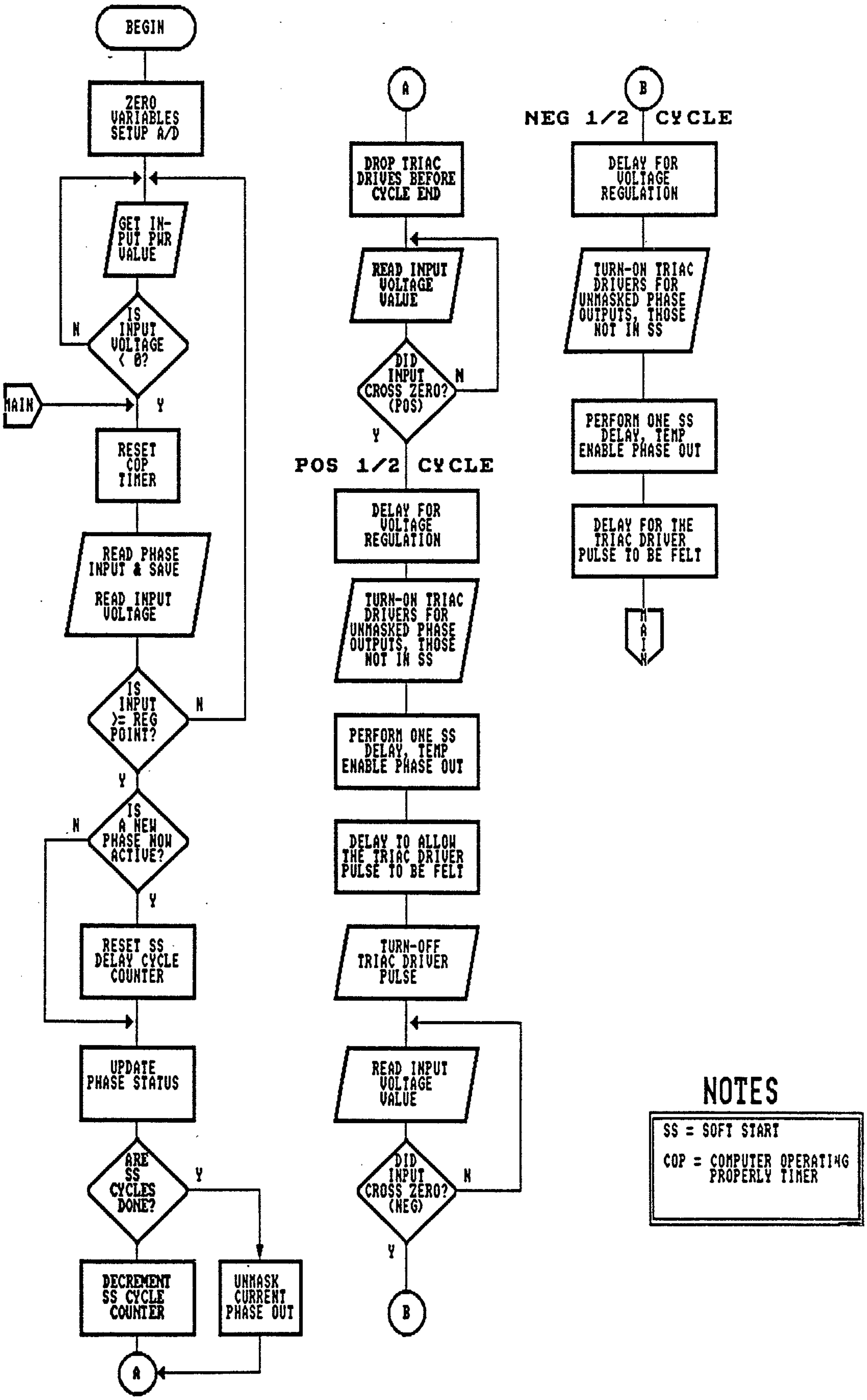


FIGURE 5 CLS Model 20867 program flowchart.

Writing the Microprocessor Program

A basic flowchart was written (Figure 5) forming the framework for the microprocessor program. The program was developed, debugged, and downloaded into several test microprocessors. The first version of the software incorporated a longer soft-start cycle than was envisioned for production models. This would assist the lab debugging technicians by causing a readily visible soft start.

Computerized Synopsis of Circuit Diagram Displaying Electrical Interconnect Points

A computerized list of the circuit design was made to ensure that all electrical design rules were satisfied. This step is a precursor to laying out the printed circuit board (PCB).

Design of PCB and the Addition of Microprocessor Fail-Safe System

The overall shape, thickness, and size of PCB was determined. Also, the fail-safe support circuitry was added to the design. This circuitry, which interconnects directly to the connector that mates the PCB to the cabinet, allows the device to continue operation even if the microprocessor becomes disabled.

PCB Layout, Manufacture, and Assembly

The layout for the PCB was implemented, using state-of-the-art CAD/CAM equipment. Ten fiberglass prototype PCBs were manufactured. The bare boards were populated with components and machine soldered. (Figure 6 shows a photograph of one of the prototype units.)

Mechanical Design

The mechanical design includes the enclosure and the connector. Care was taken to comply with NEMA specifications and to ensure that the device would interconnect to existing hardware without the need for retrofit. (Please refer to Figure 6 to see a CTCLS unit mounted in a standard NEMA load bay.)

Debugging Prototype and Initial Prototype Testing

The first boards were tested for:

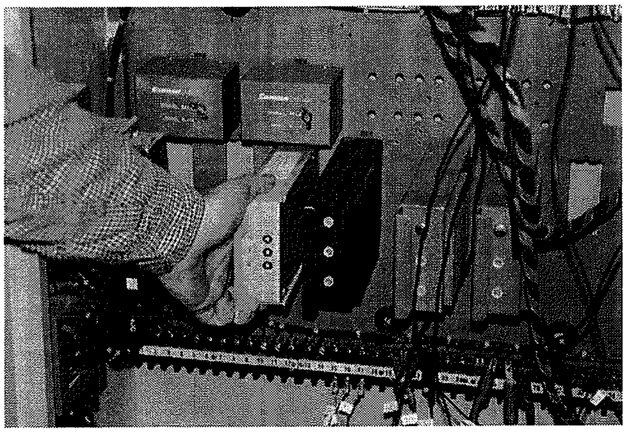


FIGURE 6 Fiberglass prototype unit.

- Voltage regulation at set points between 102 and 112 V rms, input varying between 102 and 135 V rms;
- Visible soft start;
- Mates with connector in NEMA load bay operates a traffic light without interfering with conflict monitors;
- Proper microprocessor fail-safe functions; and
- When line voltage drops below the regulation set point, unit passes input waveform without change.

Summary

The primary goal during Stage One was to ensure that the circuit design performed according to design specifications and that no major revisions needed to be made to the design. Soft start, voltage regulation, and fail-safe features were extensively tested with varying input voltages and loads. After the final circuit configuration was determined, a final circuit board layout was made and the accompanying artwork was sent to a PCB manufacturer.

STAGE TWO: PROTOTYPE FINE TUNING AND LAB TESTING

Manufacturing Prototype Units for Microprocessor and Fail-Safe Lab Testing

One hundred PCBs were produced, machine soldered and then mounted into recycled aluminum load-switch enclosures. During the manufacturing process, production personnel found that a printed-circuit mounted connector would reduce production time by as much as 10 min per unit. They also found that the triac components would solder better if fastened to the board surface prior to machine soldering because this would save time reworking soldered boards since these components tend to rise as they pass over the molten solder.

Lab Testing

Load Testing Three Units at Full Load

Of the 100 prototype boards that were extensively tested three units were randomly selected and a heat sink applied to the output triacs. A tungsten filament test load of 3,000 W was then connected to each phase, one phase at a time, and each phase was then turned on and allowed to operate for 30 min still air. The test was performed to ensure that the triac and supporting circuitry could withstand full-load conditions and still operate as a normal switch, and with the soft start and voltage regulation features. These units passed the tests with no problems.

Units Burn-In Tested in Environmental Chamber

Three more units were randomly selected and placed into an environment chamber (Blue M Model 710). These units were then connected to an external, 150 W tungsten filament test load. The temperature was run from room temperature to -34 degrees C to +74 degrees C. At these temperatures the units were tested again for soft start and voltage regulation features. At the low end of the temperature profile some of the components did not function properly. Substitute components were located and tested with excellent results.

Microprocessor Fail-Safe Circuit Test

All boards were operated without a microprocessor inserted into their sockets. This condition simulated an inoperative microprocessor. In each phase output should operate normally when activated by the external 24 VDC control signal. All units performed as specified.

Testing Soft-Start Functions

After the microprocessor fail-safe circuit test, the microprocessor was inserted into its socket and each phase was tested to ensure that the soft start functioned properly. This test was performed using a Fluke 97 Scopemeter with a digital sample and hold-in memory feature. (Soft start was visible to the eye since all 100 units were programmed for a 16-cycle delay.)

Output Consistency

Each unit was calibrated for a regulation point of 102 VAC. Each unit phase output was tested as the input voltage was varied between 102 VAC and 135 VAC. All units held their regulation point to within +/- 1 VAC. Input voltage was varied using a variac while inputs and outputs were monitored using a Fluke 97 Scopemeter, reading true rms volts. Next, input line voltage was reduced below the preset regulation point while monitoring the phase output voltage to ensure that the unit responded by passing the full input waveform. All units passed this test. Finally, each unit was inserted into a NEMA cabinet and allowed to run through at least one cycle, operating all three phases of one signal head. All units operated the signal head correctly without triggering the cabinet conflict monitor.

Accelerated Bulb Test

Initially, CLS intended to perform an accelerated test that would determine the actual life extension of incandescent lamps controlled by the unit. However, it was found that this test would duplicate previous research. An accelerated bulb test conducted by EDA Corp. was performed on a device whose function is nearly identical to the CTCLS circuit. The EDA test concluded that the average life extension was 8.4 times the rated life of the lamp under test. These results closely correlated to predicted values and validated the formula used to predict the life extension ability of CTCLS. The basic life extension formula for tungsten filament–incandescent lamps can be found below.

$$\mathrm{Life}_{\mathrm{Expected}} = (\mathrm{Life}_{\mathrm{rated}})\mathrm{Vdesigned/Vapplied})\text{\^{}}13.1$$

However, comments from potential users indicate that even the most favorable test results would not convince them. Only actual data collected from the field over a period of time would satisfy them.

Lab Test Units Sent to Selected DOT Signal Labs

After the 100 prototype units were assembled and tested, about 70 were sent to the DOT signal labs participating in CLS's research. The rest were retained for additional NEMA testing and certification.

Labs That Have Responded

New York State DOT, Mr. Michael Naumiec

Test unit was successfully tested with Safetran models 210SA, 210C, 210S as well as EDI 210S and Traffic Sensor Corp. 210 conflict monitors. Mr. Naumiec stated that they are concerned that the switch meets ITE bulb illumination specifications,which CTCLS meets as long as a 2,450 lumen output lamp is used.

Texas DOT, Mr. Don Baker

Mr. Baker indicated that Texas DOT is primarily interested in energy savings and not lamp-life extension. No tests were performed.

West Virginia DOT, Mr. Bruce Kenney

Test unit passed all pertinent tests. Mr. Kenney indicated that West Virginia DOT would be interested in phasing in CTCLS by 10 percent per year.

Ohio DOT, Ms. Satya N. Goyal

Test unit passed all pertinent tests. Ms. Goyal stated that Ohio DOT would require that the unit be tested by Underwriter Laboratories prior to unit purchases.

New Jersey DOT, Mr. Kevin R. Cassidy

The first unit they received failed in its fourth day of endurance testing. Mr. Cassidy requested a second unit. This unit passed all pertinent tests. Mr. Cassidy stated that New Jersey DOT is pleased with test results and is very interested in placing units "in the field".

City of Westerville Dept. of Traffic, Ohio, Mr. Craig Reynolds

Test unit passed all pertinent tests. Mr. Reynolds stated that test results indicated that the City of Westerville would consider phasing in CTCLS by 10 percent per year.

South Carolina DOT, Mr. John C. Rice

Test unit passed all pertinent tests. Mr. Rice indicated that South Carolina DOT would consider phasing in CTCLS by 20 percent per year. Mr. Rice suggested that a light-emitting-diode indicator be put into the device to indicate a microprocessor failure. In addition, Mr. Rice suggested distinctive marking on the CTCLS's case to differentiate it from other load switches. Mr. Rice also observed small flickering of test lamp when near the regulation point. (This was a software glitch that was eliminated in the most recent software revision.)

Labs That Were Sent Questionnaires But Have Yet to Respond

1. City of Chicago Department of Transportation, Mr. Sheldon Kirshner
2. California Department of Transportation, Mr. Floyd Workman
3. Virginia Department of Transportation, Mr. Michael Winn
4. Idaho Department of Transportation, Mr. Terry McAdame
5. Calgary, Alberta, Canada Department of Trans-portation, Mr. Shawn Curran
6. Florida Department of Transportation, Mr. Jack Brown
7. Los Angeles, California Department of Trans-portation, Mr. James F. Ferris and Mr. Al Garcia

SUMMARY

The primary goal during Stage Two was to ensure that the selected component performed according to its design specifications. If it did not, its feasibility would have to be reevaluated. Changes would have to be made in its design. It was also important to include regional departments of transportation in the design process because they would test and evaluate the first units. Their suggestions and comments would be valuable in any future design changes.

RESULTS

The progress of this research has been good. CLS began with an idea for a much needed device and has translated that idea into a viable product, the CTCLS model 20867 Solid State Load Switch. All objectives and goals have been realized, and encouraging feedback has been received from participating departments of ransportation.

All lab testing confirmed the design and yielded expected results. Only one problem was encountered during testing; the problem centered on the component selection for T1, a step-down transformer. The original component selection altered the phase angle of the output voltage waveform in secondary at temperatures approaching –34° C. This was corrected by identifying and selecting a component with a larger operating temperature range.

Initial responses from participating departments of transportation suggested that there was some problem with CTCLS's ability to operate in conjunction with the conflict monitors. However, after communicating with the respective departments of transportation it was found that their low-voltage alarm set points were higher than the CTCLS sample lab test unit's 102 V regulation set point. In order for the unit to function properly it would be necessary to reprogram the test unit's voltage regulation set point higher than the conflict monitor's low-voltage alarm set point. Also, in at least one case where a lab test unit failed, it is suspected that the testing lab overloaded the unit. Test units were not heat sunk and could only operate for extended periods with a load of 150 W or less.

The only unfavorable finding thus far has been that the connector wiring differed between NEMA cabinets and Model 170 and 200 load bay cabinets. On Model 170 and 200 cabinets the Cinch Jones #S-2412-OSB connectors do not use pin 11, which is the AC common connection for the CTCLS unit. This problem, however, can be overcome easily by providing an AC common feed.

CONCLUSIONS

Overall, the project has been a complete success. Communication with the regional department of transportations has generated a great amount of interest in CTCLS and demonstrated that the time for CTCLS has come.

This study has demonstrated the potential of CTCLS, however, several items need to be addressed before units are produced. Each regional department of transportation may have its low voltage conflict monitors set at a voltage below CTCLS's voltage regulation set point and the only way for the unit to function properly is to reprogram the unit at the factory so that the voltage regulation set point is higher than that of the conflict monitor. A much better solution to this would be to incorporate a set point selection feature on each CTCLS so that each department of transportation could choose the regulation set point that meets its need. A small modification to the existing hardware and software would need to be implemented which could use jumpers or switch settings that the user could set upon receipt. Instructions would be included to assist users in customizing their CTCLS units. It was also recommended that an indicator be added to the unit to warn if a microprocessor failure occurred. An additional light emitting diode could be added that would illuminate when such a failure occurred.

It has been confirmed that CTCLS has several immediate benefits. First, this product will dramatically reduce the exposure of maintenance personnel to hazardous and potentially life-threatening situations. Second, if this load switch were installed for the 1986 FHWA estimated 2,000,000 signal heads nationwide, it would save a minimum of 6,000,000 lamps per year (conservative estimate) since there are three lamps per signal head. Multiply this number by the average lamp replacement cost of $30.00 each to obtain a nationwide annual savings of $180,000,000 (conservative estimate). [Industry estimates (1994) go as high as 5,000,000 signal heads nationwide, which would equate to a potential nationwide maintenance savings of $450,000,000]. The capital that would normally be required to maintain and service the traffic lamps can be redirected into a multitude of highway related projects and areas.