THE UNIVERSITY OF ALBERTA

A MICROPROCESSOR CONTROLLED SURGICAL LASER SYSTEM

by

DARRELL E. SCHROEDER

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

EDMONTON, ALBERTA

SPRING, 1987

ISBN 0-315-37792-5

THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR DARRELL E. SCHROEDER

TITLE OF THESIS A MICROPROCESSOR CONTROLLED SURGICAL LASER SYSTEM

DEGREE FOR WHICH THESIS WAS PRESENTED MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED SPRING, 1987

Permission is hereby granted to THE UNIVERSITY OF ALBERTA LIBRARY to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

(SIGNED) ....

PERMANENT ADDRESS:

14433 110A Ave

Edmonton, Alta

T5N 1J7

DATED April 10, 1987

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled A MICROPROCESSOR CONTROLLED SURGICAL LASER SYSTEM submitted by DARRELL E. SCHROEDER in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

....
Supervisor

....

....

Date....16 Dec 1986..........

Abstract

A wider acceptance of laser surgery among the medical community depends in part on the development of inexpensive yet functional laser systems. This thesis presents a design for a CO_2 surgical laser system where low cost and utility have been primary design constraints. The main features of the design are: a self-diagnostic system that alerts users to possible malfunctions, the use of microprocessor control to actively regulate laser output power, and a novel power monitoring method that allows direct control of laser power without interfering with the output beam.

Table of Contents

List of Tables

List of Figures

List of Plates

I. DEFINING THE DESIGN PROBLEM

A. THE NEED FOR A CO_2 LASER SYSTEM

Lasers in Medicine

Since the first laser was built in the early 1960's, it has often been referred to as a solution in search of a problem. One of the first problems to be identified as being easily solved with a laser was the precise destruction of diseased tissue in situ.[17] Enthusiasm for the use of a laser in surgical applications started as soon as people realized that the high power density of a laser beam should be able to vaporize tissue. Even before doctors became aware of the possibilities, laser researchers were attempting to burn off warts with their experimental lasers.[7] The degree of enthusiasm can be seen by the speed with which lasers designed specifically for medical applications were produced. The first laser system designed specifically for this purpose was a CO_2 laser developed by T.G. Polanyi.[20] This laser was unveiled in 1967, only a few years after T.K.N. Patel had demonstrated the first experimental CO_2 laser in the laboratory.[18]

Although initial acceptance of laser surgery by mainstream medical opinion was slow, the advantages of the laser in specific therapies has gradually won over many proponents, so that laser surgery is now considered the primary treatment in several areas.[16] The CO_2 laser is used in neurosurgery, gynecology, otolaryngology, dermatology, and plastic surgery. It is also used to vaporize or excise cancerous tumours in any area of the body. The ability to transmit YAG laser radiation through a flexible fibre optic has made it a useful tool in urology and gastroenterology. Visible light lasers, such as dye lasers or argon-ion lasers, are used in opthomology and dermatology, and the helium-neon and ruby lasers are used at low power levels to promote wound healing.

Why is the laser preferred to other methods of treatment? The destruction of tissue by laser irradiation provides several advantages:[15,23]

1. Haemostatic action. Laser vaporization causes small blood vessels to be sealed, reducing blood loss.
2. Precise destruction of tissue. Other methods of tissue destruction, such as electrocautery or freezing, cause extensive damage to adjacent tissue.
3. Rapid healing with minimal scar tissue formation.
4. No physical contact with the tissue. This is very important when working with very sensitive areas such as the brain, where even gentle handling can cause unforseen damage.
5. Bacteriostatic action. Any infectious or carcinogenic agents are destroyed in the laser

beam. Coupled with the previous point, this provides a margin of safety when operating in cancerous or infected areas.

6. Increased patient comfort. Many patients report less post-operative discomfort after laser surgery than with other methods.

It is interesting to note that the lack of physical contact is often reported as both an advantage and a disadvantage. Most surgeons use the sense of touch to 'feel' where to cut, and use tactile feedback to control the depth and direction of their incision. When they can no longer rely on this, they feel uneasy and unsure of themselves. Once they are trained to use other cues to control an incision made with a laser, they no longer feel uneasy about the lack of contact.

The Medical Laser Market

The acceptance of laser surgery as a routine treatment has caused significant growth of the medical laser market.[21] The total dollar value of all medical laser systems sold in the U.S. market was expected to rise by 30% in 1985, to a total of nearly 270 million dollars. The CO_2 laser currently accounts for nearly 30% of all medical laser sales, with YAG and argon-ion lasers being the other major market contenders. Further growth in this area is expected to taper off, as most major hospitals have already aquired one or more laser systems, and smaller hospitals do not have the heavy case loads required to justify the high capital cost of present laser systems. In order to include smaller hospitals in the laser market, less expensive systems must be developed.

A market survey was recently completed by Information Resources International,[12] which attempts to identify the market areas which are still open to expansion. They interviewed a number of practicing doctors from a wide range of disciplines, and included both laser enthusiasts and those still skeptical of the benefits of laser surgery. The results of this survey indicate that the primary users of CO_2 systems are neurosurgeons, gynecologists, dermatologists, and plastic surgeons. Gynecologists and dermatologists treat common disorders of a simple nature, such as the removal of warts or tatoos, as well as operating on several types of cancer. Neurosurgeons perform a relatively small number of complex and therefore expensive operations, where a large capital cost of equipment is justified. The laser market has therefore been restricted to those hospitals large enough to have a department of neurosurgery or those with an influx of patients large enough to ensure constant use of a laser in dermatology or gynecology. It was determined that if the price of a CO_2 surgical laser system could be brought below a threshold of about US $25,000 the market could be expanded to include the 3200 smaller hospitals in the U.S., as well as approximately 14,000 private practices, primarily in gynecology. This represents a potential market of 430 million dollars, which has not yet been exploited by any of the established laser manufacturers.

Technical Considerations

In addition to the price barrier, there are several other considerations which need to be addressed in providing a laser system acceptable to the general medical community. The first concern is power, or more specifically, how much power is needed to perform the desired operations. While this is a subject of some debate, and the actual power requirements depend as much on how the surgeon operates as what operation he performs, most doctors say that a maximum power of about 40 watts is adequate.

Another concern is reliability. When aquiring one of the currently available lasers, hospitals generally purchase a service contract for around $4000 to $5000. This service contract provides for on-site repair, maintenance, and re-calibration of the laser. When relying on a service contract, hospitals are generally displeased if the down time of the machine is more than a few days. If a laser system is purchased for under $25,000 , it is not reasonable to expect that a service contract will be signed. The laser should therefore be capable of providing reliable operation without servicing, for periods exceeding one year. When servicing is required, the down time of the system must be kept to a minimum.

The laser system should be as small and compact as possible, without any special requirements for power or cooling. Modern operating rooms are crowded with all kinds of equipment, so space is at a premium. Doctors are unimpressed by the large, bulky systems currently available, and express a desire for smaller units. Many laser surgical procedures are performed on an outpatient basis, so the ability to move the laser system between treatment areas is a definite advantage. Along with portability comes the need to keep external connections as simple as possible. If unusual external connections are required, there will be few locations where a hospital could install the system, and the system will not be moved around very much. Also, doctors in private practice are likely to have only basic sources of power and water in their offices, and would not purchase a laser system that could not connect to these simple hook-up facilities.

Finally, the system should be simple to use. The target customer is the average doctor, not the laser enthusiast. Some of these doctors will be intimidated by complicated control panels with flashing lights and rows of interlock switches. They do not want to have to wade through long technical manuals to learn how to operate the system. The controls should be simple and of an obvious nature, relating to the end effect desired by the surgeon, not the adjustment of laser parameters.

Statement of Thesis

Meeting all of the above requirements in a system to be priced at less than $25,000 presents a difficult task to the engineer, but not an impossible one. In this thesis I will present a design for an economical, 40 watt surgical laser system. The primary consideration is to provide an economical system that meets the basic requirements for laser surgery, not necessarily one with optimal performance. The system is "trans-portable"; it can be moved without major effort but is not easily carried. The controls are functional, and the technical performance of the laser is adequate for the intended use. It would be a competetive contender in the market it is designed for.

B. LASER-TISSUE INTERACTIONS

In order to know how to design a laser system to perform surgical operations, we must first know what effect the laser beam has on tissue. Once we know this, we can determine how to best achieve the desired effect of cutting through tissue.

Damage Mechanisms

The soft tissue of the body is composed mostly of water. The radiation of the CO_2 laser is strongly absorbed by water, having an extinction length of about 0.01 millimeters.[6] This means that all of the energy in the laser beam will be absorbed at the suface of the tissue.[8]

The absorption of energy leads to heating of the tissue, which can have several different effects, depending on the amount of the temperature rise.[4] If the temperature of the tissue is raised from its normal temperature of 37 degrees celcius to about 45 to 60 degrees celcius, there will be some enzyme damage, but no gross effects. The area in which this is the only effect is called the thermal edema zone. As the temperature is increased to 70 degrees, denaturation of protein and drying of the tissue leads to the sealing of small blood vessels. This results in the hemostatic action of laser surgery, and this area is therefore called the coagulation zone. When the temperature reaches 100 degrees celcius, the water in the tissue vaporizes, resulting in the destruction of the cells and severe shrinkage of tissue. The phase change of the water absorbs most of the heat so that there is very little thermal damage to the surrounding tissue. When all the water is vaporized the temperature can rise well above 100 degrees, resulting in the carbonization of the solid remnants of the destroyed cells. This layer of carbonization effectively blocks the laser radiation from penetrating to the underlying tissue, and further tissue damage results primarily from conduction of heat from the carbonized zone to the surrounding tissue.

Continuous Exposure

If the laser beam is applied to one location for a period of time, the result will be a shallow pit, or lesion,

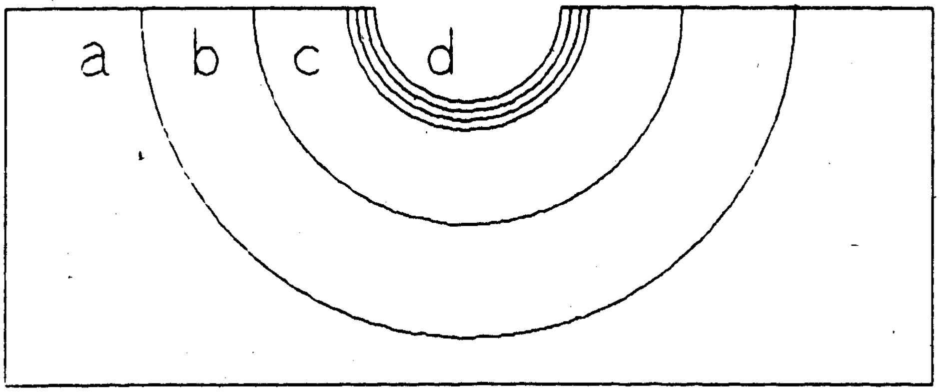


Fig. 1. Lesion caused by continuous exposure. a: Undamaged tissue, b: Thermal edema zone, c: Coagulation zone, d: Carbonized zone.

where the cells have been vaporized by the laser beam.[13] The lesion will be lined with the carbonized remnants of the destroyed cells, and surrounded by a zone of thermal damage caused by heat conduction from the carbonized zone into the surrounding tissue (Fig. 1). The size of the lesion and the width of the carbonized zone are only slightly dependent on the laser power and exposure time, but the zone of thermal damage increases rapidly with both increasing power and exposure time. To minimize the extent of this zone, the power of the laser should be limited to the level needed to vaporize the surface tissue. The exposure time in any one spot should also be limited by continously moving the laser beam over the surface. As the power of the laser is increased, the speed with which the beam is moved over the surface should also be increased.

This type of exposure is used by the surgeon when there is a relatively small area of diseased tissue that needs to be destroyed. The laser is set to a high power and the beam is rapidly swept over the area to be destroyed. If a single pass is not enough to penetrate completely through the diseased tissue, the surgeon clears away the carbonized debris and repeats the procedure until a sufficent depth of tissue has been destroyed. This method destroys all of the diseased tissue, and so is not used when a sample of the tissue is needed for a biopsy.

Pulsed Exposure

Thermal damage to the tissue surrounding a laser induced lesion can also be limited by pulsing the laser on and off at relatively low repetition rates.[14] The pulse is limited in duration so that the temperature in the irradiated area does not increase to the level needed to carbonize the solid remnants of the destroyed cells. Because there is no carbonized layer, the laser beam can penetrate further into the tissue, so that the lesion caused by pulsed exposure is narrower and deeper than the lesion caused by continuous exposure (Fig. 2a). The pulses must also be spaced far enough apart so that the plume of steam generated by the vaporized cells has time to dissipate and carry away the excess heat of the previous pulse. If the pulses are too close together, a phenomena known as the "Yoko effect" is seen.[1] The Yoko effect occurs when steam still trapped in the lesion is superheated by laser radiation. This superheated steam expands and comes into contact with the

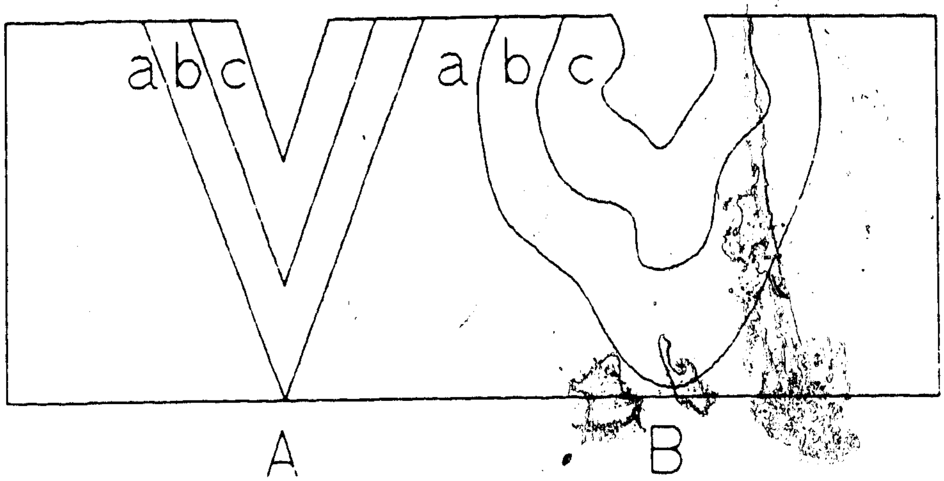


Fig. 2. Lesions caused by pulsed exposure. A - Optimal pulse rate, B - Yoko effect. a: Undamaged tissue, b: Thermal edema zone, c: Coagulation zone.

sides of the lesion, causing additional damage and creating a pit with irregular sides (Fig. 2b).

The length of the pulse and the repetition rate needed to avoid both carbonization and the Yoko effect depend on the amount of water in the tissue. This means that the surgeon must be able to select the appropriate pulse length and repetition rate for the particular case he is dealing with. Since the amount of water in body tissue can vary considerably, the surgeon must be able to change these parameters as he feels fit, and should not be restricted to four or five preselected values.

Pulsed exposure is used by the surgeon when he wants to make an incision rather than simply destroy tissue. It can be used to cut out a large, bulky tumour that would take too long to vaporize, or it can be used to remove a small sample of tissue for a biopsy. Because this type of exposure gives rise to a much different effect than continuous exposure, the surgeon should be able to quickly and easily select the type of exposure he wants to use in the situation he is facing.

C. ACHIEVING THE DESIGN GOALS

The surgical laser system can be roughly divided into three subsystems. The actual laser itself, along with its driver, is considered one subsystem. The second subsystem consists of the electronics and sensors needed to monitor and control the operation of the laser. The rest of the surgical laser system, the cooling system, pumps, and power supplies, are grouped together as auxiliary systems. A block diagram of the system is shown in figure 3. Since the design of everything else depends on the choice of laser we use, we will look at the design of the laser subsystem first.

The Laser

Most of the CO_2 lasers used in surgical laser systems are flowing gas DC discharge lasers. These lasers have the advantage of being easy to build and control, as they have been around for a relatively long time. They also have several inherent disadvantages. The laser tube itself is usually fairly long and fragile, being made out of glass. This means that a sturdy structure must be used to support the tube. Because the gas flows through the laser and is then vented to the air, a large reserve of gas is required.

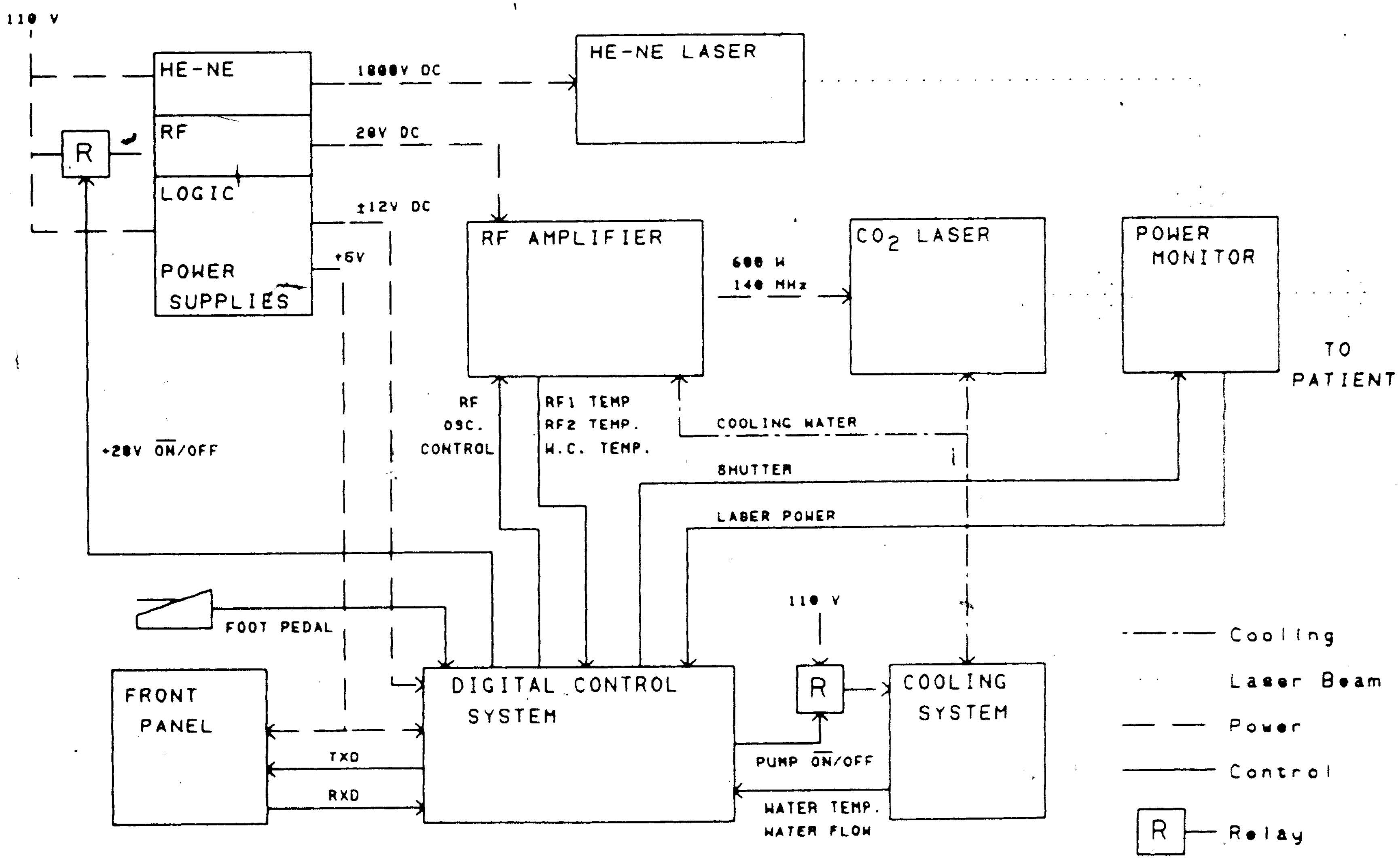


Fig. 3 - Block Diagram of CO_2 Surgical Laser System

This is usually kept in a high pressure gas bottle, and requires a regulator and vaccuum lines to bring the gas to the laser at the proper pressure. A vaccuum pump is also needed to keep the gas pressure in the laser low enough so that a discharge can be induced at resonable power levels. In order to break down the gas and maintain the discharge, a high voltage DC power supply is needed. Although these power supplies are fairly standard equipment, care must be taken to ensure that no one comes in contact with the high voltage lines when the laser is in operation. All of this means that the laser system will be big and bulky, and will be difficult to move around.

One of the design goals is to keep the laser system as small and portable as possible. To do this we will use a different type of laser; a hard sealed, radio frequency, transversely excited, waveguide laser. This type of laser can develop a very high power per unit length; up to 0.83 watts/cm has been reported.[10] Since the laser is hard sealed, with no gas flowing through it, there is no need for gas bottles, regulators or vaccuum pumps, thus reducing the size of the system. The radio frequency driver can be built using solid state devices, resulting in a compact driver unit. While care must still be taken to ensure that no one becomes part of a live circuit, these precautions are less stringent than those for high voltage power supplies. This should result in a smaller, more portable system than would be possible using a DC discharge flowing gas laser.

Control Electronics

In order to obtain consistent, repeatable results from laser surgery, it is necessary to have a constant, well regulated power output. This is usually done by building the laser to exacting specifications. All the possible sources of power variation are eliminated or compensated for in some way, so that the laser will perform predictably. This method is quite expensive, so we will attempt to control the laser power in another way. Rather than trying to eliminate sources of power variation by precise construction, we will monitor the power output of the laser and regulate it with feedback control techniques.[11] This will allow us to use inexpensive lasers without worrying about the stability of their power output.

The controller used in this laser system will be a microprocessor based controller. Additional hardware will be included that will ease the task of providing the control function. The use of a microprocessor controller brings an added benefit. If appropriate sensors are installed, software can be written to enable the microprocessor to monitor the system for any faults. This will increase reliability, as the micro will be able to alert the users to the need for maintenance before the system fails. Since the micro can indicate what area of the system is malfunctioning, the time needed to diagnose the fault will be reduced, and the servicing time can be kept to a minimum. If a fault occurs during an operation, the micro will be able to indicate how serious the fault is, allowing the surgeon to make an informed decision whether to continue the operation, switch to a backup procedure, or cancel the operation and reschedule it after the laser system has been serviced. This will result in increased safety for the patient.

The most noticed part of any system is the user interface, or front panel. This is where the controls for the system are located. In order to facilitate interaction with the digital controller, the controls and displays on the front panel will be digital. The doctor using a surgical laser system must be able to use these controls to; set the power level of the laser, select continuous or pulsed mode operation, set the pulse width and repetition rate for pulsed mode operation, and turn the laser on or off. There must be a visual indication when the laser is on, as the CO_2 beam is invisible. In addition to this, there should be a display of the actual power coming out of the laser. Most surgical laser systems do not have a display of the actual laser power. The power is set to the desired level beforehand, and it is assumed that it will not deviate from this setting. Since we will be monitoring the power in order to provide the control function, the system will be able to display the actual power of the laser.

Auxiliary Systems

The auxiliary systems are the cooling system, the power distribution system and the He-Ne aiming system. The cooling and power distribution systems are the systems which will have the most impact on portability, since they provide connections to the external world. The cooling system also has a major impact on the performance of the laser, because both power output and power stability are adversely affected by a rise in temperature.[3] While we are relatively unconcerned with power stability, we want to keep the power output at a high level. The usual way to provide cooling is to pass cold water around or through the laser head. The cooling water can be an open loop, with the cold water coming from an external source and the heated water simply drained away, or it can be a closed loop, with the water being pumped through the system and the waste heat removed by a water cooler or radiator. Using an open loop system minimizes size, but restricts portability by requiring a source of water and a drain at every location where the laser is to be used. If a closed system is used, the best way to keep the water cold is to use a water cooler; these are large, heavy units not easily moved, so they are not suitable for a portable system. The proposed system will use closed loop cooling with the waste heat being removed by a forced air radiator. This will give the best compromise between portability and cooling.

The power distribution system is the system which takes in external energy, transforms it into a usable form, and distributes it to the point of use. The most common source of external energy in both the hospital and the doctors private practice is the 110 volt, 15 amp AC line socket. If any other source of external energy were used, the locations available for laser surgery would be limited. The maximum amount of power available from this type of socket is 1650 watts, which sets the upper limit on power dissipation for the system. It is felt that this limit will not be too restrictive for the surgical laser.

The 110 volt AC voltage must be transformed into different forms to provide power for the different systems. The pumps and fans of the cooling system can be driven directly by the AC line. The microprocessor control system will need +5 volts DC for the digital logic and ±12 volts for the analog devices. The RF driver for the laser will need +28 volts DC. To provide these voltages from the AC line, commercially available switching power supplies will be used. These supplies will give the needed power conversion and use up as little space as possible.

The final component of the auxiliary systems is a He-Ne laser which provides a visible beam used to aim the CO_2 beam. Since the CO_2 beam is invisible, some method of determining where it is aimed must be employed. If the He-Ne beam is made co-axial with the CO_2 beam, a red spot of light will appear wherever the CO_2 beam will strike. As with the power supplies, the He-Ne laser system used will be a commercially available system.

II. BUILDING THE SYSTEM

A. THE LASER HEAD

The laser is the most important component of the surgical laser system, but it will receive the least amount of attention. The details of the laser construction only need to be considered where they affect the performance of the medical system. The laser itself can be treated as a 'black box'; specified only in terms of its inputs and outputs.

Proposed Laser Head

The laser head intended for the final system is a 40 watt, sealed, RF discharge, waveguide laser, operating at a frequency of 140 MHz. The construction and design of the laser will be guided by the results of Hall.[9] Since the power output of the laser can be expected to decline over a period of time, due to such factors as chemical reactions in the gas mixture and degradation of optical components, the maximum power of the laser should actually be somewhat greater than 40 watts. This will enable the laser to maintain the specified output power for an extended period of time. If the laser is designed for a maximum power output of 60 watts under ideal conditions, it will be able to withstand a 30% reduction in power output and still put out the nominal power of 40 watts.

PLATE 1. The experimental workbench. The RF driver, laser head, and control electronics are at the far left end of the optical rail. The power monitoring system is in the middle, and the cryogenic pulse detector can be seen at the lower right.

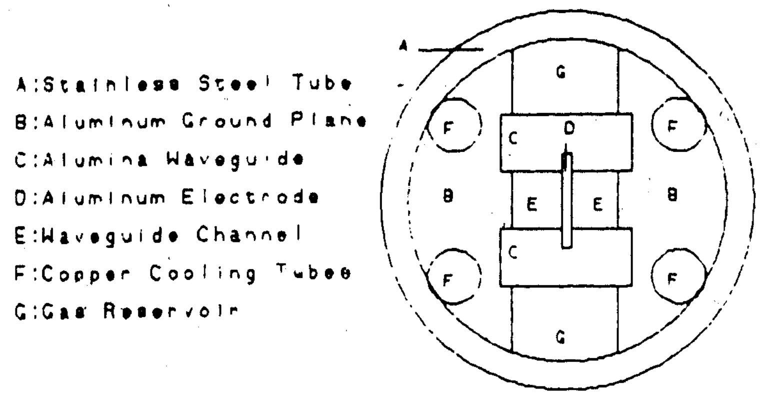


Fig. 4 Cross-section of the proposed laser head.

In order to produce 60 watts of laser power, the laser head will have to be supplied with 600 watts of RF power. This assumes an efficiency of 10% for the laser head, which is an average value for CO_2 lasers. If it is also assumed that the power per length will be about 0.8 watts/cm, the length of the waveguide channel will have to be approximately 75 cm to produce 60 watts. To reduce the length of the laser head, the waveguide is split into two sections side-by-side. Turn-around optics are used to direct the laser beam from one channel into the other. In this way the 75 cm of waveguide channel can be fitted into a laser head only 40 cm long.

A cross-section of the laser head is shown in figure 4. The two waveguide channels are driven from a single center electrode. This reduces the space needed and also reduces the electrical impedance of the laser head, since the two discharge impedances are connected in parallel. Cooling tubes are arranged symmetrically around the heat producing channels in order to equalize the thermal stress on the channels and reduce any thermally induced power variations. The waveguide structure is clamped inside a stainless steel tube which is hard sealed to provide the partial vaccum needed for the low pressure discharge. The space between the waveguide structure and the stainless steel tube is used to provide gas ballast, reducing the effects of chemical changes taking place in the discharge.

Experimental Laser Head

Unfortunately, a laser head such as the one proposed is on the leading edge of technology, and so is not readily available. Building this kind of laser presents many difficult design problems, which require significant time and effort to solve. In order to reduce the time needed to complete the laser system, the development of the system is being performed concurrently with the development of the laser. Because of this, a laser head of the type intended to go into the final system will not be available for system testing. This means that a laser with similar characteristics will have to be used in developing the system. Then, when the final laser head is finished, it can be incorporated into the system with only minor 'fine tuning' needed.

The laser head that will be used for system testing is nearly identical with the desired laser head. The differences between the two laser heads are differences of construction, not type. The experimental laser head is physically larger and relatively bulky, but it has only a single channel 40 cm long, so the power output is less. It has a maximum power of about 20 watts, and the typical working power is 6 to 10 watts. This power level, while too low for medical purposes, is sufficient to perform the necessary tests for system development. The discharge of the experimental laser head is cooled on one side only, which makes the power and mode stability quite poor. This makes it a good laser for system development, since the microprocessor controller will have to do a good job to stabilize the power output. Finally, there is a gas port on the experimental laser head which allows the gas mixture inside to be changed.

While the use of the experimental laser head allows us to develop the medical laser system without waiting for the development of the final laser head to be complete, it should be remembered that the system is designed to incorporate the 40 watt laser head. All of the subsystems must be able to support a 40 watt laser head, otherwise the laser system will not be useful in a medical role.

B. THE RF DRIVER

The sub-system which provides the power to create and maintain the discharge in the laser is the RF driver. This sub-system generates a 140 MHz signal and amplifies it to the 600 watts needed by the laser head. It also provides the control of the laser power by switching the discharge on and off and by regulating the amount of power going into the laser.

Proposed Driver

A block diagram of the proposed RF driver is shown in figure 5. The oscillator consists of the circuitry needed to generate the 140 MHz signal, a pre-amplifier, and control electronics to regulate the power level and turn the signal on and off. A 20 MHz crystal generates the initial signal, which is amplified to a usable level. The non-linearities inherent in the amplifier generate harmonics, and the seventh harmonic, 140 MHz, is extracted. Two amplifier stages then boost the signal to the desired level. The first stage is a low gain buffer that can be turned on or off by a TTL level voltage. The second stage is a variable gain amplifier, the gain being controlled by changing the collector voltage of the transistor. These two stages give control of the RF power going into the laser right at the source of the RF signal. The maximum output power of the oscillator is about 400 mW.

The signal from the oscillator is amplified by a three stage pre-driver with an output of 80 watts. The output of the pre-driver is then delivered to the inputs of two 300 watt power amps by means of a Wilkinson coupler.[5] A Wilkinson coupler is a type of power splitter that uses transmission line techniques to match a single source into

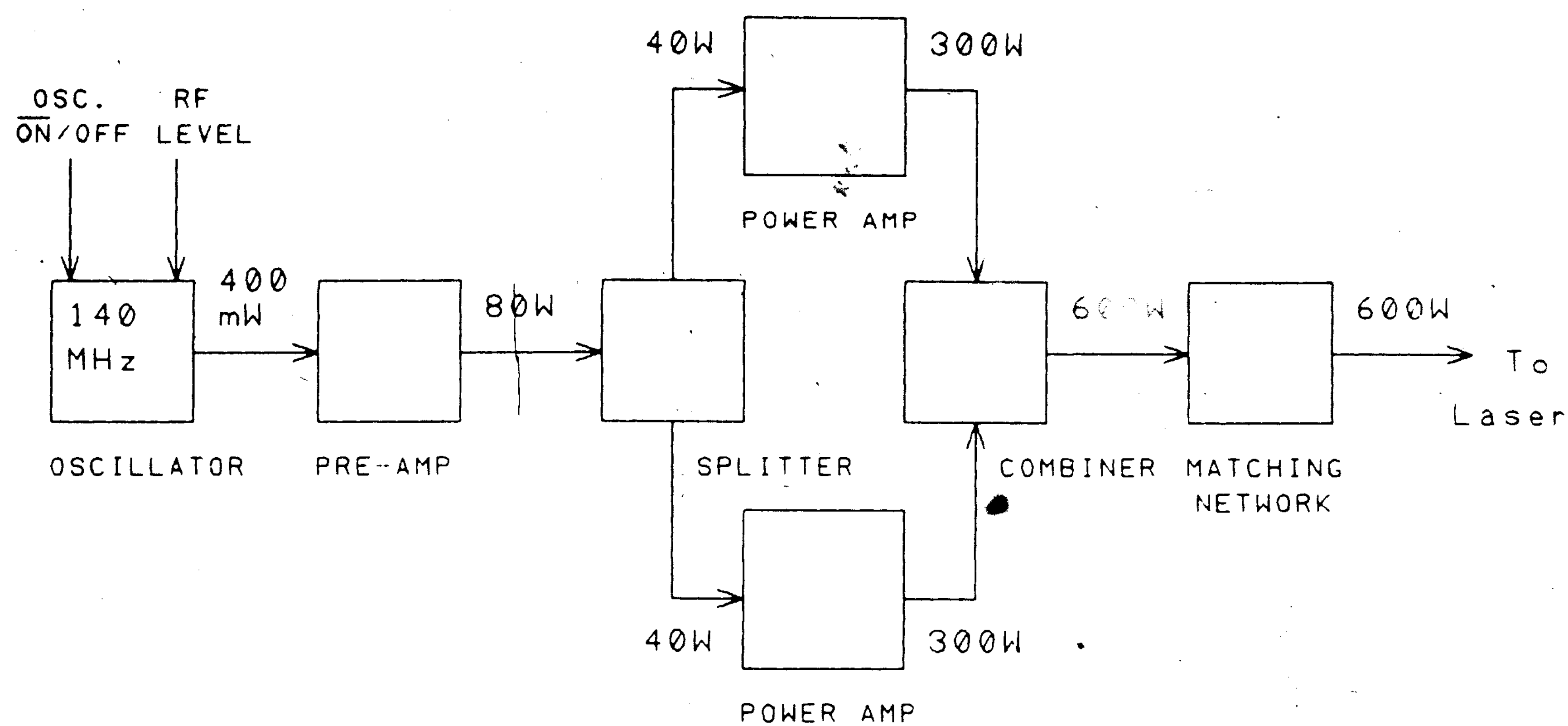


Fig. 5 - Block Diagram of RF Driver

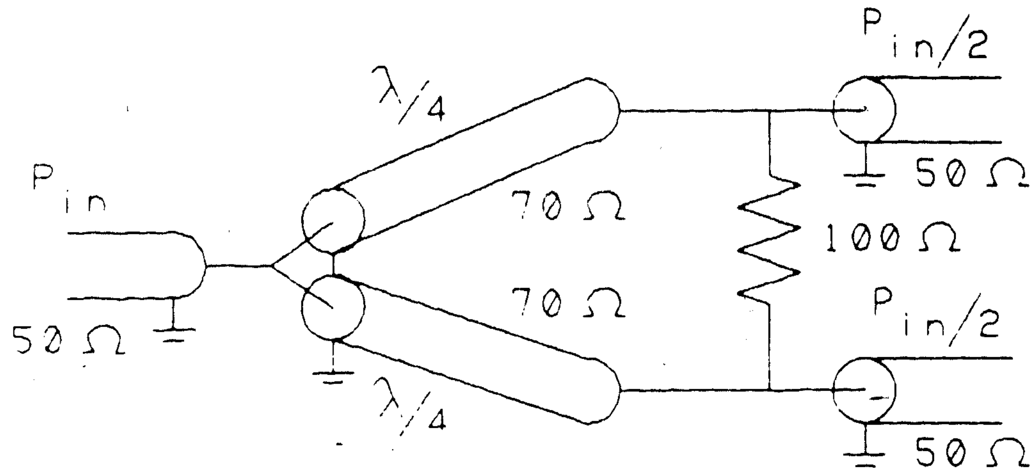


Fig. 6 Wilkinson coupler made from two quarter-wavelength 70 ohm co-ax cables.

two loads, or two sources into a single load (Fig. 6). If there is any imbalance between the two loads, a compensating current will flow through the balance resistor connecting the loads, so the imbalance can be detected by monitoring the temperature of the resistor. Each load receives half of the power delivered from the source, so that each of the two power amps is driven by a 40 watt signal.

The power amplifier is a single stage amp, with two transistors configured in a push-pull type arrangement. The maximum power out of each power amp is 300 watts, and the two outputs are combined into a single 600 watt source by using another Wilkinson coupler. The 50 ohm output of the coupler is then matched to the laser impedance by a matching network, allowing maximum power transfer into the laser with a minimum of power being reflected back into the RF amplifiers.

The proposed RF driver was built and tested using a 50 ohm load. Further testing and installation of the driver in the surgical system will have to wait until a suitable laser head is available for use as an appropriate load. The driver operates off of 28 volts DC, and draws 32 amps of current. At the rated output power of 600 watts, this results in an efficiency of 67%, relative to the DC power input. If the efficiency of the DC supply is included in the calculation, the overall efficiency of the RF driver system, relative to the power input at the wall socket, is found to be about 45%.

Experimental Driver

As is the case with the laser head, the proposed design for the RF driver was not the actual system used for experimental purposes. There are several reasons for this. First of all, the use of a lower power laser head greatly reduces the power needed from the RF driver. The amount of RF power needed to get maximum power from the experimental laser head is about 200 watts, one-third of the power output of the proposed RF driver. The requirements for small size and portability are also de-emphasized for the experimental system, since it is going to be sitting on a testing bench for the entire period of system development. Finally, the solid state amplifiers used in the RF driver offer great advantages in size and efficiency, but they are very sensitive to high VSWR levels. If the amount of RF power

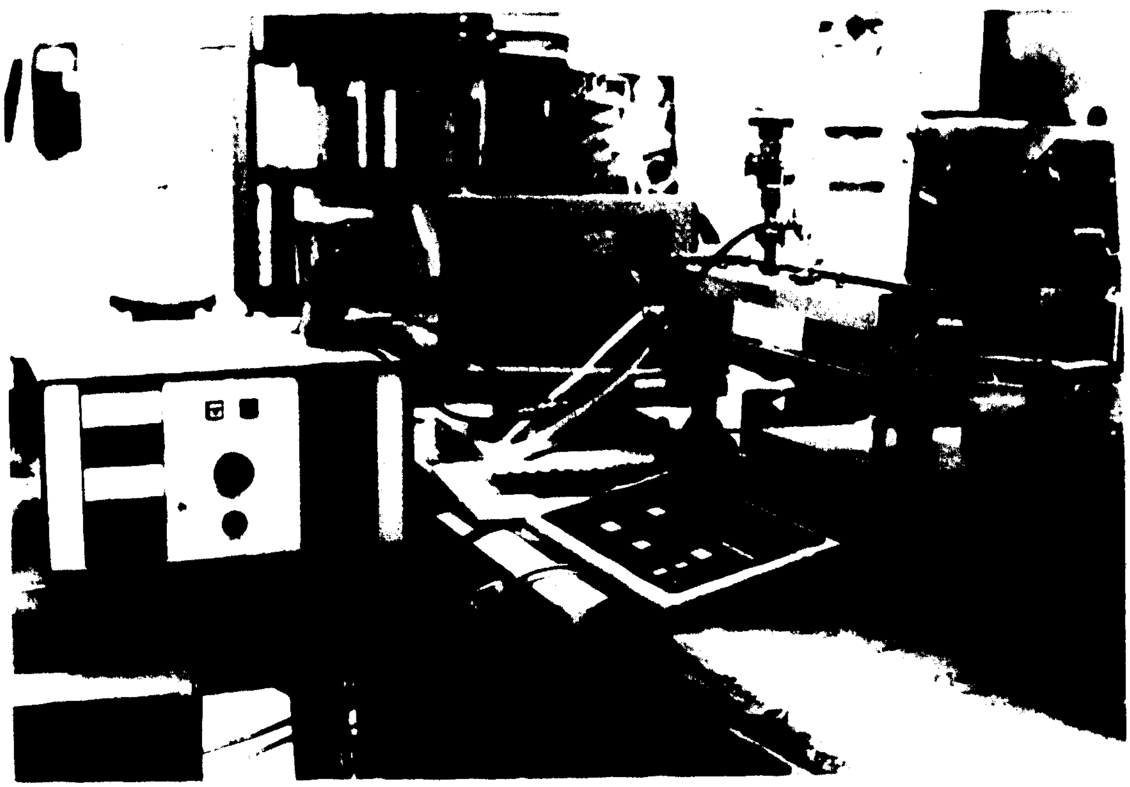


PLATE 2. The laser head and RF driver. Note the 50 ohm to 200 ohm transmission line transformer used to connect the tube amplifier to the laser head.

reflected back into the amplifier becomes significant, the transistors are likely to experience catastrophic failure. Since a small VSWR cannot be guaranteed while the system is under development, the transistors would need to be replaced quite often. For these reasons it was decided to use a tube amplifier as the final power amplification stage during system development.

The oscillator designed for use in the proposed driver is still used in the experimental system, but the pre-driver is replaced by a two stage amplifier with a maximum output power of 25 watts. The splitter, power amps, and combiner are replaced by a tube amplifier which delivers nearly 500 watts of RF power into a 50 ohm load when driven by the 25 watt pre-driver (Fig. 7). This power level cannot be realized in the laser head however, because of the nature of the gas discharge, which presents an active rather than a passive load.

The load characteristics of the gas discharge can be determined by examining figure 8. These measurements were obtained by detuning the output stage of the tube amplifier to approximately match the load impedance of the discharge, and then measuring the amount of power being transmitted into the discharge as well as the amount of power being reflected back into the amplifier. It can be seen that if the oscillator control voltage is less than two volts, the tube amp is not being driven into the active region, and no power is generated. When the control voltage is increased

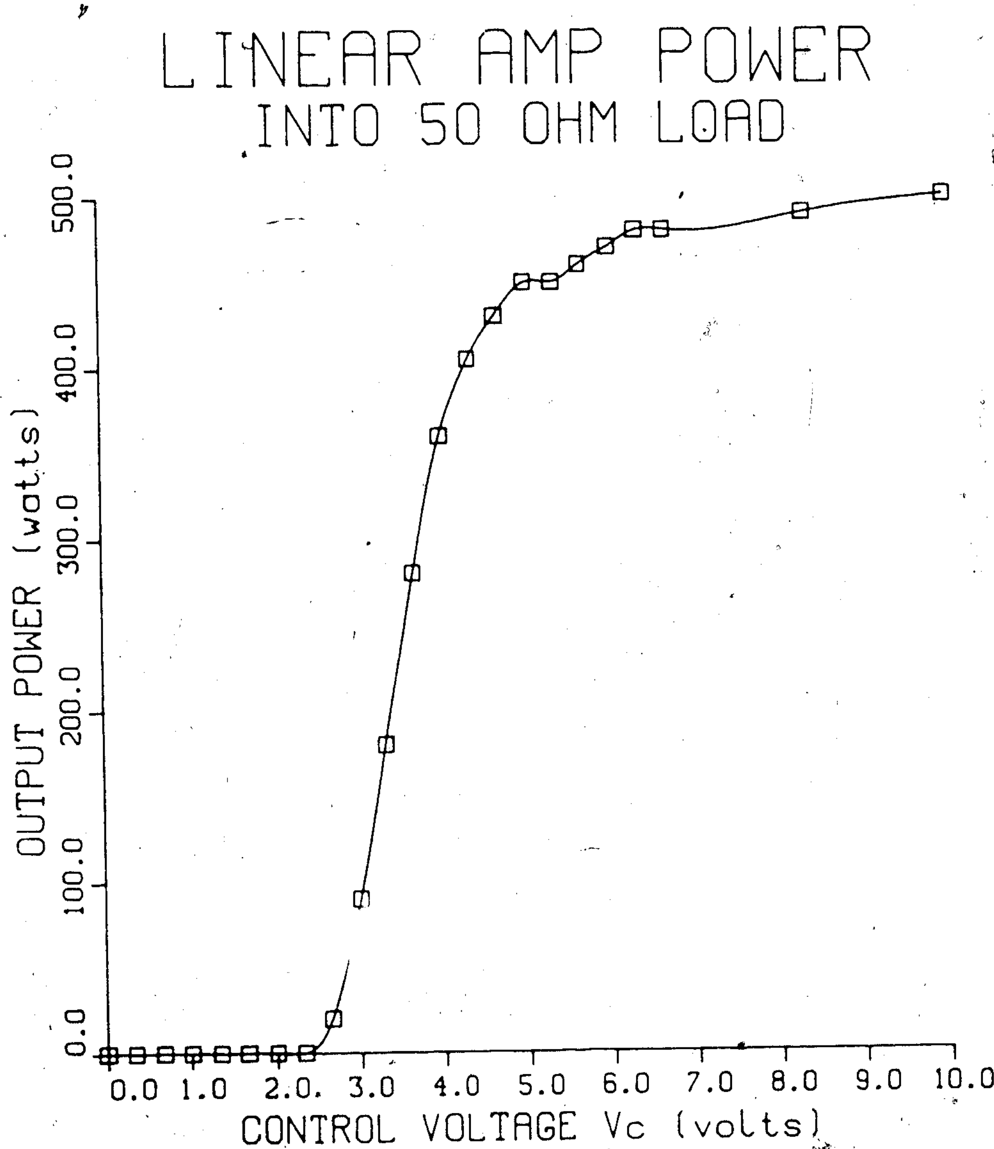


Fig. 7 - RF Driver Power Output

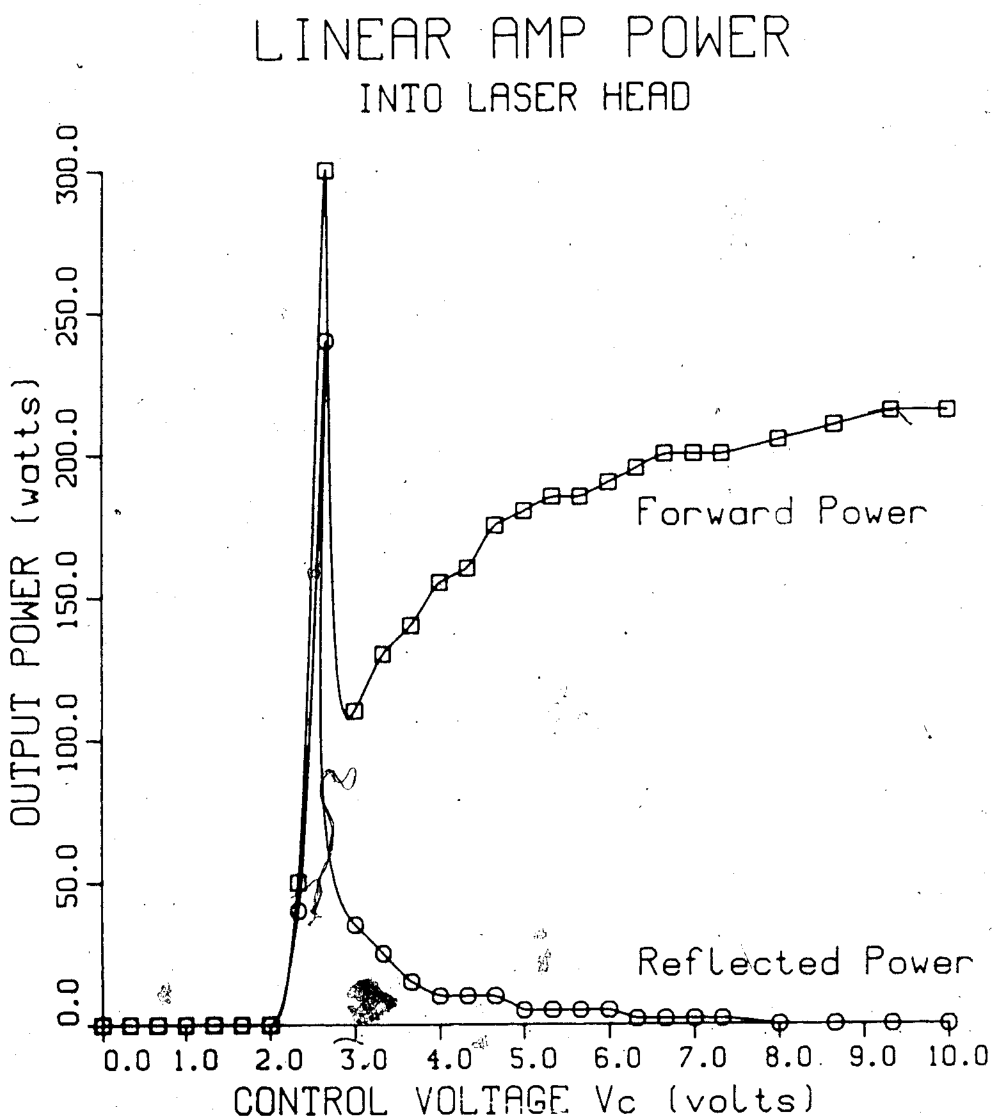


Fig. 8 - RF Driver Power Output

beyond two volts, the tube amp begins to develop power, but there is not enough energy to initiate a gas discharge and the laser head remains an open circuit. As all of the power is reflected from the open circuit, a standing wave develops, resulting in very high values for both forward and reflected power. If the control voltage is increased beyond about three volts, there is enough energy to initiate a discharge in the laser head, and the values of forward and reflected power drop as the standing wave collapses. The amount of power being dissipated in the discharge is now equal to the difference between the forward and reflected powers. There is still a mismatch in impedances at the laser head, since some amount of power is still being reflected back into the amplifier. As the control voltage is increased, the amount of power being transmitted into the gas discharge also increases, and the impedance mismatch is reduced, resulting in a lower reflected power. Even when the reflected power is completely reduced to zero, the amount of power delivered into the laser head is still considerably less than the maximum obtained with a 50 ohm load, because of the detuning of the output stage. The main points to remember are these: the tube amp needs a finite amount of power input before it starts to generate power, the gas in the laser head will not break down until after a certain power threshold has been passed, the load impedance of the gas discharge changes with the amount of power in the discharge, and there is a maximum power that can be transmitted into the discharge.

Since the laser head does not behave as a 50 ohm load, a matching network of some kind is needed to efficiently transfer power into the laser head. A transmission line transformer is used as a matching network, as it is better able to withstand the high power levels than discrete components, and at 140 MHz the quarter wavelength cables are short enough to work with. The transformation of impedances over a quarter wavelength co-ax cable can be determined from the formula

$$Zi * Zo = Zl^2$$

Zi - input impedance
Zo - output impedance
Zl - impedance of the co-ax cable

Several different transformers were built and tested, each with a different effective impedance (Fig. 9). The transmission line transformer which transformed the 50 ohm output of the tube amp to 200 ohms was chosen because it provides a good match to the actual impedance of the laser discharge over a wide range of power levels.

The curves in figure 8 are very non-linear, even for the 200 ohm transformer. This non-linearity could conceivably cause problems for the control program, so it needs to be compensated for. This is done by the addition of the circuit in figure 10, which is connected between the D/A voltage coming from the microprocessor and the oscillator control voltage input. The circuit compensates for the

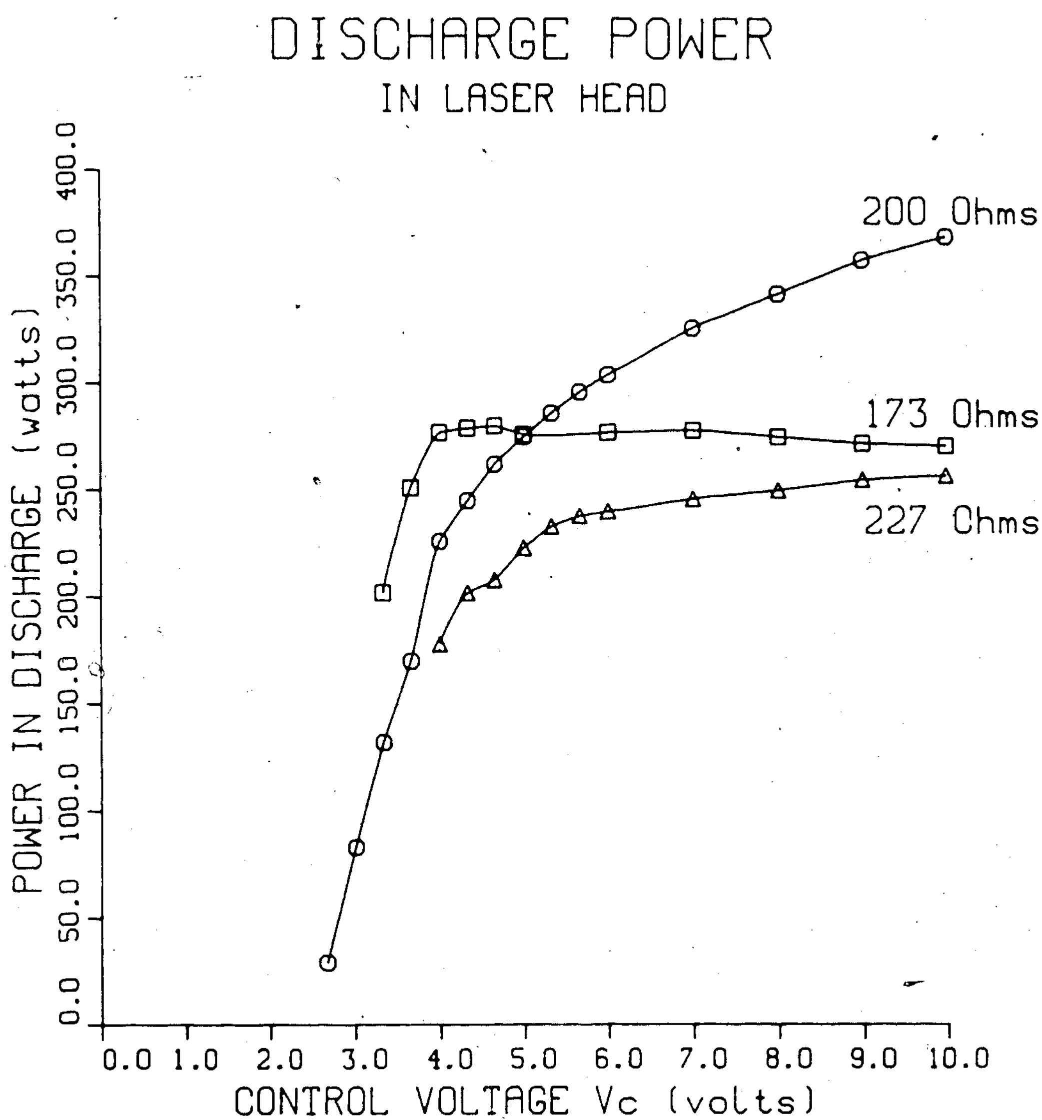


Fig. 9 - Use of Co-ax Transformers

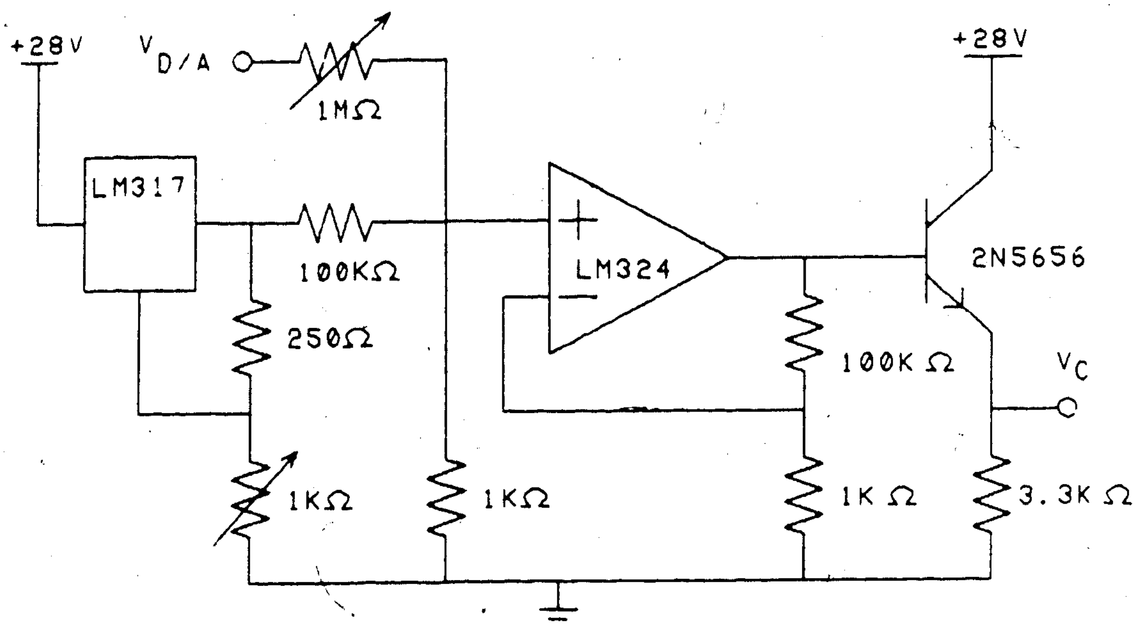


Fig. 10 Linearization Circuit for RF Driver.

finite turn on power by adding a fixed voltage to the D/A voltage being output by the microprocessor. Thus, when the D/A voltage is zero, the oscillator will be putting out enough power to put the power amplifier on the verge of turning on. The circuit also provides variable gain for the D/A voltage, so that when the maximum D/A voltage is applied, the RF driver will just be entering the saturation region. This linearization of the RF driver power characteristics allows the use of relatively simple control algorithms in the microprocessor controller.

C. CONTROL ELECTRONICS

The control electronics for the laser system are physically divided into three categories: the hardware controller, transducers, and the front panel. The hardware controller consists of the central microprocessor and all of the associated logic needed to provide the various control functions. In the interest of space the controller will sometimes be referred to as the CPU. Transducers are the devices that either generate signals for the controller to process or transform signals from the controller into physical effects. The front panel is used to select and display the functions desired by the operator, and organizes this data into a form acceptable to the controller. It can then transmit this data to the controller over a serial data link.

The Hardware Controller

In order to preserve as much modularity as possible, the controller is built on three different cards which are connected by the STD bus.[19] The STD bus provides a simple and compact means of sharing information among several boards. Pinouts for the STD bus are shown in Table 1. All internal communication (i.e. data bus, address bus, and control signals) is accomplished over the STD bus, and is completely buffered. Signals that connect the microprocessor to the external world are transmitted through connectors on the outer edge of the boards. The power supply for all logic

Pin #	Mnemonic	Signal
1-2	+5VDC	Logic Power
3-4	GND	Logic Ground
5-6	VBB	Logic Bias
7-14		Data Bus
15-30		Address Bus
31	WR*	Write to Memory or I/O
32	RD*	Read Memory or I/O
33	IORQ*	I/O Address Select
34	MEMRQ*	Memory Address Select
35	IOEXP	I/O Expansion
36	MEMEX	Memory Expansion
37	REFRESH*	Refresh Timing
38	MCSYNC*	CPU Machine Cycle Synchronization
39	STATUS1*	CPU Status
40	STATUS0*	CPU Status
41	BUSAK*	Bus Acknowledge
42	BUSRQ*	Bus Request
43	INTAK*	Interrupt Acknowledge
44	INTRQ*	Interrupt Request
45	WAITRQ*	Wait Request
46	NMIRQ*	Nonmaskable Interrupt
47	SYSRESET*	System Reset
48	PBRESET*	Push Button Reset
49	CLOCK*	Processor Clock
50	CNTRL*	Auxiliary Timing
51	PCO	Priority Chain Out
52	PCI	Priority Chain In
53-54	AUXGND	Auxiliary Ground
55	AUX +V	+12 Volts
56	AUX -V	-12 Volts

TABLE 1.Organization of the STD Bus.
A * indicates a low-active signal.

and analog circuitry is also housed in the card rack and connects directly to the bus, giving a very compact package.

The first of the three boards is a commercially available CPU board supplied by Enterprise Systems Corporation. It houses the central microprocessor, a math co-processor, serial and parallel I/O, and memory. The second board is referred to as the I/O board. It contains two programmable timers, a real time clock, an A/D converter, a D/A converter, and a serial data port, all of which are controlled by the micro through the STD bus. This board was developed on the Computervision CAD/CAM system. A third board contains signal processing circuitry that buffers the signals passing between the I/O board and the transducers. The general architecture of the microprocessor and I/O boards is shown in figures 11 and 12, and detailed schematics can be found in Appendix III.

The "brain" of the laser system is the central microprocessor. This microprocessor is responsible for providing several control functions. It must accept input from the front panel, convert this information into a form appropriate for manipulating the laser parameters, and configure the laser system to provide the desired function. It must also provide power regulation by sensing the laser output and implementing a feedback control algorithm. Finally, it must monitor the system through an assortment of sensors and provide a controlled shutdown in case of system failure, alerting the operator to the nature of the failure.

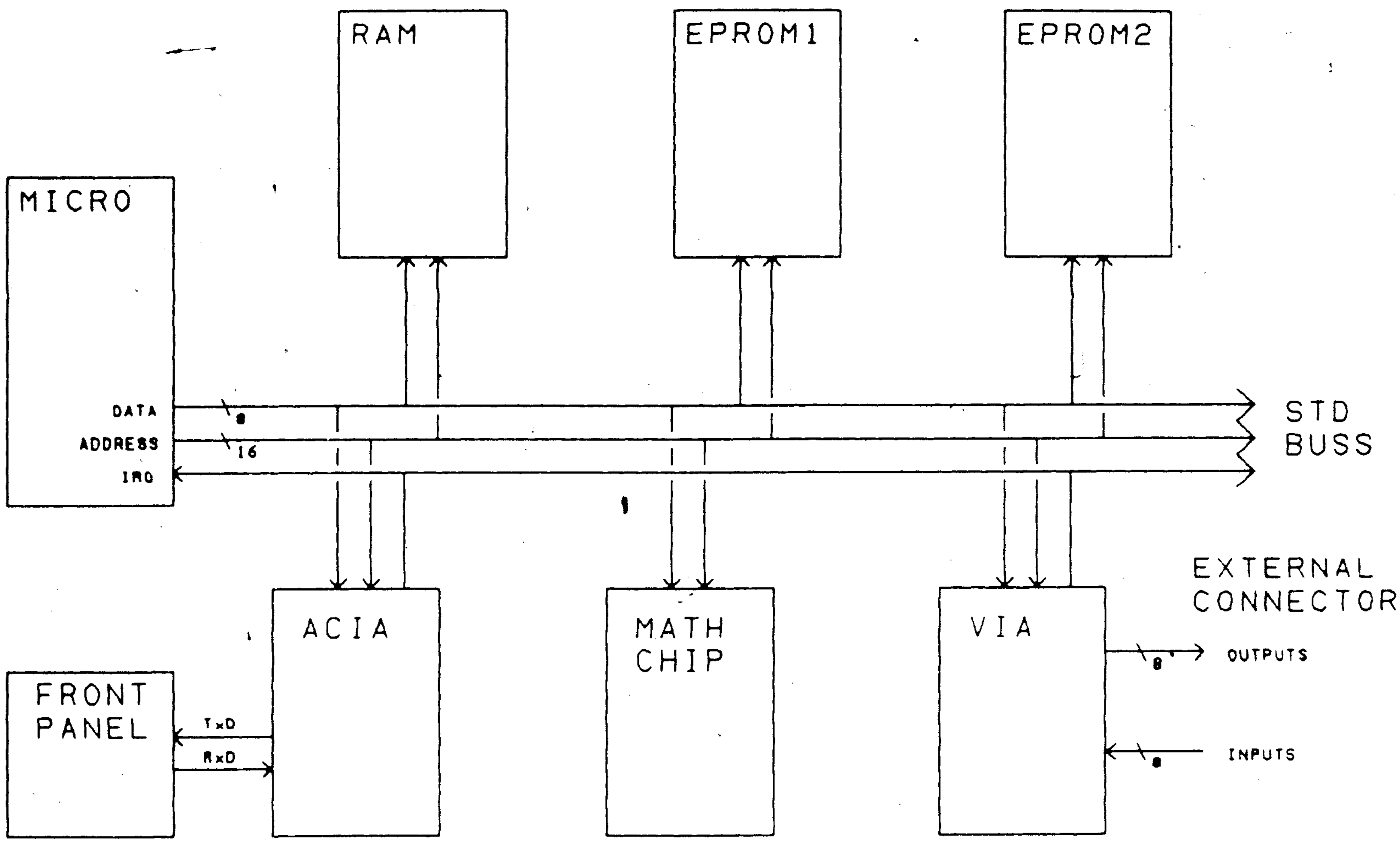


Fig. 11 - Microprocessor Board Architecture

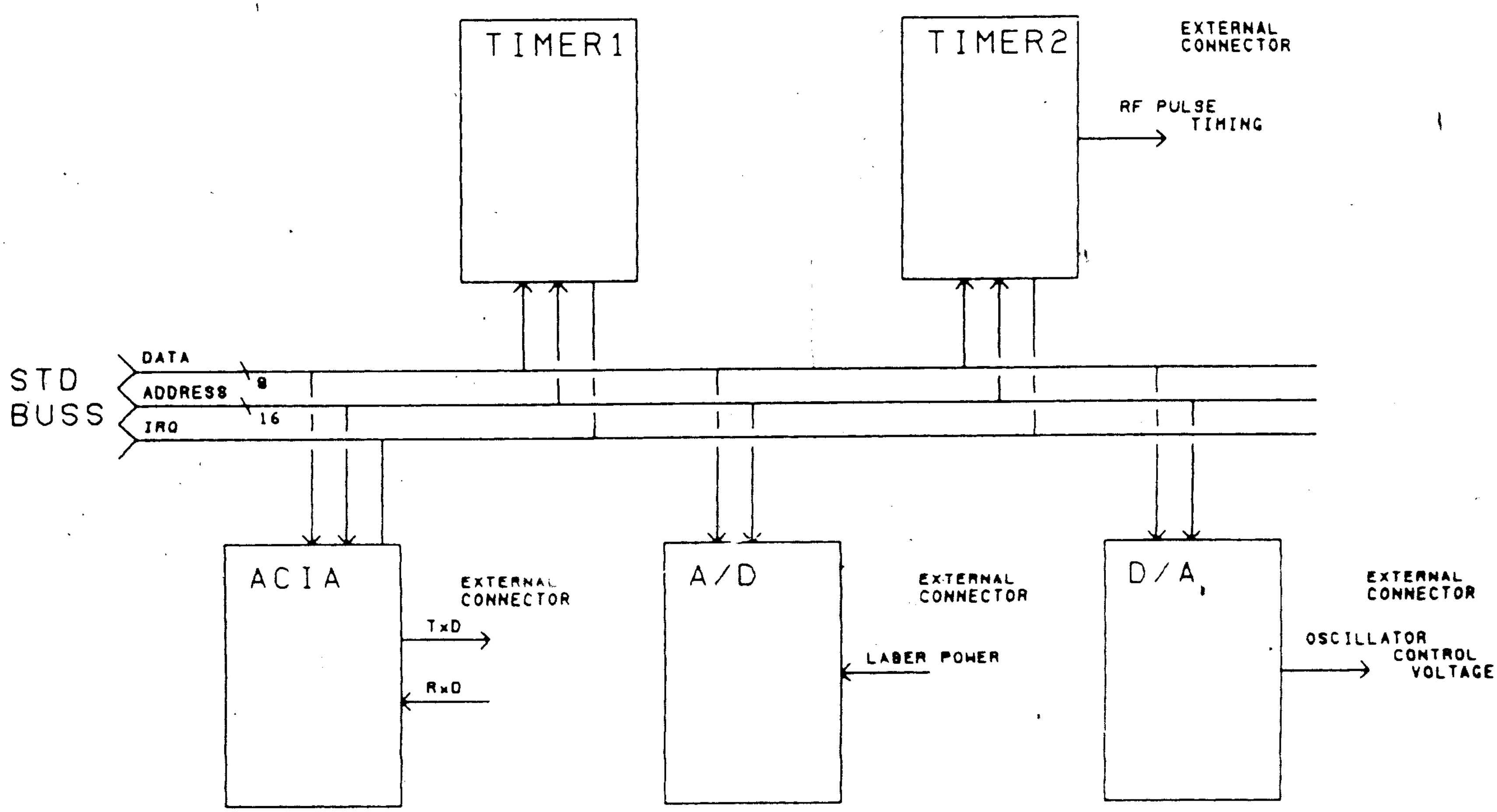


Fig. 12 - I/O Board Architecture

To provide all of these functions, a Motorola 6809 microprocessor is used. This processor provides the simple bit manipulations needed to efficiently control hardware, without sacrificing the ability to provide moderately complex control algorithms.

In order to ease the load of the CPU in providing the control algorithm, a math co-processor is used. The use of the math co-processor allows the power regulation software to be much faster than if the math was implemented in software. The co-processor used in this system is the AMD Am9511A. It is used to provide 32 bit fixed point math, which provides ample resolution for the relatively simple algorithms that will be used.

Program memory for the CPU is provided by two 2716 EPROMs. One 2716 EPROM contains the software for the laser system, the other holds a modified ASSIST09 monitor that provides facilities used in debugging the system. A total of 2K of RAM is provided as system memory, which is sufficient for this application.

Parallel I/O is provided on the CPU board by a Rockwell 6521 VIA. This chip has a total of 16 individually controllable I/O lines that are used to monitor or control on/off type transducers (Table 2). The VIA also contains two 16 bit hardware timers. One of these timers generates a periodic interrupt which is used to synchronize the power regulation algorithm. The other timer is used to provide a program watchdog function. The program watchdog is a

VIA Port A - Inputs

Pin #	Signal
0	Wilkinson Combiner Temperature
1	RF Power Amp 1 Temperature
2	RF Power Amp 2 Temperature
3	Cooling Water Temperature
4	Water Flow
5	Service Door Interlock
6	Foot Switch
7	Operate/Monitor Switch

VIA Port B - Outputs

Pin #	Signal
0	RF Oscillator Enable
1	CO_2 Beam Shutter
2	Cooling System Power
3	RF Driver Power
4	Error Indicator 1
5	Error Indicator 2
6	Error Indicator 3
7	Error Indicator 4

TABLE 2. I/O Signal Lines.

hardware timer which is set to generate an interrupt if it is not re-initialized during every iteration of the main program loop. If the micro fails to execute one loop of the program in the proper amount of time, the interrupt can be used to reset the program or provide a safe shutdown.

The last function provided on the CPU board is an asynchronous serial port. This port is realized as a Rockwell 6551 ACIA, and is connected to a terminal. Normally, this terminal would only be connected if the system needed servicing, but during the system testing the terminal is used to gain access to the internal workings of the controller. It is initialized to provide standard ASCII communication at 9600 baud.

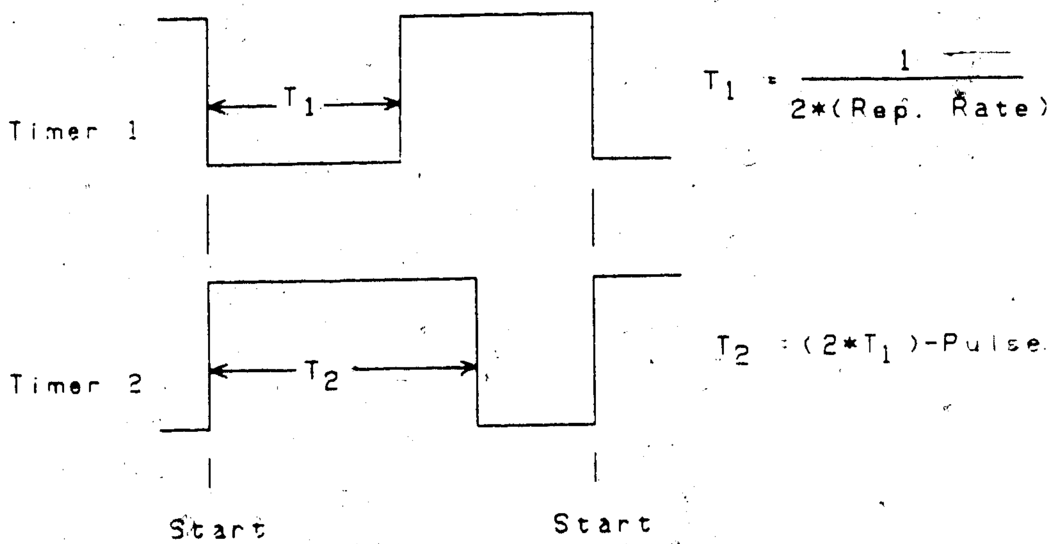


Fig. 13 Pulsed Mode Timing. Timer one is configured to generate a continuous time signal corresponding to the repetition rate selected on the front panel. Timer two generates a single pulse starting on the falling edge of the signal from timer one. The RF is activated on the low level of timer two output, so the high level pulse generated by timer two must correspond to the off time of the laser pulse.

The I/O board contains most of the chips necessary for communicating with the outside world. Additional timing capability is provided by two Motorola 6840 PTMs. The program trace function and pulse mode timing are generated off of these modules (Fig. 13). In addition to these timers, a real time clock is used to keep track of the actual time of day. While the real time clock is not used in the control functions, it could be used in several features that may be provided as options to the basic surgical laser system.

In order to connect the controller into the analog world, both an anlaog-to-digital and a digital-to-analog converter are needed. The A/D converter used during system testing was an Analog Devices RTI 1260 data aquisition board that used the STD bus. Since the full power of this board is not needed, it is being replaced by a Harris HI674A 12 bit A/D converter that will reside on the I/O board. It will provide a 12 bit conversion in only 12 microseconds. This fast conversion time is needed in order to keep the power regulation software as fast as possible, while the 12 bit resolution enables fine control over a wide range. Conversion from the digital to the analog world is accomplished using an Analog Devices AD558 D/A converter, which provides only 8 bits of resolution. While this means that some resolution is lost in the controller, it is felt that resolution greater than 8 bits will not be realizable in the RF oscillator, due to the amount of RF noise present.

Another Rockwell 6551 ACIA is located on the I/O board. This serial port is dedicated to communication with the front panel. Since the front panel can only handle a maximum of 8 bits per word, and one of these bits will be used for parity, this port is initialized for 7 bit communication. Also, the data transfer needs to be as fast as possible so the maximum data rate of 9600 baud is used.

A memory map of all the chips used on the microprocessor board and the I/O board is shown in Table 3.

The final board in the controller, the signal conditioning board, is not connected to the STD bus. This board provides the connections between all of the external signals coming from the micro and I/O boards and the transducers that receive these signals. Residing on the

Base Address	Hardware
FFFF F800	ASSIST09 EPROM
F7FF F000	LASER CONTROL EPROM
BF0B	A/D CONVERTER
9880	SERIAL PORT 2 - TERMINAL
9840	MATH CO-PROCESSOR
9820	PARALLEL PORT
9180	TIMER MODULE 2
9140	TIMER MODULE 1
9100	SERIAL PORT 1 - FRONT PANEL
9040	REAL TIME CLOCK
9000	D/A CONVERTER
0BFF 0800	RAM 2 - DEBUG MEMORY
03FF 0000	RAM 1 - SYSTEM MEMORY

TABLE 3. Memory Map of the Hardware Controller.

board is all of the circuitry needed to convert the I/O signals from the levels used by the transducers to the levels needed by the I/O chips. Comparator circuits are used to signal when the temperature sensors have exceeded the normal temperature range. Pull-up resistors are provided for all of the switch type interlocks. The combination of signals to provide the appropriate RF oscillator on/off signal is accomplished on this board by using hard wired TTL logic. A capacitor discharge circuit is located here to provide the current pulse needed to quickly open the shutter on the laser. The analog signal from the power monitor is buffered by a high impedance voltage follower. Finally, a 4-16 demultiplexer is used to decode the error signal from the CPU and light one of 16 error LEDs visible along the edge of the board. If a signal does not need to be adjusted, as in the case of the serial communication lines, a direct path is provided to its appropriate connector.

Transducers

The transducers are scattered throughout the laser system, each device located where it must sense or control its associated physical effect. Control lines from the transducers are brought back to a signal conditioning board where the signals are converted to levels compatible with the I/O device monitoring them. The transducers are part of either the interlock system or the power monitor.

Most of the sensors come under the heading of interlocks. These sensors monitor a specific parameter of the laser system. If the parameter passes outside of its normal range it is considered to indicate a major malfunction of the system. The laser is then shut down and the cause of the shutdown is displayed to the operator.

The interlock sensors monitor the operation of several sub-systems. A flow switch monitors the flow of water through the laser head and the RF driver, and a temperature sensor keeps track of the cooling water temperature. If the flow switch indicates a low flow, there could be a blockage of the cooling system, a failure of the pump, or simply not enough water in the reservoir. A high water temperature indicates either insufficient dissipation of heat in the

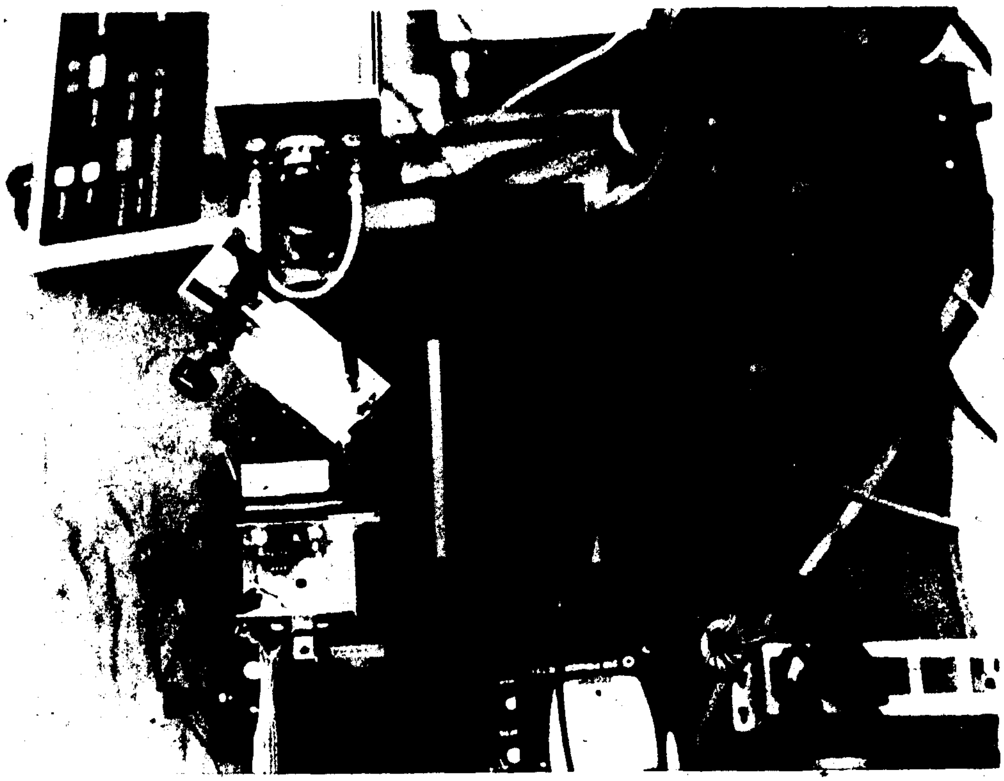


PLATE 3. Top view of Laser Power Monitoring system. The laser beam emerges from the laser head, top center, and is then split into two beams. The high power beam (approx. 95% of total laser power) is reflected to the right, through the beam analyzer and into a thermopile power detector, the finned cylinder on the right. The low power beam continues straight ahead, through an attenuator (not shown) and is focussed onto a small power detector (bottom center).

PLATE 4. Side view of the Laser Power Monitoring system. The beam splitting optic is visible in the angled lens holder, while the focussing optic is in the dark lens holder in the middle. The open box on the right contains the power detector.

radiator or an abnormal discharge in the laser head. The RF driver is monitored by temperature sensors on the balance resistors of the Wilkinson couplers and on the power transistors themselves. Any problems in the RF driver will show up as increased temperatures at one of these points. Finally, safety regulations require an interlock on the service door of the system, so that the laser cannot be operated if the service door is open. This ensures that no one will accidentally become part of a live circuit. The status of these interlocks will be displayed on a row of LEDs on the signal conditioning board. This will enable a serviceman to quickly determine the nature of a system failure.

The rest of the interlock system is comprised of solid state relays that control the distribution of power through the laser system. These relays control the flow of power to the water pump, cooling fans, and the RF driver. Each of the relays is controlled by the CPU, so that if a fault is detected in one of the systems, power to that system can by shut off before major damage occurs. The solid state relays were chosen because of their reliability and their compatibility to the TTL level I/O circuitry.

The rest of the transducers form the power monitor, which does more than just monitor the power output of the laser. A block diagram of the power monitor is shown in figure 14. It is in the power monitor that the CO_2 and He-Ne laser beams are combined, using an optic that is transparent

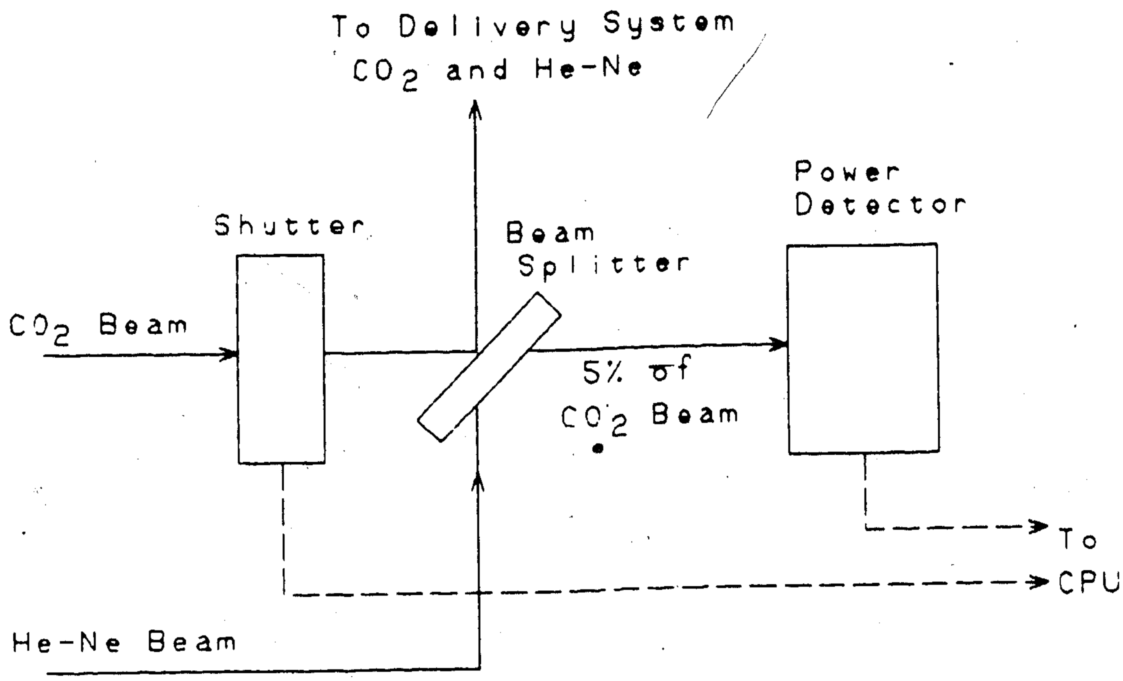


Fig. 14 Block Diagram of Power Monitor.

to the He-Ne beam but reflects the longer wavelength CO_2 radiation. A shutter is also part of the beam monitor, it controls the delivery of the CO_2 beam to the patient. The shutter is driven by a rotary solenoid, and a capacitor discharge circuit is used to deliver the pulse of current needed to activate the solenoid. The actual power sensor used to monitor the output power of the laser is actually a combination of optical and electrical components. The design of this power sensor will critically affect the ability of the CPU to control the output of the laser, and will be looked at in more detail in the section on the operation of the system.

The Front Panel

As has been mentioned, the front panel is the most noticed part of the laser system. It is here that the operator controls the laser by selecting the desired parameters. While the operator is setting these parameters the laser cannot be fired, so the system is said to be in a standby mode. When all of the parameters have been set, the operator puts the system into the operating mode by pressing a button on the front panel. Now the laser will fire whenever the foot switch is pressed. Any attempt to change the control parameters while the system is in the operating mode will immediately force the system back into the standby mode, and the foot switch will again be disabled. This ensures that the laser cannot be inadvertently fired when the controls have not yet been properly set. Standby mode can also be selected directly by pushing the appropriate button on the front panel. An LED lights up next to either the operate or standby button to indicate which mode the system is currently in.

The first parameter the operator sets is the type of laser exposure to be used, continuous or pulsed. Either type of exposure can be selected by pressing a button on the front panel, and an LED indicates the type of exposure selected. If continuous exposure is selected, the only other parameter that can be altered is the power level of the laser. If pulsed exposure is selected, the pulse width and repetition rate of the laser must be set as well as the laser power. Since the pulse width and repetition rate are only needed in pulse mode, the displays that set them are blanked and inoperative when the laser is in continuous mode. This is so that the operator sees only the pertinent information when he looks at the front panel.

The pulse width, repetition rate and laser power are all displayed on 2 digit LED displays. Each display digit is incremented by pressing a button directly beneath it. If the switch is kept pressed, the display continues to increment as long as the button is pressed. When the display is a 9 and the button is pushed, the digit resets to 0 without affecting the other digit of the display. If the laser exposure is set to continuous, so that the pulse width and repetition rate displays are blanked, the value that they were last set to is stored, and this value will be displayed again if pulsed exposure is re-selected.

In addition to these operator selected parameters, the front panel displays information coming from the CPU. A 30 segment LED bar graph displays the actual laser output power as a percentage of the maximum laser power available from the system. There is also an LED that lights up whenever the laser is being fired. This is necessary because the laser beam is invisible and silent, so some visible display is needed when the laser is on. Finally, there is an additional two digit display that can be used to display the power density at the focal spot of the laser beam. This would be useful if the focal spot size was under operator control, probably by changing the optics of the delivery system. This display is not used in the experimental system under development.

All of these functions could be directly controlled by the CPU, but it was decided to reduce the load on the CPU by using a separate microprocessor to keep track of the data on the front panel. The CPU could then access the data that it needed by communicating to the front panel over a serial link. This reduces the number of wires needed to connect the CPU to the front panel from 24 to just 4, so that a simple telephone type retractile cord can be used as a connector. As a result, the front panel can be physically separated from the laser system, so that the operator could locate the front panel in an accessible place without concern for the location of the laser system. A block diagram of the front panel is shown in figure 15, and detailed schematics can be found in Appendix III.

The microprocessor chosen for the front panel is the Motorola 68701 single chip microcomputer. This device contains three parallel ports, a serial port, scratchpad RAM, and 2K EPROM all on a single chip. Using this device resulted in considerable savings in space on the front panel, without any sacrifice in capability. While not code compatible with the 6809 microprocessor used in the CPU, the two are similar enough to allow the same style of programming, which simplifies the programmers job.

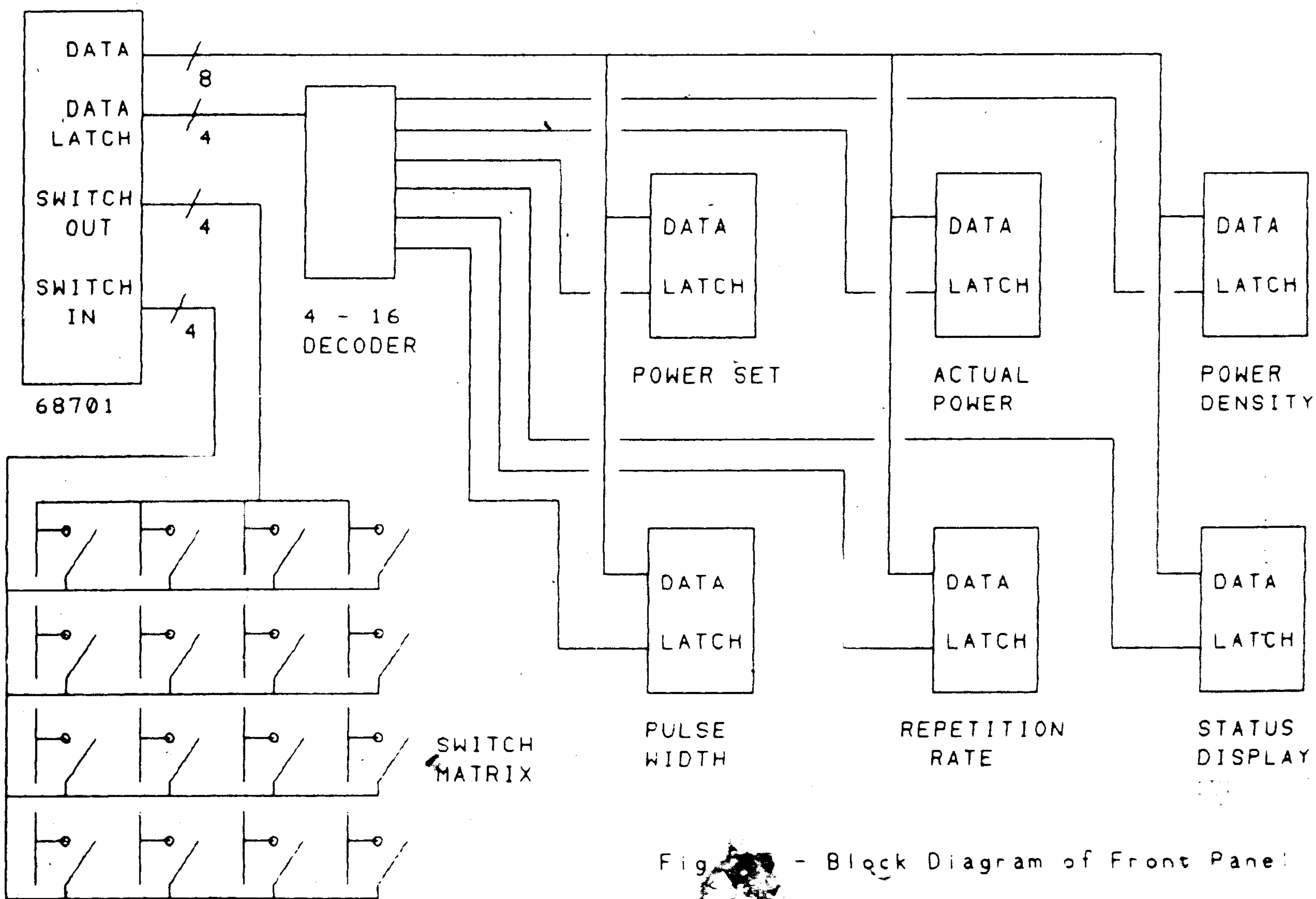


Fig. - Block Diagram of Front Panel

Each two digit LED display is driven by a pair of BCD to seven segment decoder-drivers, each of which drives a single digit. This pair of drivers is fed from an eight bit latch which is connected to a common data bus coming from the 68701 micro. Another eight bit latch is used to drive the individual LEDs on the front panel. Each bit in this latch drives a single LED or a combination of single LEDs. The LED bar graph is controlled by LM3914 Bar Display Driver chips driven from an analog signal generated by an AD558 8-bit A/D converter. This converter has an internal latch to hold data written to it. Data is written to any of these displays by placing data on the common data bus. The data is then transferred into the appropriate display by selecting the latch driving that display through a 4-16 multiplexer. In order to ensure that the displays will be stable, all of the displays are deselected when data is being written on the data bus.

To be able to take the action desired by the operator, the microprocessor must be able to distinguish when a button has been pressed. The microprocessor determines which button has been pressed by using a matrix method. Each push button makes a connection between a row and a column of the matrix. The microprocessor monitors the rows and columns and is able to distinguish when a row has been connected to a column. When a single row is connected to a single column, one button is uniquely determined as causing the connection. Using this method, the microprocessor can monitor 16 switches with only 8 I/O lines.

D. SOFTWARE

The programs that specify the procedures to be executed by the system in providing control of the laser system will be discussed in three parts. First, the main program, which is executed in a continuous loop by the central 6809 processor. This main loop provides the communication with the front panel, checks the interlocks to ensure that all the sub-systems are operating properly, and controls the setting of the laser parameters. The second area to be discussed will be the power regulation software, which is provided on an interrupt basis on the 6809 processor. Finally, the front panel software will be discussed. The front panel software controls the organization of the information displayed on the front panel, and feeds this information to the CPU when requested to do so. A Motorola ASSIST09 monitor program that has been slightly modified to fit the system hardware is also used to provide debugging capability.

All of these programs are written in assembler, which provides the maximum capability for direct control of the hardware devices. While the control program is moderately complex, writing it in assembler is not an insurmountable problem for a competent programmer. The primary concern in writing the software is to maximize the speed of execution, since the performance of the controller will be compromised if the controller is too slow. Towards this end, all of the variables used in the program will be stored in page zero, which allows the fastest access time. Also, subroutine calls are minimized, and when a subroutine is used parameters are passed in the accumulators rather than on the stack. As a result of writing the code to maximize speed, the program is not position independant ~~or~~ re-entrant, but since the software is dedicated to a single fixed system this does not result in any problems.

Main Program Loop

The main program used during system development has several features that would not be present in the final surgical laser system. Provision has been made to change some of the control parameters from the terminal connected to one of the serial ports. There is also the capability to pulse the laser on and off at high repetition rates. This has been done by configuring one of the hardware timers to put out a high repetition rate pulse and switching this pulse mode on or off through the use of an error indication line that has been 'borrowed' for this purpose. Finally, the control provided can be either open or closed loop. This allows the effectiveness of the closed loop control to be evaluated. None of these features will be needed after the system has been optimized for its final configuration, and they would be removed at that time.

A flowchart depicting the main loop of the laser control program is shown in figure [illegible] and detailed source code is given in Appendix I. The main program begins when control is transferred to it from the ASSIST09 initialization after a hardware reset. The RAM control registers are then initialized. In order to provide the fastest memory access, the control registers begin at memory location 0000, and zero page addressing is used to access them. The power set point table, which provides the conversion from the power in watts to the control voltage sent to the RF oscillator, is then transferred into RAM. Having the power table accessible in RAM gives the capability of providing a dynamic calibration procedure or an adaptive control process. Neither of these facilities has been developed for this system, but having the set point table in RAM allows the possibility of future modifications.

After all the RAM has been initialized, the hardware devices are initialized. The program then either enters the control loop or exits to the monitor to allow modification of the initialized parameters. If the program is signalled to exit to the monitor, the ASSIST09 monitor is fired up, and the operator now has access to the parameters through a terminal connected to the system. Several additional commands have been added to the monitor, and the operator can use these to adjust any of the control loop parameters. When all of the control loop parameters have been set as the operator desires, the operator can re-start the control

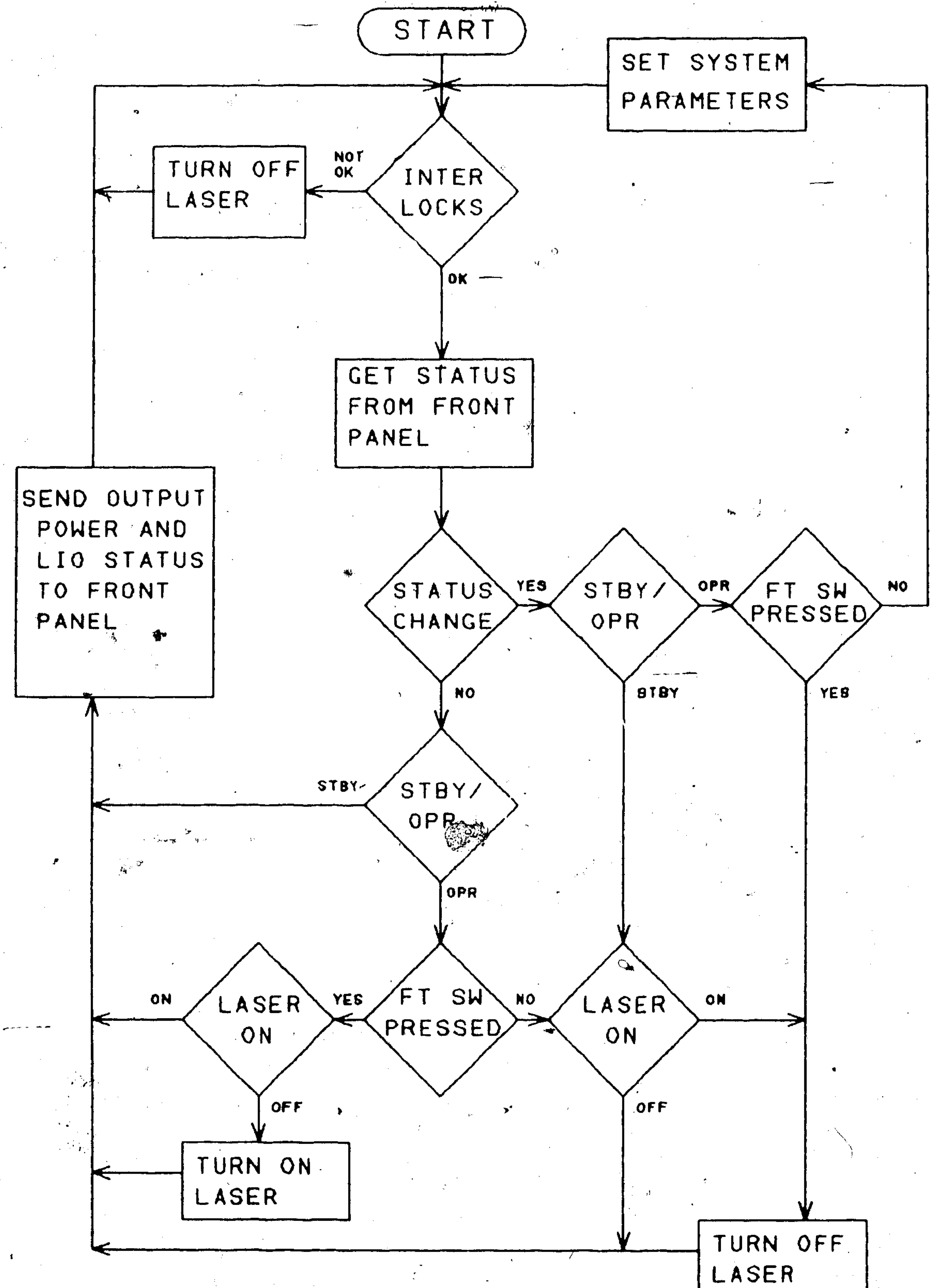


Fig. 16 - Flowchart of main control loop

loop. If at any time the operator wishes to change the control parameters, the program can be stopped from the terminal and adjustments made.

When control is returned to the program, the hardware devices are started and the laser is set in the off state. Since most of the hardware access in the main loop is to the VIA, the address of the VIA is stored in one of the processor's registers. All access to the VIA is now referenced to this register, which improves the speed of the control loop and reduces memory requirements.

At the start of the main control loop, the program watchdog is reset and the interlocks are checked for any device malfunctions. After this, the front panel is asked to send the system status selected by the operator. The action next taken by the controller depends on the status received from the front panel. As long as the status indicates that standby mode is selected, no action is taken by the controller. When the status changes from standby to operate mode, the front panel is asked to send all of the appropriate data that has been selected by the operator. The laser system is then configured to provide the selected operation. Once the laser is in operate mode, the foot switch is checked to determine if the laser should be turned on or off. If the status should change back to standby mode from operate mode, the controller ensures that the laser has been turned off, regardless of the foot switch position. This arrangement of the status and foot switch checks ensures that a two step procedure is always taken in the proper order before the laser is turned on. The final action taken before repeating the control loop is to send the Laser In Operation (LIO) status and the output power of the laser to the front panel for display.

The procedure to turn the laser on or off is more complicated than simply flipping a switch. When turning the laser on, the procedures are slightly different for continuous mode and pulsed mode. In continuous mode, the pulse timers must be disabled, while the power regulation synchronization timer must be initialized. The status is then changed to show that the laser is on, the RF oscillator is turned on, the power regulation timer is started and the interrupt associated with the timer is enabled. When starting the laser in pulsed mode, the procedure is similar but the pulse timers are initialized and started while the power regulation timer is left off. If the laser is to be turned off, the RF oscillator is turned off, and all timers are disabled. All of the registers and hardware used in the power regulation are then reset to zero so that power regulation will start from a known state when the laser is turned on again. Finally, the status is changed to show that the laser is off.

During the execution of the main control loop, several different pieces of data need to be transferred between the CPU and the front panel. All data transfer is initiated by the CPU, which indicates to the front panel what data will be transferred, and in which direction the transfer will take place. The first word received by the front panel is stripped out of the data stream and is interpreted as a control word, not data. If the CPU is requesting data from the front panel, the control word will indicate what data is to be sent. The front panel then transmits the requested data, and resets itself to receive the next control word. If the CPU is sending data to the front panel, the front panel configures itself to receive the data, and after it has all been received, resets itself. The data is transferred between the two processors in a set sequence, so that the processors are in agreement as to how the data is interpreted.

Power Control Algorithm

The power control algorithm implemented in the controller is a simple proportional controller given by

$$U(kT) = Kp * (R(kT) - Y(kT))$$

U(kT) - control variable
Kp - controller gain
R(kT) - set point
Y(kT) - feedback signal

This type of controller was chosen over more sophisticated algorithms for several reasons. First, it is easy to implement, and takes very little time to execute. The results expected from this type of controller are well known, so that simple measurements [illegible] provide information about the system, and any deviation from the expected result will probably have an obvious source. Finally, this type of control is unlikely to completely suppress the variations in output power, and the residual variation can be examined to provide a means to compare the several proposed power monitoring systems.

The power regulation routine is executed at a fixed interval (T) by generating an interrupt off of a free running counter. When the interrupt occurs, execution of the main control loop is suspended and the power regulation function is implemented. The maximum frequency that the digital controller can handle is fixed by the length of time between implementations of the power regulation function. A rule of thumb is that the sampling period be kept to less than 10% of the rise time of the system. Since the rise time of the system is limited by the response of the power detector, all other processes being instantaneous in comparison, the choice of power detector to some extent determines the speed which the controller must run at. The M5 detector used in the power monitor has a rise time of about 50 ms, which gives a maximum sampling interval of 5 ms. Several different sampling times between 0.1 and 5 ms were tried, and a sampling period of 1.0 ms was selected.

The first task of the controller after receiving an interrupt from the power regulation timer is to get a reading of the output power of the laser through the A/D converter. This feedback signal is stored and th[illegible] signal is generated by subtracting the feedback si[illegible] the set point. The value of the control variable is then calculated, using the math co-processor to perform the required multiplications. Since the math co-processor is accessed repeatedly during the calculations, the address is stored in a register and all access to the co-processor is made relative to that register. This improves the speed of execution and reduces memory requirements. Once the value of the control variable has been calculated, it is sent to the D/A converter to set the RF oscillator control voltage. Software linearization of the control voltage is also provided at this point, but the addition of the hardware linearization circuitry eliminated the need for this and the software limits are set to the upper and lower limits of the D/A converter.

Front Panel Program

The program for the front panel is relatively simple compared to the program for the CPU. All the front panel has to do is keep track of the data entered by the operator, put it into a format acceptable to the CPU, display it on the displays, and send it to the CPU when asked. Detailed source code for the front panel program can be found in Appendix II.

The main part of the front panel program is the determination of when a switch has been pressed and what switch it is (Fig. 17). This is done by assigning each switch in the switch matrix a number. The switches are then

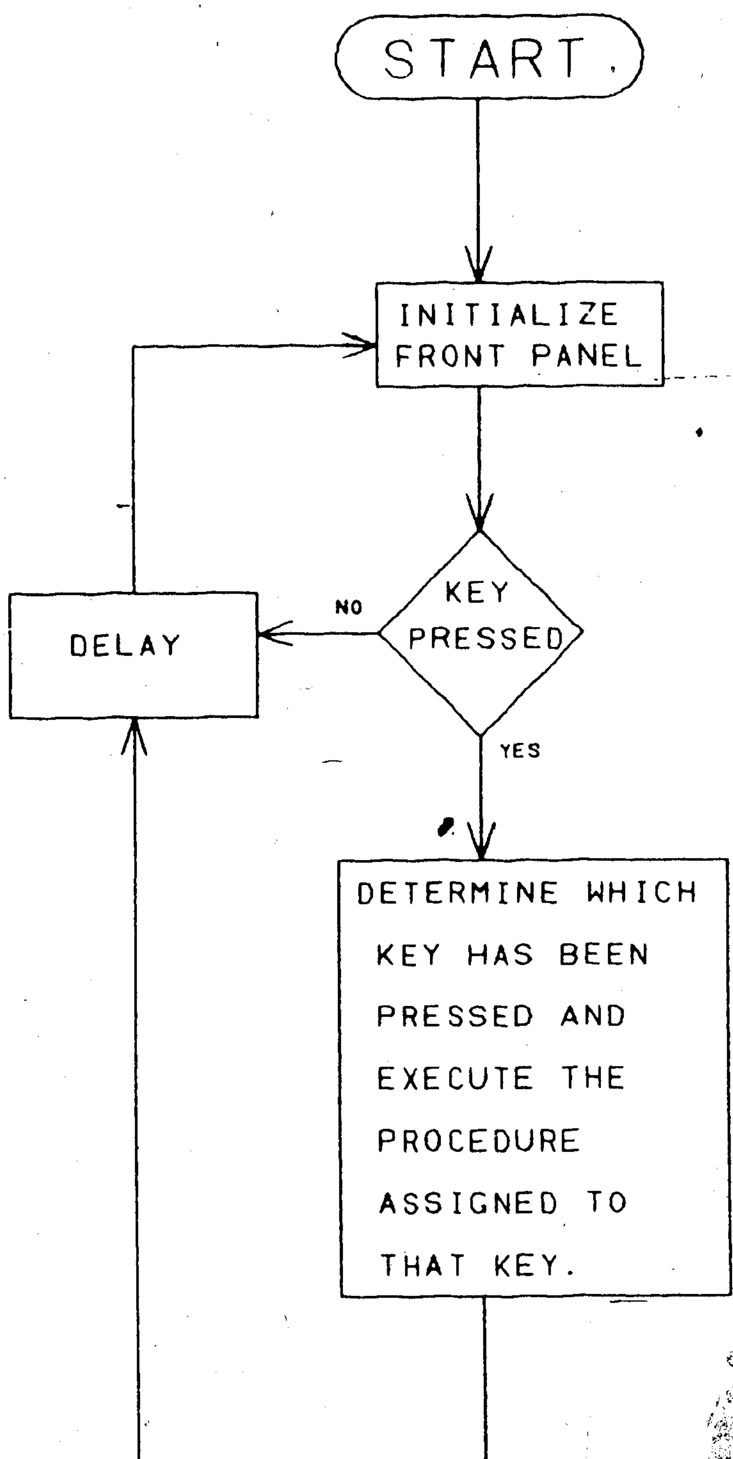


Fig. 17 Flowchart of front panel program.

Switch #	Subroutine to Execute
0	N.C.
1	N.C.
2	Increment laser power by 1
3	Increment laser power by 10
4	N.C.
5	Change to continuous exposure
6	Enable rapid pulse (Superpulse)
7	Change to pulse exposure
8	Increment pulse width by 1
9	Increment pulse width by 10
10	Increment repetition rate by 1
11	Increment repetition rate by 10
12	Enable closed loop control
13	Enable open loop control
14	Change to operate mode
15	Change to standby mode

TABLE 4. Front Panel switch assignments.

checked in order to see if any have been pressed, and a counter keeps track of which switch is currently being checked. If the processor finds a switch that is pressed, the counter is used as an offset into a table of subroutine addresses, and control is passed to the address located at that point in the table. The subroutine then updates the information in the front panel memory.

Some of the switches on the front panel are used to increment numerical displays. Since it would be tiresome to push a switch many times in order to increment one of the displays a considerable number of times, provision is made to repeatedly increment a display if a switch is kept pressed down. This means that some delay must be inserted between increments, to allow the operator time to react to the appearance of the desired number on the display. A relatively long delay is inserted when the switch is pressed the first time so that the operator can slowly increment the displays one digit at a time. If the switch is kept pressed down, the delay is shortened so that only a small amount of time is needed to increment the display a large amount.

Since the CPU is operating on binary data, and the displays on the front panel take BCD data as input, some method must be used to convert between these two types of data. Rather than use time consuming conversion routines, each display is associated with two memory registers. One memory register contains BCD data, the other contains the same data in binary form. When the data is to be incremented, both registers are incremented by the same amount, so that the same number is represented in both registers. The BCD data is then used to drive the display, while the binary number is transmitted to the CPU.

A communication package complimentary to the one on the CPU is used to facilitate transfer of data between the two processors. This presents some difficulty, since the serial port on the 68701 is not fully compatible with the Rockwell serial port used by the CPU. In order to provide reliable communications, parity checking of the data is used, and this must be provided as software capability in the 68701. Since the use of parity checking limits the 68701 to 7 bit serial transfer capability, all data transfers are limited to 7 bits. This presents no difficulty for most transfers, since the two digit LED displays have a maximum value (99) that can be encoded in just 7 bits, but the D/A converter that drives the bar graph power display needs the full 8 bits. To overcome this problem, only the 7 most significant bits are stored in memory for the bar graph display. Just before the data is to be stored in the D/A, the data is shifted into the most significant positions on the data bus. This ensures that the full range of the D/A is realized, with little loss of resolution.

E. AUXILIARY SYSTEMS

The Cooling System.

The system used to remove the waste heat from the laser head and the RF driver is a closed loop cooling system using water as the working fluid. The water is pumped through the laser head and the RF driver, removing the waste heat and maintaining a tolerable operating temperature. The heated water then flows through a radiator, which dissipates the waste heat to the external environment. In order to minimize the increase in water temperature, the cooling loops for the laser head and the RF driver are connecte in parallel, not series.

The specification of this type of cooling system proceeds in three steps. First, the amount of waste heat generated and the maximum temperature rise allowable are used to determine the flow rate of the working fluid. This is determined by the equation

$$Q = F * c * T$$

Q - amount of waste heat generated, watts
F - flow rate of the working fluid, kg/s
T - temperature rise, °C
c - specific heat of working fluid, J/kg*K

Once the flow rate has been determined, a radiator is specified by examining the power dissipation and flow rate characteristics of the radiator. Finally, the pressure-flow characteristic of the entire system, including the laser head, RF cooling, radiator and all the connecting plumbing, is determined. A pump is then chosen by comparing its pressure-flow characteristic to that of the system, and selecting a pump that can deliver the necessary flow rate at the operating pressure.

The amount of waste heat generated by the system can be easily be estimated. For the sake of simplicity it is assumed that all 600 watts of RF power are dissipated inside the laser head. If the efficiency of the RF driver is taken to be 60%, there will be an additional 400 watts dissipated in the RF driver. The flow rate needed to cool the devices to a specific temperature can now be calculated, using water as a working fluid. It has been calculated that the output power of a waveguide laser drops by 20% for every 10°C rise in wall temperature.[2] In order to maximize the power output of the laser, only a small temperature rise is allowable, and a limit of 5°C is set. For a temperature rise of 5 degrees celcius, there must be a flow of 1.7 liters per minute through the laser head, and 1.2 liters per minute through the RF cooling loop.

When the pressure-flow characteristics of the two branches of the cooling system are determined (Fig. 18), it can be seen that the above calculations need to be revised. The cooling tubes inside the laser head are quite small, which restricts the flow of water through them. This means that for any given pressure, the flow rate through the laser head is less than the flow rate through the RF cooling loop. The result is that the temperature rise in the laser head is greater than the rise in the RF cooling loop. Since the operating temperature of the laser is the critical parameter, the water flow through the laser head must not be decreased below the flow rate needed to limit the temperature rise to 5 degrees. If the two branches are connected in parallel without any flow restricting devices, the pressure needed to pump 1.7 liters per minute through the laser head will result in a flow of 4.0 liters per minute through the RF cooling loop. The temperature rise in the RF driver will now be 1.5 °C, and the net temperature rise across both branches after the two water streams are mixed is 2.5 degrees.

A suitable radiator for the system can now be chosen by using the values calculated above. The radiator must be capable of dissipating 1000 watts of heat from a water flow of 5.7 liters per minute. It must also reduce the water temperature to as close to the ambient air temperature as

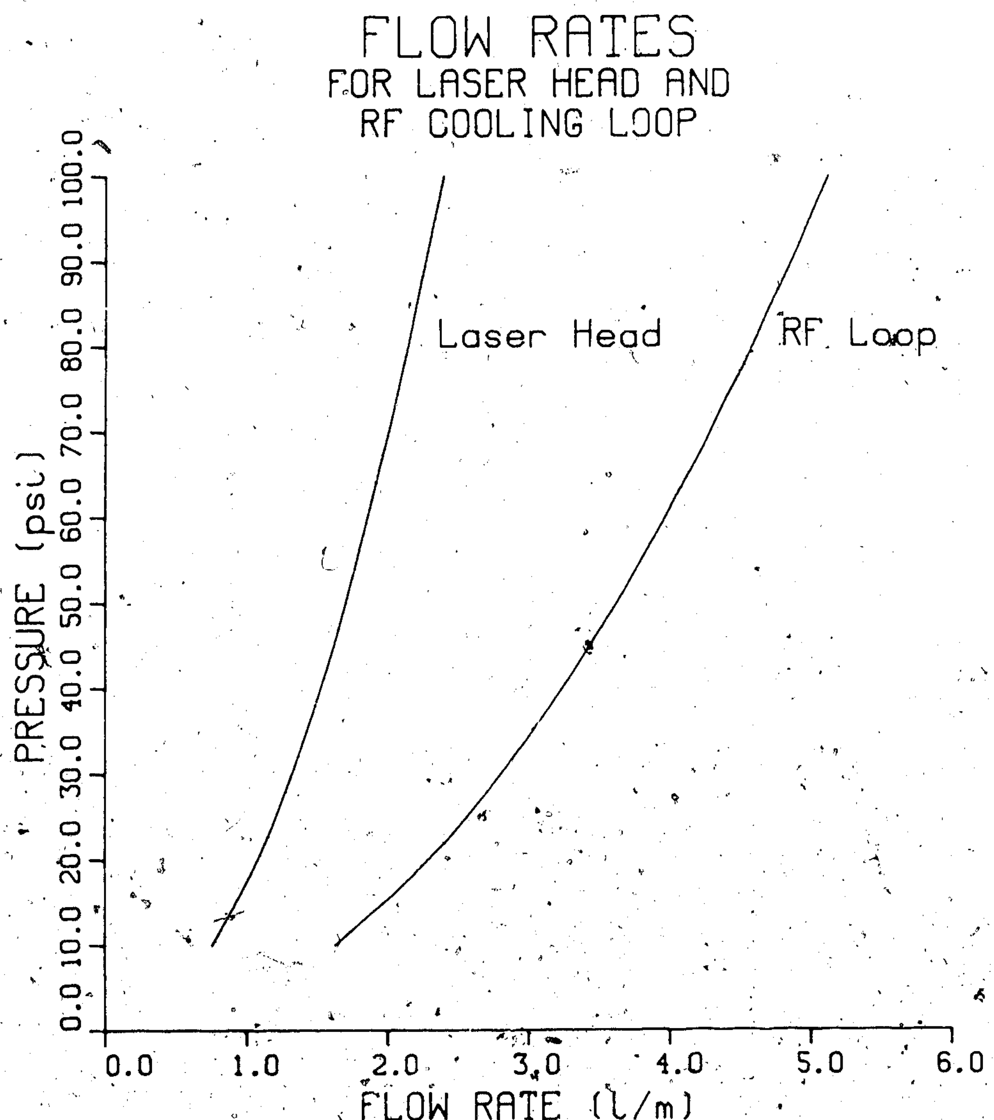


Fig. 18 - Pressure-Flow Diagram for Laser Head and RF Cooling Loop

possible. A radiator was selected which reduces the incoming water temperature by 25% when operated at the desired flow rate. This gives an incoming hot water temperature of 10 °C, and a net laser head cooling temperature of 38 degrees celcius. Note that the actual laser operating temperature will be higher than this due to thermal resistance between the laser channel and the cooling tubes.

The pressure-flow characteristic of the entire system is now determined (Fig. 19). The system includes the laser head and RF cooling loop connected in parallel, a flow switch to indicate adaquate flow through the laser head, a temperature sensor to monitor the hot water temperature, the radiator, and all the connecting plumbing. It can be seen from the pressure-flow characteristic that a positive displacement pump of some type is needed to produce the relatively high pressure needed to produce a flow of 5.7 liters per minute. The pump selected is a dual diaphragm pump, which comes with an automatic shut off switch to prevent the pressure from rising too high.

An operational test of the cooling system with the proposed laser head yielded some significant results. The water for cooling the laser head had previously been provided from the water mains. Even though the water from the mains was considerably cooler than the water used in the closed loop cooling system, the increased flow rate provided by the pump resulted in better cooling. The dual diaphragm pump was also found to be excessively noisy, a condition

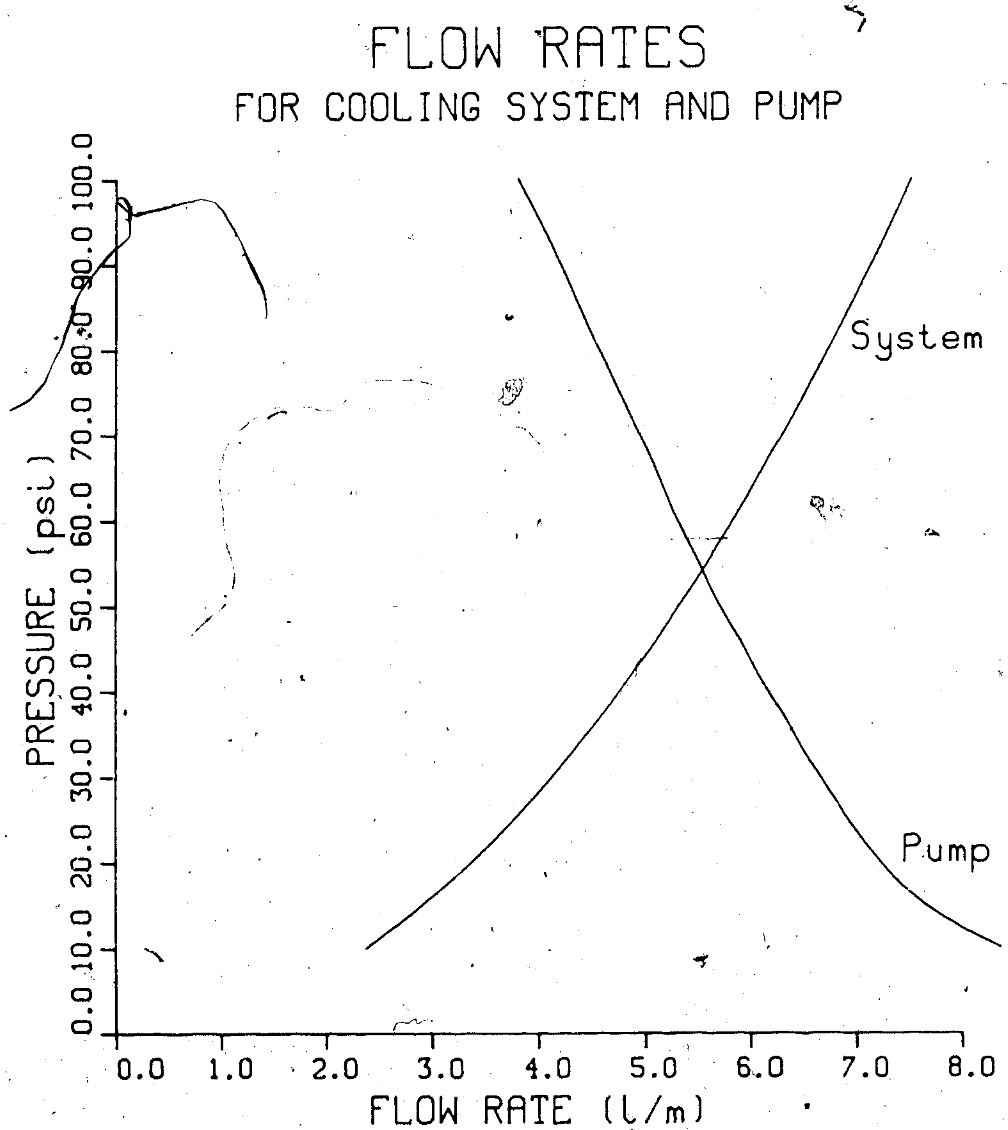


Fig. 19 - Pressure-Flow Diagram for Cooling System and Pump

caused by the pulsed nature of the water flow. Addition of an air chamber in the plumbing system reduced the noise, but it was still judged to be too loud for an operating room system. In order to use a quieter, lower pressure centrifugal pump, the cooling tubes in the laser head would have to be made larger. This provides an example of the feedback between the design of the system and the design of the laser head which would not be possible if the two were to be designed separately.

The Power Distribution System.

The different components of the medical laser system require power in different forms. The pump and fans of the cooling system require 110 volts AC, the RF driver needs 28 volts DC, the digital logic of the CPU runs off of 5 volts DC, and the analog signal processing requires ±12 volts DC. All of these voltage levels must be developed from a single 15 amp, 110 volt AC wall socket. The maximum amount of power which can be delivered from this type of socket without tripping the 15 amp breaker is 1650 watts. This puts an upper limit on the amount of power the system can consume.

The power supplies used to generate the different voltage levels needed by the system are commercially available switching power supplies. This type of power supply delivers the necessary power conversion in a compact and economical package. One power supply is used to provide 36 amps at 28 volts DC, and another supply generates 6 amps

COMPONENT	110V	28V	±12V	5V
RF DRIVER				
Oscillator		0.1A		
Pre-driver		4.0A		
Power Amp (ea)		14.0A		
CONTROLLER				
Front Panel				1.5A
Processor Board				0.1A
I/O Board			0.1A	0.1A
Signal Conditioning Board		0.2A	0.2A	0.1A
AUXILIARY SYSTEMS				
Water Pump	1.1A			
Radiator Fan	0.9A			
28V Power Supply	10.0A			
Logic Power Supply	2.0A			
TOTAL	14 A	32.3A	0.3A	1.8A

TABLE 5. Power balance sheet for the medical laser system, showing the amount of current consumed at each voltage level.

at 5 volts and 2 amps at ±12 volts. The AC lines for the power supplies, the pump, and the fans are individually fused, providing isolation from electrical faults. In addition, a 15 amp breaker is used as the main power switch for the system. This provides maximum safety for both the operators and the patient. The logic power supply is turned on by a key switch, while the power to the RF power supply and the cooling system is controlled by solid state relays activated by the CPU. This allows the CPU to maintain an orderly power up/ power down sequence as well as providing the ability to cut off power to a malfunctioning component.

III. OPERATING THE LASER

A. CONTINUOUS MODE OPERATION

When operated in the continuous mode, the main function provided by the CPU is the regulation of the power output of the laser. In order to provide adequate power regulation, a means of measuring the power output without interfering with the operation of the laser must be found. The method chosen is to split the laser beam into two, a high power beam that is delivered to the patient, and a low power beam used to measure the output power. As long as the ratio of power in the two beams remeains constant, regulating the power of the low power beam will result in the regulation of the power in the high power beam. The quality of power regulation therefore depends on how well the beam splitter performs, as well as on the accuracy of the power detector. Both the beam splitter and the power detector must be insensitve to frequency and mode shifting for the power regulation to give good results.

The Experimental Set-up

In order to assess the performance of various methods of power measurement, an experimental system was developed. The laser head, RF driver and microprocessor system were assembled and tested to ensure reliable operation. One of the main problems at this point was the amount of RF radiated from the laser. This high frequncy radiation was picked up by the power and control lines and made it quite difficult to obtain accurate readings, as well as adversely affecting the operation of the system. The problem was finally reduced by shielding all the power and control lines and by ensuring that all components were adequately grounded. The measurements still show some DC offset and noise due to residual RF radiation being fed through on the power and control lines, but the noise level is tolerable. Once the laser could be reliably operated, the power monitoring system was set up.

The power monitoring system consists of a beam splitter, a power detector used in the low power beam to regulate the power, and equipment to analyze the high power output beam. The beam from the laser is split by a beam splitting optic that is 95% reflecting at a wavelength of 10.6 microns when the angle of incidence is 45°. This beam splitting optic is essentially transparent at the He-Ne laser wavelength, so it can be used in the final system to mix the CO_2 beam with the He-Ne aiming beam. Approximately 5% of the power of the CO_2 beam passes through the beam splitter straight ahead into the power regulation detector, while the rest of the beam is reflected off the beam splitter at an angle of 90° to the laser. Normally, this high power beam would be directed into a delivery system to be used in the operation, but here it is directed into a Laser Beam Analyzer and a standard thermopile power meter.

The Laser Beam Analyzer (LBA) uses a rotating wire passing through the laser beam to determine the mode structure of the beam. When the rotating wire passes through the beam, some of the power is reflected onto two pyroelectric detectors. These two detectors are arranged in such a fashion that the power reflected onto them comes from two orthogonal slices through the laser beam. The output of each detector therefore gives a profile of the power along the section of the laser beam that is reflected into that detector. Any change in the mode of the laser will show up as a change in the shape of the profile or as a change in the proportions of one profile as compared to the other. An example of the output of this device is shown in figure 20. The use of this instrument enables the detection of mode shifts that may affect power regulation.

Continuous Mode Power Regulation

The first step in analyzing the effectiveness of regulating the power output of the laser was to determine the open loop performance of the laser. Figure 21 shows a typical variation in output power over a period of about 90 seconds. The power stability of the laser was quite poor, with the power output varying up to 30% from the average value.

Once the open loop perfomance had been determined, the amount of improvement obtained by employing a feedback control algorithm could be measured. The algorithm used to

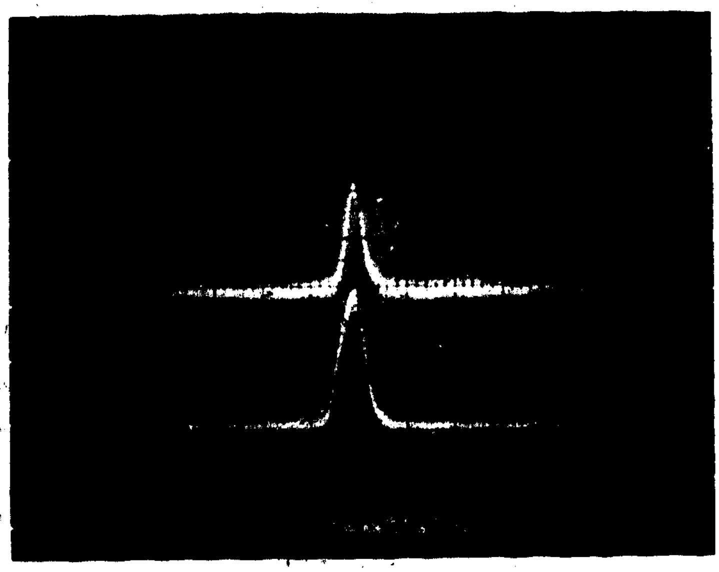


Fig. 20 Example of LBA output.
Top trace - X direction. 1 div = 20 mV
Bottom trace - Y direction. 1 div = 20 mV
Horizontal div = 200 micro seconds = 5.0 mm

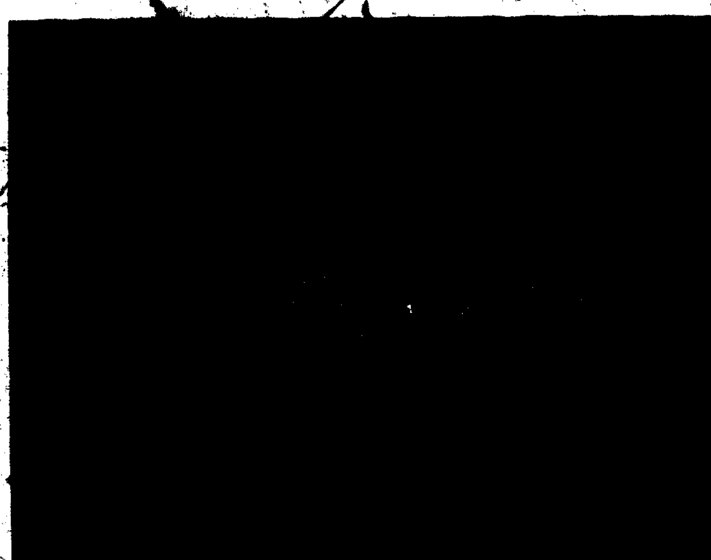


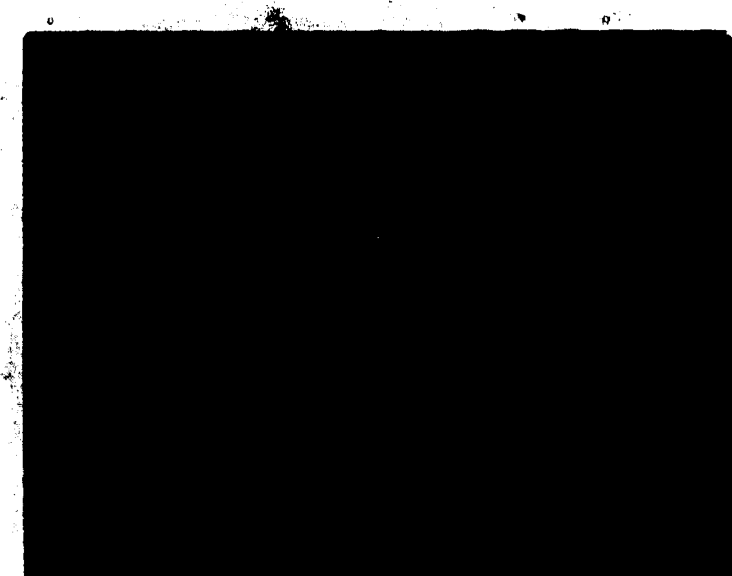
Fig. 21 Unregulated laser power output.
Vertical div = 1 watt
Horizontal div = 10 s

provide the regulation in all of the power regulation tests is a simple proportional controller. While this controller does not give the best results in terms of eliminating variations in the output power, it is good enough to give an indication of the effectiveness of the power detection scheme under examination.

The first method of power detection used to generate the feedback signal was a simple thermopile detector. This detector has the advantage of being very rugged and inexpensive. It is also capable of detecting a wide range of powers, and will not be damaged at the maximum output power of the laser. Its only disadvantage is its slow speed. The detector used in the experiment had a response time of about 1 second. With such a slow time constant, the detector was essentially acting as an integrator with a long time constant, and any reasonable amount of gain sent it into oscillation (Fig. 22). This type of power detector was therefore judged to be unacceptable, since the use of the very low gains needed to obtain stable operation would not provide much protection against power fluctuations.

To reduce the response time of the detector, the mass of the thermocouple must be reduced. This was accomplished by using a miniature multijunction thermopile, made using integrated circuit techniques. The size of this detector is quite small, so that the response time is much faster than the thermocouple. As a trade-off, the small size of the detector limits the amount of power that can be absorbed

(a) Controller gain = 8.0

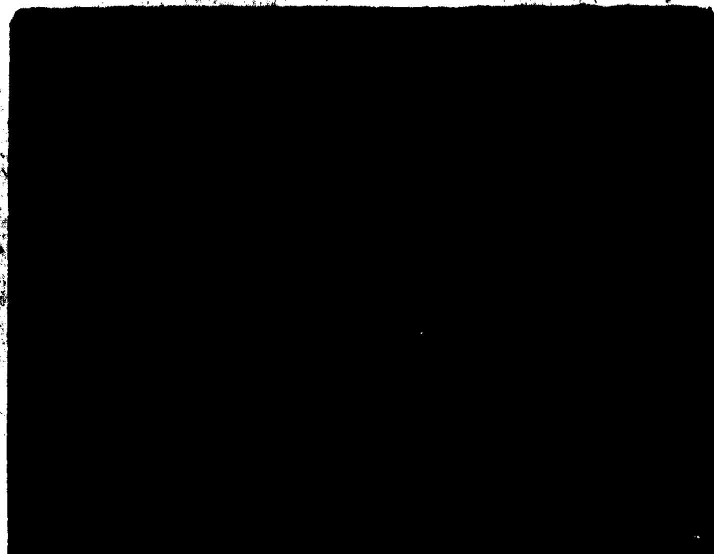


(b) Controller gain = 1.0

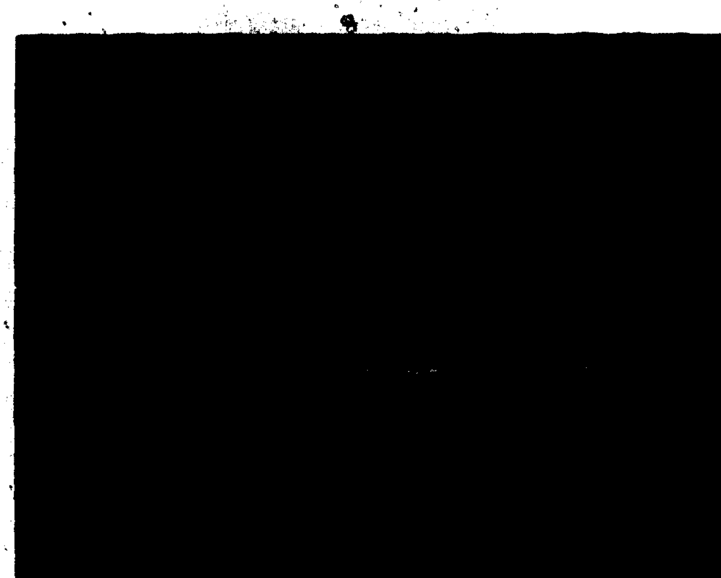
Fig. 22 Oscillations due to slow detector.
Top trace - Control variable. 1 div = 2 V
Bottom trace - Output power. 1 div = 1 watt
Horizontal div = 1.0 s

without damaging the device. The damage threshold of the 0.5 mm diameter detector is only about 0.2 milliwatts. Since this power level will be exceeded by the output power of the laser, some method of reducing the amount of power impinging on the detector has to be found.

The first method used to reduce the amount of power seen by the power detector was to sample only a portion of the beam. This was accomplished by placing the detector far enough from the laser so that the power density at the detector was below its damage threshold. Because of the small divergence angle of the laser beam, the detector had to be placed some distance away from the laser in order to sufficently reduce the power density. This could not easily be done in a system where small size was one of the design goals. To reduce the required distance between the laser and the detector, a lens was used to increase the divergence angle of the beam. In addition to reducing the distance between the laser and the detector, it was thought that the defocussing effect of the lens would reduce sensitivity to mode changes, since many points of the beam would contribute to the amount of power entering the detector. This method of detecting the power of the laser worked quite well as long as the mode was stable (Fig. 23). As soon as the mode shifted, however, the fraction of the total beam power directed onto the detector changed, resulting in [illegible] regulation of the output power.



(a) No mode shift, Kp = 16

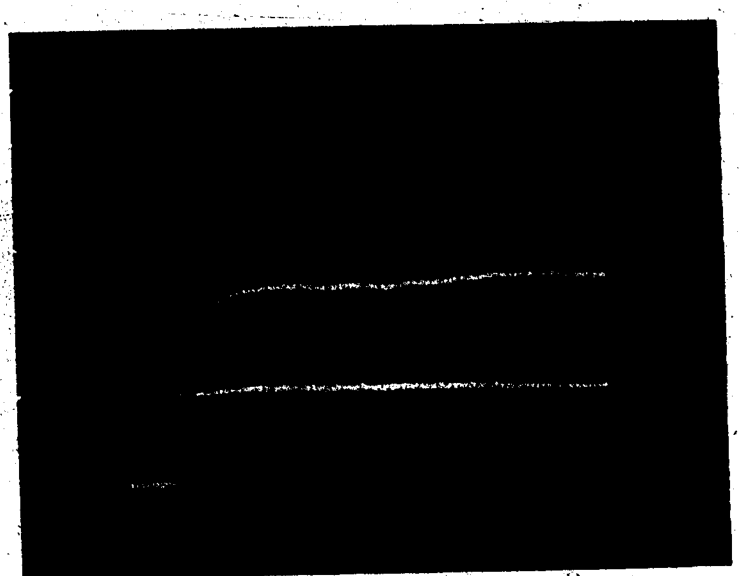


(b) Mode shift @ 4 s, Kp = 16

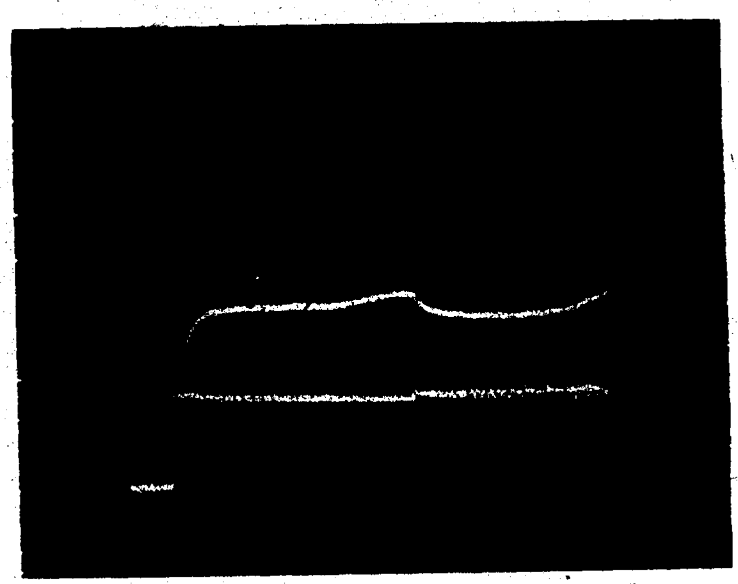
Fig. 23 Power regulation with unfocussed beam.
Top trace - Output power. 1 div = 1 watt
Bottom trace - Feedback signal. 1 div =0.5 V
Horizontal div = 5.0 s

Clearly, it was necessary to detect the power of the entire beam, not just a portion of it. To do this, the 2 mm spot size of the laser would have to be focussed onto the 0.5 mm diameter detector, but doing this with the full power of the measuring beam would exceed the damage threshold of the thermopile. In order to reduce the power of the focussed spot down to an acceptable level, a 99.5% reflecting optic was used to attenuate the beam. With the power density reduced to an acceptable level the power control tests were repeated, this time with the power detector located at the focal point of the lens.

The performance of this method of power detection was comparable to the performance using the defocussed beam, with the sensitivity to mode changes remaining about the same (Fig. 24). The reason for the lack of improvement in sensitivity to mode shifts became clear when a spectral analysis of the reflector was done. The reflecting optic was a coated optic, with a nominal reflectance of 99.5% at 10.6 microns. As the wavelength of the radiation was changed from 10.6 microns, the reflectance of the optic also changed, at a rate of about 0.6%/micron. When the laser shifted modes, it also tended to shift frequency, with the output wavelength varying anywhere between 10.58 and 10.66 microns. This meant that the actual amount of power being transmitted to the power detector could change by nearly 50% when a mode shift occurred. The spectral analysis also indicated that the coatings on the optic were not uniform over the surface



(a) No mode shift, Kp = 16



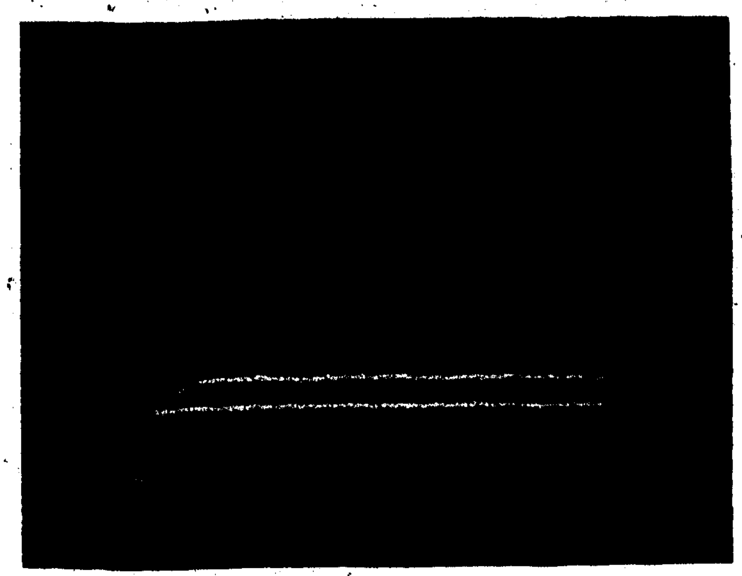
(b) Mode shifts @ 18 s, 40 s, Kp = 16

Fig. 24 Power regulation with 99.5% reflector.
Top trace - Output power. 1 div = 0.5 watt
Bottom trace - Feedback signal. 1 div =0.5 V
Horizontal div = 5.0 s

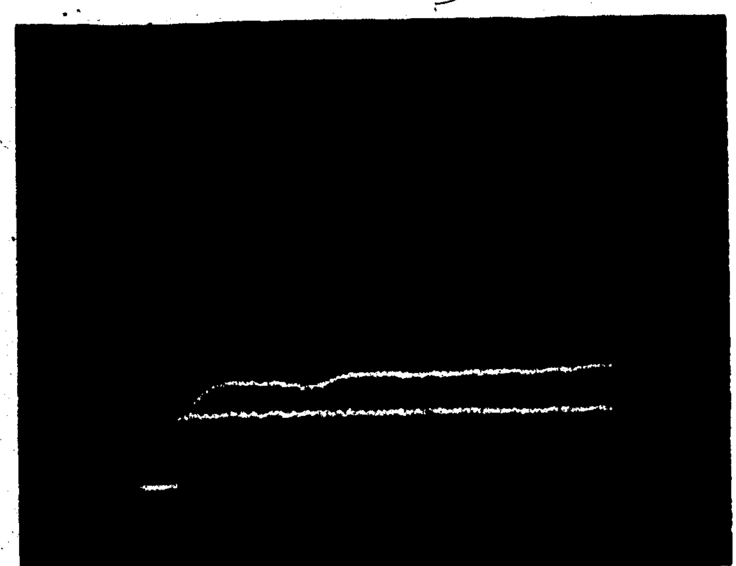
of the optic, so that the amount of power transmitted depended on where the laser beam passed through the optic. Both of these mechanisms contributed to the sensitivity of this method of power detection to mode shifts.

To eliminate the variation of power transmitted to the detector caused by changes in mode and frequency, a piece of calcium floride was used to provide the necessary power attenuation. The attenuation with this method is based on the bulk absorption of the material, not the reflectance of a coated optic, and so is less sensitive to frequency shifts. Also, there are no coatings involved, so that the transmission through the attenuator should be uniform across the surface of the crystal. A piece of calcium flouride approximately 12 mm thick was found to provide an adequate amount of attenuation, and this was used in the final configuration of the power monitor.

Results of using this configuration to provide the power feedback signal are shown in figure 25. It can be seen that the variation in power when the mode shifts has been drastically reduced, but some variation still remains. This is due to the coated optic used as a beam splitter, which gives rise to the same sources of power variation that the 99.5% attenuator did. The relative magnitude of these variations is much reduced however, since they are now measured against 5% of the incident power, instead of 0.5%. The stability of the output beam power is now judged to be acceptable for a surgical laser system.



(a) No mode shift, Kp = 32



(b) Mode shift @ 13 s, Kp = 32

Fig. 25 Power regulation with CaF_2 absorber.
Top trace - Output power. 1 div = 0.5 watt
Bottom trace - Feedback signal. 1 div =0.2 V
Horizontal div = 5.0 s

Measurement of Loop Gain

One of the system parameters that can be determined with a simple measurement using this controller is the loop gain of the system. This can be determined using the formula

$$Y / R = K / (K + 1)$$

Y - output signal
R - set point
K - loop gain

The loop gain measurements for the system were made with the controller gain set to 16, which was the gain which gave the best results in keeping the output steady. The measured loop gain varied over the period of the experiments, from a high of 97 to a low of just over 9.

The variation in loop gain was due to a change in the gain of the laser, and came from two sources. The first variation was a short term decline in the loop gain taking place over several days. The cause of this was a change in the gas mixture, from either a slow leak in the laser head or chemical action initiated by the discharge. Refilling the laser head with a fresh gas mix restored the loop gain to its previous value, but changes in the new gas mixture soon started to reduce the loop gain again. There was also a long term decline in the loop gain due to the gradual degredation of the laser's reflecting optics. This decline could not be reversed except by installing new optics. The gradual reduction of the laser gain due to this process eventually reduced the maximum output power of the experimental laser to 2 or 3 watts.

B. PULSED MODE OPERATION

The other mode of laser operation is pulsed mode. In this mode, the laser beam is turned on and off at a moderate rate to provide a cutting action rather than simply ablating the tissue. When a CO_2 waveguide laser is pulsed in this manner, a narrow spike of relatively high power occurs when the laser is turned on.[22] This power surge, known as a gain switched pulse, must be investigated for its possible effect on tissue. The nature of the laser pulse must also be investigated on a longer timescale to insure its suitability for cutting tissue. Finally, some method of regulating the power of the pulses should be implemented so that pulsed operation will provide the same level of power stability that is available in continuous operation.

The Gain Switched Pulse

The gain switched pulse is a phenomena that occurs when a CO_2 laser discharge is initiated. Because of the low gain of the CO_2 gas mixture, the onset of lasing lags behind the initiation of the RF discharge. During this period, the RF discharge is storing energy in the gas mixture, but no energy is being removed by lasing. Once lasing begins, the energy stored in the gas mixture during this initial period is released in a high energy pulse. There are two possible effects of this high energy pulse on the interaction between

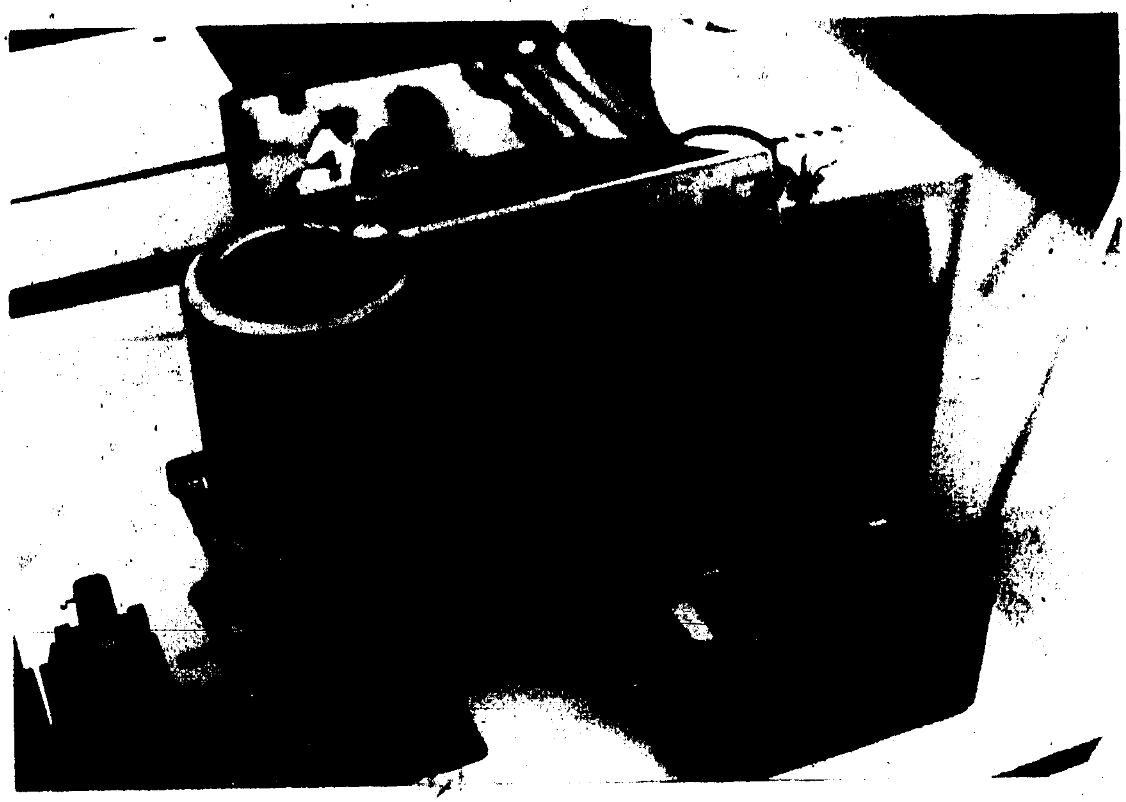


PLATE 5. The cryogenic pulse detector. The dewar at the left contains a gold doped germanium detector and is filled with liquid nitrogen to bring the temperature of the detector into the operating region. The small box connected to the back of the dewar contains the voltage divider and buffer circuitry. The pulse shape is displayed on the oscilloscope.

the laser beam and tissue. The gain switched pulse may pre-heat the tissue, raising the temperature of the tissue to the point of vaporization and increasing the efficiency of the cutting action. The gain switched pulse might also be able to increase the average power of the laser, if the discharge can be switched on and off fast enough so that the gain switching action predominates over normal lasing. Both of these possibilities will be investigated.

Determining the effect of the gain switched pulse requires a detector fast enough to record a submicrosecond pulse. The detector used in this experiment was a piece of gold doped germanium cooled with liquid nitrogen. When there is no laser radiation impinging on the detector, the detector remains at the temperature of the liquid nitrogen, about -76 °C. At this low temperature the carriers in the gold doped germanium remain in the low energy valence band, and the resistance of the detector is quite high. The off resistance of the particular detector used in this experiment was measured as 4.6 megohms. When the detector is exposed to the CO_2 laser radiation, the energy absorbed by the detector boosts the carriers into the conduction band and the resistance of the detector is reduced. The reduction of the detector resistance is directly proportional to the power of the laser beam.

In order to detect the reduction in resistance, the detector is used as one leg of a voltage divider. The high source impedance of the detector is isolated by using a high speed op amp as a fast voltage follower, and displaying the output voltage on an oscilloscope. Although the signal level at the oscilloscope is quite small, it is sufficient to allow the detection of submicrosecond pulses when the power of the pulse is not less than one or two watts. With this particular configuration of the equipment, the decrease in detector resistance causes a decrease in the output voltage, so that the pulse shape shown on the scope is inverted.

The first question investigated was whether the gain switched pulse could be used to increase the average power of the laser. When the laser was pulsed on and off at a variety of pulse lengths and repetition rates it was noted that the amplitude of the gain switched pulse was reduced as the repetition rate of the laser was increased (Fig. 26,27). It was also found that when the time between pulses was decreased to less than about 70 microseconds, the lasing of the gas never completely died out, and no gain switched pulse occured. The conclusion made from these observations was that gain switched pulsing could not be used to increase the effective power of the laser, and that rapid pulsing of the laser discharge is not advantageous in a surgical application of a CO_2 laser.

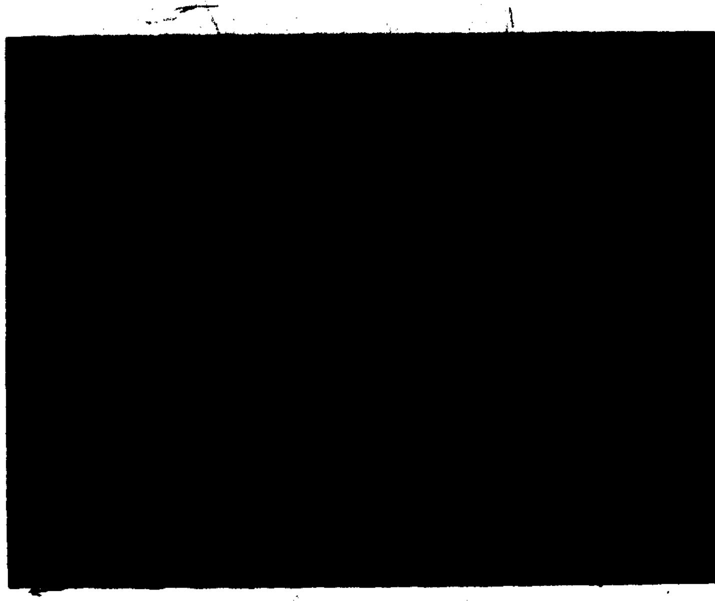
The next aspect of the gain switched pulse to be examined was whether it could provide enough pre-heating to increase the efficiency of the laser cutting action. It has been stated that the best method of providing a cutting action with a CO_2 laser is to generate a pulse with a

(a) 10 microsecond pulse, 12,000 pps

(b) 10 microsecond pulse, 9,000 pps

Fig. 26 Gain switched pulse for various pulse repetition rates.
Top trace - laser pulse. 1 div = 10 watts
Bottom trace - RF enable pulse. 1 div =0.5 V
Horizontal div = 5.0 microseconds

(a) 10 microsecond pulse, 2,000 pps



(b) 10 microsecond pulse, 1,000 pps

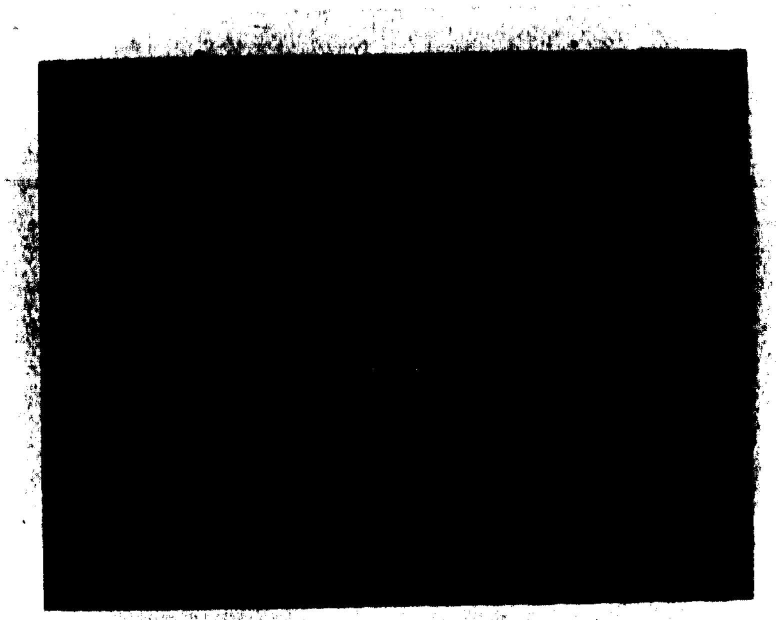
Fig. 27 Gain switched pulse for various pulse repetition rates.
Top trace - laser pulse. 1 div = 10 watts
Bottom trace - RF enable pulse. 1 div =0.5 V
Horizontal div = 5.0 microseconds

relatively high power front followed by a low power trailing section.[1] If the gain switched pulse would generate a high enough power output, it could provide the desired pulse shape.

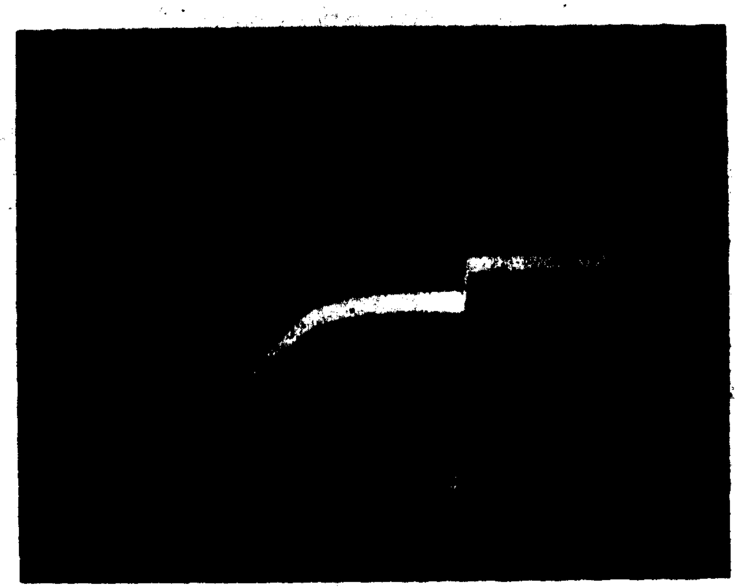
At the pulse durations and repetition rates expected to be commonly used on a surgical laser, the gain switched pulse did not produce a peak power significantly greater than the steady state power of the laser. It can be seen in figure 28 that the peak of the gain switched pulse is approximately the same as the power of the rest of the pulse. This, coupled with the extremely short duration of the gain switched pulse led to the conclusion that the pre-heating effect of the gain switched pulse would be negligible, and that the net effect on laser operation was so small that the entire phenomena of gain switched pulsing can be safely ignored in the design of a surgical laser system.

Long Term Characteristics of Pulsed Operation

The characteristics of the laser pulse also need to be investigated over a longer time scale. Since there is no longer a need to discriminate events shorter than 100 microseconds, the Laser Beam Analyser will be used to measure the pulses. The LBA can be used as a pulse measuring device by locking the rotating wire in a fixed position and aiming the laser beam at the wire. The power reflected back to the pyroelectric detectors will now give an indication of



(a) 100 microsecond pulse, 100 pps



(b) 1.0 millisecond pulse, 100 pps

Fig. 28 Gain switched pulse at typical pulse repetition rates.
Vertical div = 10 watts
Horizontal div = 5.0 microseconds

the pulse shape. Because there are several variables in the measuring process, such as the reflectivity of the wire and the fraction of the beam intercepted by the wire, only the relative power can be measured, not the absolute power in watts. This is still enough to give an indication of the pulse shape.

When the pulse shape is examined over a relatively long time period (approximately 10 ms), it is found to be very non-uniform (Fig. 29). The pulse starts with a burst of high power, after which the power decreases to zero. If the pulse length is long enough, the laser power increases again to the steady state value. This variation in power could come from one of three sources; instability in the RF power being input to the laser, instability in the gas discharge, or changes in the gain of the laser due to thermal effects. It would be difficult to determine if the power variation is due to instability in the gas discharge because the waveguide channel is not open to inspection. The expenditure of considerable time and effort to investigate this possibility should only be done if the variation in pulse power can be shown not to arise from either of the other possibilities.

To establish if the power variation arises from a variation in the input power, the RF input power was monitored by measuring the voltage level at the laser head. The voltage level showed a slight variation at the very beginning of the RF pulse, but this was due to effects

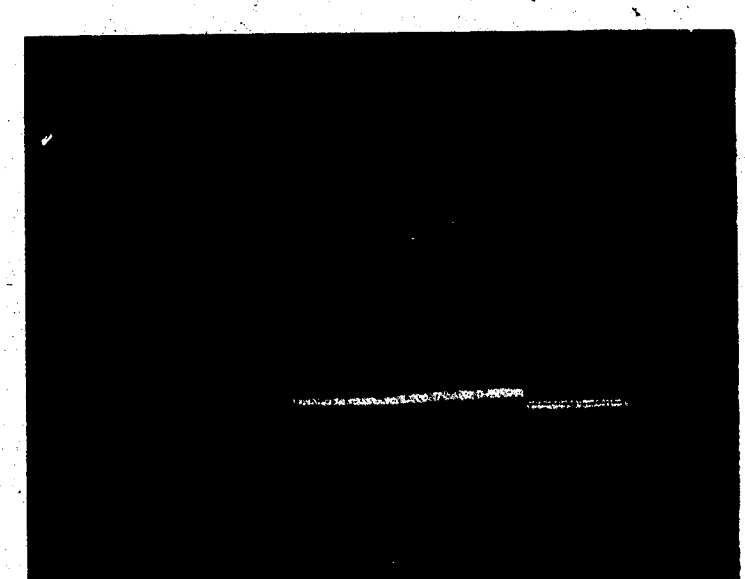


Fig. 29 Long term behaviour of pulse.
Vertical div = 10 watts
Horizontal div = 2.0 milliseconds

accompanying the initiation of the discharge. After this, the voltage level was stable enough to indicate that the variation in power was not due to instability in the RF input power.

The other source of power variation, changes in laser gain due to thermal effects, is the most probable source. This conclusion was arrived at by examining the leading edge of the first pulse for various cooling conditions. First, the laser was allowed to reach its minimum temperature by running the cooling system with the laser off. A pulse of RF power was then applied, which produced a laser pulse with a very high initial power spike and no complete reduction in laser power after (Fig. 30). The experiment was then repeated, but this time the laser was allowed to come to thermal equilibrium by running the laser in continuous mode, then a brief period of cooling was followed by the RF pulse. This time the initial power spike was much smaller, and the power dropped nearly to zero afterwards (Fig. 31). Finally, a typical pulse from the middle of a pulse train was measured (Fig. 32). It is assumed that the laser is in complete thermal equilibrium during this pulse, since the laser was left running for some time before the measurement was taken. This pulse has a very small initial power spike, and the power drops to zero for a considerable period of time before rising to the steady state value.

The only difference between the three pulses is the amount by which the laser channel is out of thermal

Fig. 30 Pulse shape with minimum thermal equilibrium.
Top trace - pulse shape
Bottom trace - ground line
Horizontal div = 1 ms

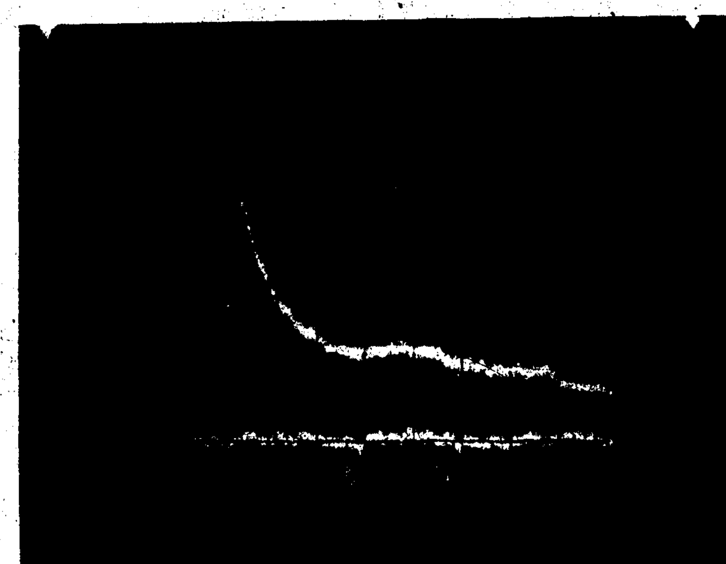


Fig. 31 Pulse shape with intermediate thermal equilibrium.
Top trace - pulse shape
Bottom trace - ground line
Horizontal div = 1.0 milliseconds

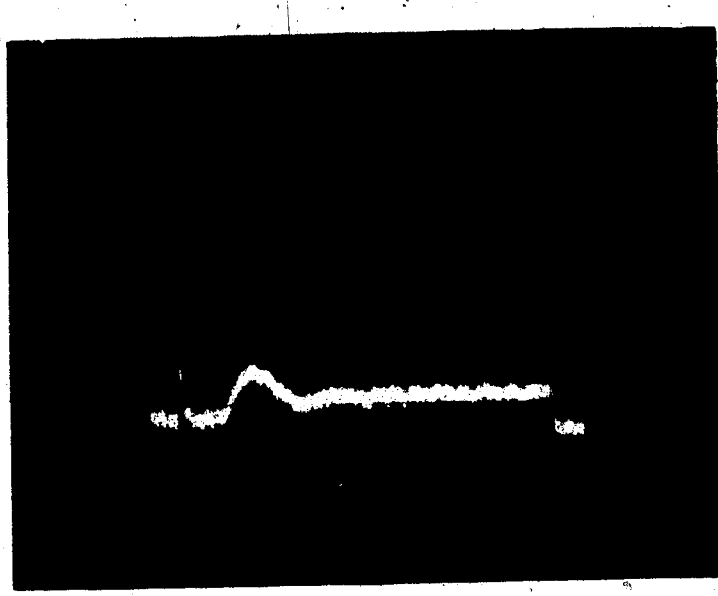


Fig. 32 Pulse shape with maximum thermal equilibrium.
Horizontal div = 1 ms

equilibrium when the pulse starts, but the shapes of the pulses are quite different. This would indicate that the power variation in the pulse is due to thermal effects taking place inside the laser head. In the proposed design for the laser head the cooling of the waveguide channel is symmetric and more efficient than the cooling in the experimental laser head, so the pulse shape obtained from the proposed laser should be more uniform than those shown here.

Pulsed Power Regulation

Theoretically, the CPU-should be able to control the power in pulse mode by monitoring the average power at the detector. The average power at the detector can be calculated from the formula

$$A = P * L * RR$$

A - average power, watts
P - power of single pulse, watts
L - length of pulse, seconds
RR - repetition rate, pulses per second

Since the length of the pulse and the repetition rate are fixed quantities, regulating the average power would in effect control the power of each pulse.

Unfortunately, there are several factors that mitigate against the implementation of pulsed mode power regulation. First, we have seen that the power of a single pulse is not a constant, but rather varies over the duration of the pulse, and the amount of variation depends on the length of the pulse. Also, the responsivity of the detector is not constant, but varies with the repetition rate of the pulses. Finally, the response time of the detector is such that it falls among the range of repetition rates that need to be controlled. This means that the detector that is so useful in continuous mode is not very useful at all in pulsed mode.

The need for power stability in pulse mode is not the same as it is for continuous mode operation. When operating in continuous mode, the surgeon wishes to ablate the tissue to a uniform depth, which requires even, uniform power. If the surgeon is making an incision in pulsed mode, he is more concerned with cleanly separating the tissue, and not so concerned with keeping the depth of the incision uniform. Even if the pulse power was completely stable, the depth of the incision would still vary to some degree, due to the varying composition of tissue along the length of the incision. Taking all of these factors into account, it was decided to let the laser run open loop when in pulse mode.

IV. CONCLUSION

A. SUMMARY OF RESULTS

The objective of this thesis has been to set out a design for a surgical CO_2 laser with a rated output power of 40 watts. The primary design objective is to provide an economical laser system, with a price ceiling of approximately US $25,000. It is also desired to make the system as small and compact as possible, with an eye to keeping the system portable. The system should also maintain high reliability, with down time being minimized, and the safety of the operators and the patient must be ensured under all forseen failure conditions. Finally, the controls for the system are to be simple and functional, so that any surgeon or operating room nurse can easily control the effect of the laser on tissue. How well have these design criterion been met?

In the area of the user interface, the system is certainly more than adequate. By placing the controls on a removable front panel, the operator is free to place the controls at any convenient place, and does not have to continually move between the laser system and the operating table. The displays are large and clear, and the controls relate directly to the effects of the laser beam on tissue. A particularly useful feature is the display of the actual amount of laser power being delivered to the patient, a feature that is not found on present surgical laser systems.

This design must also receive high marks for system reliability. While the intrinsic reliability of the system components can not be ascertained without long term lifetime data, the use of the microprocessor controlled self test feature will certainly enhance reliability. The micro can detect indications of potential failure, and alert the operator to the need for maintenance. If a failure does occur, downtime is minimized because the micro can immediately indicate the nature of the failure, reducing the time needed to diagnose the problem. The modular construction of the system also reduces down time by facilitating replacement of faulty sub-systems.

Safety of the operators and patients is also enhanced by the microprocessor monitoring system. The microprocessor provides a buffer between operator commands and system response, and ensures that safe operation is always maintained. Even if a sub-system failure should occur during operation of the system, the micro will provide a safe shut down of the system and can alert the operators to the nature of the problem.

Portabilty is an area in which this design must receive mixed reviews. The decision to use an internal cooling loop rather than relying on external cooling adds considerable weight and bulk to the system. This reduces the portability of the system, so that it is said to be 'trans-portable'; it can be moved but it is not easily carried. While the use of external cooling would increase portability in terms of reduced system size, the use of the laser system would be limited to those areas where external cooling is readily available. With internal cooling, the use of this system in outpatient therapies is greatly enhanced, since the only connection needed is a 15 amp, 110 volt wall socket. The use of an internal cooling-loop is considered the best compromise in a situation where neither option is truly satisfactory.

Certainly the support systems achieve the goal of adequate performance for minimum price, but it is the performance of the laser itself that will cause this design to stand or fall. It is at this point that we run into one of the hard facts of life: there are no economical 40 watt waveguide lasers currently available. The commercially available waveguide lasers provide rated output powers of about 20 to 30 watts, and the OEM versions of these systems are priced at over US $20,000. Because of this lack of a suitable laser, the system development could not be carried to completion. Each sub-system was built and tested as a single unit, but the operation of the system with a 40 watt laser head could not be verified.

While the lack of the finished laser head prevented complete system check out, the experimental laser head provided some indication of the system performance to be expected. The use of feedback control to stabilize power output provided very good power stability when the laser operated single mode, and adequate power stability when mode shifts occured. This means that considerable savings can be realized in the design of the laser head without compromising the operation of the surgical laser system.

B. DIRECTIONS FOR FURTHER RESEARCH

As is usually the case, this research has uncovered the need for further investigations into several areas. First and foremost is the need to develop a 40 watt waveguide laser. Once an appropriate laser head is found, the final few system tests can be done and the result should be a marketable CO_2 surgical laser system. One of the significant problems pointed out by this research is the rapid degradation of laser gain with extended use. A successful surgical laser would have to maintain its rated output power for a period of at least one year without servicing. The 80% reduction in maximum output power seen over one year of what would be considered light to moderate use in a hospital is clearly unacceptable.

Another area which requires further investigation is the long term pulse shape seen in pulsed mode operation. While the experiments done here indicate a thermal origin of the power fluctuations, this needs to be confirmed by research on different configurations of the waveguide structure.

Finally, research needs to be done on increasing the effectiveness of the feedback controller by implementing more sophisticated control algorithms. While the proportional controller used in this research was adequate for the purpose, more sophisticated controllers may be able to increase power stability during mode changes, or reduce the influence of the long term gain loss of the laser head. It may also be possible to increase the range over which the control function can be effectively exercised.

List of References

1. J.M. Berthet, "Laser surgery and the Yoko effect." unpub.

2. G.M. Carter & S. Marcus, "A high power CO_2 waveguide laser.", **Applied Physics Letters**, Vol 35, No 2, p 129, 1979

3. S.C. Cohen, "Waveguide CO_2 laser gain, Dependence on gas kinetic and discharge properties.", **IEEE Journal of Quantum Electronics**, Vol QE-12, No 4, p 237, 1976

4. M. Edwards, J. Boggan, & T. Fuller, "The laser in neurological surgery.", **Journal of Neurosurgery**, Vol 59, p 555, 1983

5. E. Franke, "Wilkinson hybrids.", **Ham Radio Magazine**, p 12, Jan 1982

6. T.A. Fuller, "Fundamentals of lasers in surgery and medicine." in J.A. Dixon, ed. **Surgical Applications of Lasers**, Year Book Medical, 1983

7. Leon Goldman, **Biomedical Aspects of the Laser**, Springer-Verlag, 1967

8. T. Halldorson & J. Langerholc, "Thermal action of laser irradiation in biological material.", **Applied Optics**, Vol 20, p 822, 1981

9. D. He & D.R. Hall, "A 30 W radio frequency exited waveguide CO_2 laser.", **Applied Physics Letters**, Vol 43, p 726, 1983

10. D. He & D.R. Hall, "Frequency dependence in RF excited waveguide CO_2 lasers.", **IEEE Journal of Quantum Electronics**, Vol QE-20, No 5, p 509, 1984

11. C.C. Huang, N.E. Buholz, & J. Scholtz, "Computer controlled laser amplitude modulation.", **Laser Focus** Vol 19, No 12, p 60, 1983

12. Information Resources International, **Surgical Lasers: Market, Applications, Trends.**, Information Resources International, 1983

13. K.K. Jain, **Handbook of Laser Neurosurgery**, Charles C. Thomas, 1966

14. K.K. Jain, "Current status of laser applications in neurosurgery.", **IEEE Journal of Quantum Electronics**, Vol 20, No 12, p 1401, 1984

15. I. Kaplan & J. Raif, "The Sharplan carbon dioxide laser in clinical surgery: 7 years experience", in L. Goldman, ed. **The Biomedical Laser**, Springer-Verlag, 1981

16. H.K Koebner, ed. **Lasers in Medicine**, J. Wiley & Sons, 1980

17. P.E. McGuff, **Surgical Applications of Laser**, Charles C. Thomas, 1983

18. C.K.N. Patel, "High powered CO_2 lasers.", **Scientific American**, Vol 219, p 23, 1968

19. E.C. Poe & J.C. Goodwin, **The S-100 and Other Buses**, Howard W. Sams & Co., 1981

20. T.G. Polanyi, "Development of instrumentation for surgery with Carbon Dioxide lasers.", **Proceedings of the NATO Symposiun on Lasers in Biology and Medicine**, Plenum Press, 1980

21. P. Speser, "Politics of praise and politics of support for medical laser research.", **Laser Focus and Electro-optics**, Vol 21, No 4, p 14, 1985

22. L.V. Sutter, "Gain switched pulsed RF CO_2 waveguide lasers.", **Proceedings of SPIE**, Vol 227 CO_2 Laser Devices and Applications, p 2, 1980

23. R.C.J. Verschueren, J. Koudstaal, & J. Oldhoff, "CO_2 laser surgery.", **Proceedings of the NATO Symposium on Lasers in Biology and Medicine**, Plenum Press, 1980

APPENDIX I - MAIN PROGRAM LISTING

```
;-------------------------------------------------
;
;       LASER CONTROL ROUTINE
;
;-------------------------------------------------
;
;       HARDWARE EQUATE TABLE
;
;       THIS SETS THE BASE ADDRESS OF ALL THE CHIPS USED IN
;       THE SYSTEM. SPECIFIC REGISTERS ARE ACCESSED AS
;       OFFSETS FROM THE BASE ADDRESS
;
RAM1    EQU     $0000
RAM2    EQU     $0800
VIA1    EQU     $9820
MATH    EQU     $9840
ACIA1   EQU     $9100
ACIA2   EQU     $9880
PTM1    EQU     $9140
PTM2    EQU     $9180
ATD     EQU     $91C0
DTA     EQU     $9000
RTC     EQU     $9040
EPROM1  EQU     $F000
EPROM2  EQU     $F800
;
;       PROGRAM EQUATE TABLE
;
;       THIS SETS ALL OF THE CONSTANTS USED IN THE PROGRAM
;
CPSTAT  EQU     $60         ;CPU SEND STATUS -> FRONT PANEL
CPDENS  EQU     $48         ;CPU SEND POWER DENSITY -> FR. PAN.
CPPOW   EQU     $44         ;CPU SEND LASER POWER -> FR. PAN.
LIOOFF  EQU     $40         ;CPU SEND LASER OFF -> FR. PAN.
LIOON   EQU     $60         ;CPU SEND LASER ON -> FR. PAN.
FPSTAT  EQU     $01         ;FRONT PANEL SEND STATUS -> CPU
FPPULS  EQU     $02         ;FR. PAN. SEND PULSE WIDTH -> CPU
FPRR    EQU     $04         ;FR. PAN. SEND REP. RATE -> CPU
FPPOW   EQU     $08         ;FR. PAN. SEND POWER -> CPU
KPINIT  EQU     $100        ;PROPORTIONAL CONTROL CONSTANT
HIINIT  EQU     $FF         ;LINEARIZING LIMIT, HIGH
LOINIT  EQU     $00         ;LINEARIZING LIMIT, LOW
POWFRQ  EQU     1000        ;POWER REGULATION INTERVAL - usec
SPFREQ  EQU     $0A0A       ;SUPER PULSE PATTERN
TOTTIM  EQU     15000       ;WATCHDOG TIMER DURATION
EOT     EQU     $04         ;END OF TABLE MARKER
;
;       MATH ROUTINE CALL NUMBERS
;
DMUL    EQU     $2E         ;32 BIT MULTIPLY, RETURN LOWER HALF
DSUB    EQU     $2D         ;32 BIT SUBTRACT
SDIV    EQU     $6F         ;16 BIT DIVIDE
;
;       MONITOR EQUATES
;
```

```
;
;       THESE ARE CONSTANTS USED TO ACCESS MONITOR ROUTINES
;
OUT4HS  EQU     5           ;OUTPUT 4 HEX DIGITS TO TERMINAL
PCRLF   EQU     6           ;SEND NEW LINE TO TERMINAL
MONITR  EQU     8           ;ENTER ASSIST09 MONITOR
VCTRSW  EQU     9           ;CHANGE MONITOR VECTORS
.IRQ    EQU     12          ;IRQ VECTOR CHANGE
.CMDL2  EQU     44          ;2ND COMMAND TABLE VECTOR CHANGE
NUMBER  EQU     $079B       ;LOCATION OF TERMINAL INPUT
CMDBAD  EQU     $F956       ;COMMAND ERROR ROUTINE
BLDNUM  EQU     $FCE0       ;TERMINAL INPUT ROUTINE
;
;       PROGRAM CONSTANT STORAGE ALLOCATION
;
        ORG     RAM1        ;STORE IN ZERO PAGE
;
KP      RMB     2           ;PROPORTIONAL CONTROL CONSTANT
SPULSE  RMB     2           ;SUPER PULSE PATTERN
LIMHI   RMB     1           ;LINEARIZING CONSTANT - HIGH
LIMLO   RMB     1           ;LINEARIZING CONSTANT - LOW
CONFRQ  RMB     2           ;POWER REGULATION DURATION
STACK   RMB     2           ;STORAGE FOR STACK POINTER
;
;       PROGRAM VARIABLE STORAGE ALLOCATION
;
YT      RMB     2           ;FEEDBACK SIGNAL FROM A/D CONVERTER
RT      RMB     2           ;SET POINT
UT      RMB     2           ;LASER DRIVE LEVEL
ET      RMB     2           ;ERROR SIGNAL - kT
ET1     RMB     2           ;ERROR SIGNAL - (k-1)T
ET2     RMB     2           ;ERROR SIGNAL - (k-2)T
;
;STATUS REGISTER FORMAT
;
;       BIT0 - CONTINOUS EXPOSURE  1 = ON
;       BIT1 - LIO LIGHT           1 = ON
;       BIT2 - PULSED EXPOSURE     1 = ON
;       BIT3 - CONTROL LOOP        1 = OPEN LOOP
;       BIT4 - SUPER PULSE         1 = ON
;       BIT5 - READY/STANDBY       1 = STANDBY
;       BIT6 - INTENSITY           1 = ON
;       BIT7 - NA
;
STATUS  RMB     1           ;STATUS
PULSE   RMB     1           ;PULSE WIDTH
REPRAT  RMB     1           ;REPETITION RATE
;
;       START OF CONTROL PROGRAM
;
        ORG     EPROM1
;
        BRA     $           ;ROM2 FLAG FOR ASSIST09 FIREUP
        LBRA    RESET       ;GO TO INITIALIZATION ROUTINE
;
;------------------------------------
```

```
;
;       COMMAND TABLE 2 FOR ASSIST09 MONITOR
;
;       ENTRY FORMAT        :# OF BYTES IN TABLE ENTRY
;                           :COMMAND NAME
;                           :OFFSET TO START OF ROUTINE
;
COMTB2: FCB     5           ;MOVE DATA IN RAM
        FCB     'MO'
        FDB     MOVE-$
        FCB     6           ;RESTART HARDWARE
        FCB     'RES'
        FDB     RESTRT-$
        FCB     6           ;GET AND DISPLAY A/D CONVERSION
        FCB     'CON'
        FDB     DISCON-$
        FCB     5           ;CHANGE PROPORTIONAL CONSTANT
        FCB     'KP'
        FDB     KPCHNG-$
        FCB     5           ;CHANGE HIGH LIMIT
        FCB     'HI'
        FDB     HICHNG-$
        FCB     5           ;CHANGE LOW LIMIT
        FCB     'LO'
        FDB     LOCHNG-$
        FCB     6           ;CHANGE INTERRUPT FREQUENCY
        FCB     'FRQ'
        FDB     FREQST-$
        FCB     -2          ;END OF COMMAND TABLES
;
;       MOVE MEMORY PROGRAM
;
;       FORMAT - MO (BEGIN BLOCK) (END BLOCK) (NEW LOCATION)
;
MOVE:   JSR     BLDNUM      ;GET START OF MEMORY BLOCK
        LDX     NUMBER
        JSR     BLDNUM      ;GET END OF MEMORY BLOCK
        LDY     NUMBER
        JSR     BLDNUM      ;GET NEW LOCATION
        CMPX    NUMBER      ;CHECK DIRECTION OF MOVE
        BLS     TOPDWN      ;? MOVE UP, START AT TOP OF BLOCK
;
;       MOVE BLOCK STARTING WITH LOWEST MEMORY LOCATION
;
        PSHS    Y           ;SAVE END LOCATION OF BLOCK
        LDY     NUMBER      ;LOAD NEW LOCATION
MOVE1:  CMPX    ,S          ;CHECK IF MOVE IS COMPLETE
        BEQ     MRET        ;? DONE, RETURN
        LDA     ,X+         ;MOVE DATA
        STA     ,Y+
        BRA     MOVE1       ;LOOP
;
;       MOVE BLOCK STARTING WITH HIGHEST MEMORY LOCATION
;
TOPDWN: PSHS    X,Y         ;SAVE ADDRESSES OF BLOCK
        LDD     NUMBER      ;LOAD NEW LOCATION
```

```
         ADDD    ,S          ;CALCULATE END OF NEW LOCATION
         SUBD    2,S
         PULS    Y           ;RETRIEVE TOP ADDRESS OF BLOCK
         TFR     D,X         ;SET INDEX TO TOP OF NEW BLOCK
         LEAX    1,X         ;PRE-INCREMENT REGISTERS
         LEAY    1,Y
MOVE2:   CMPY    ,S          ;CHECK IF MOVE IS COMPLETE
         BEQ     MRET        ;? DONE, RETURN
         LDA     ,-Y         ;MOVE DATA
         STA     ,-X
         BRA     MOVE2       ;LOOP
;
MRET:    PULS    D,PC        ;CLEAR TEMPORARY STORAGE AND RETURN
;
;        RESTART AT HARDWARE INITIALIZATION
;
;        FORMAT - RES
;
RESTRT:  LEAS    2,S         ;THROW AWAY RETURN ADDRESS
         LEAX    HDWARE,PCR  ;SET PCR TO HARDWARE INITIALIZE
         STX     10,S
         RTI                 ;GO AT NEW ADDRESS
;
;        DISPLAY CONVERSION OF SPECIFIED CHANNEL
;
;        FORMAT - CON
;
DISCON:  LBSR    CONVRT      ;DO A/D CONVERSION
         LEAS    -2,S        ;READY TEMPORARY STORAGE
         LEAX    ,S          ;GET ADDRESS OF TEMPORARY STORAGE
         STD     ,X          ;STORE CONVERSION VALUE
         SWI                 ;SEND CONVERSION TO TERMINAL
         FCB     OUT4HS
         SWI                 ;NEW LINE
         FCB     PCRLF
         PULS    D,PC        ;RETURN
;
;        STORE NEW PROPORTIONAL CONSTANT
;
;        FORMAT - KP (HEX VALUE OF CONSTANT)
;
KPCHNG:  JSR     BLDNUM      ;GET NEW GAIN FROM TERMINAL
         LDD     NUMBER
         LBEQ    BAD         ;? GAIN ZERO, FLAG ERROR
         LBMI    BAD         ;? GAIN -VE, FLAG ERROR
         STD     >KP         ;STORE NEW GAIN
         RTS
;
;        STORE NEW LOWER D/A LIMIT
;
;        FORMAT - LO (8 BIT HEX VALUE OF LOWER LIMIT)
;
LOCHNG:  JSR     BLDNUM      ;GET NEW LIMIT FROM TERMINAL
         LDD     NUMBER
         TSTA
         LBNE    BAD         ;? IMPROPER LIMIT, FLAG ERROR
```

```
        STB     >LIMLO   ;STORE NEW LIMIT
        RTS
;
;       STORE NEW UPPER D/A LIMIT
;
;       FORMAT - HI (8 BIT HEX VALUE OF HIGHER LIMIT)
;
HICHNG: JSR     BLDNUM   ;GET NEW LIMIT FROM TERMINAL
        LDD     NUMBER
        TSTA
        LBNE    BAD      ;? IMPROPER LIMIT, FLAG ERROR
        STB     >LIMHI   ;STORE NEW LIMIT
        RTS
;
;       SET NEW CONTROL INTERRUPT FREQUENCY
;
;       FORMAT -
;         FRQ (HEX VALUE OF NEW REGULATION DURATION IN usec)
;
FREQST: JSR     BLDNUM   ;GET CONTROL FREQ. FROM TERMINAL
        LDD     NUMBER
        LBEQ    BAD      ;? FREQUENCY ZERO, FLAG ERROR
        STD     >CONFRQ  ;STORE NEW FREQUENCY
        RTS
;
BAD:    JMP     CMDBAD   ;JUMP TO BAD COMMAND HANDLER
;
;---------------------------------------
;
;       INITIALIZATION ROUTINES
;
;
RESET:  ORCC    #$50     ;MASK INTERRUPTS
        LDA     #$02     ;MASK IRQ FROM ACIA'S
        STA     ACIA1+2
        STA     ACIA2+2
        LDA     #$0F     ;INIT VIA1 OUTPUT LINES
        STA     VIA1
        LDA     #$FF
        STA     VIA1+2
        CLRA             ;SET DP REGISTER
        TFR     A,DP
;
        LEAX    COMTB2,PCR ;CHANGE 2ND COMMAND TABLE VECTOR
        LDA     #.CMDL2
        SWI
        FCB     VCTRSW
;
        LEAX    IRQ,PCR  ;CHANGE IRQ VECTOR
        LDA     #.IRQ
        SWI
        FCB     VCTRSW
;
        LEAS    3,S      ;DISCARD MONITOR RETURN ADDRESSES
;
;       INITIALIZE PROGRAM CONSTANTS
```

```
;
INIT:   LDD     #KPINIT   ;INITIALIZE PROP. CONTROL CONSTANT
        STD     KP
        LDA     #HIINIT   ;SET SOFTWARE LINEARIZING CONSTANTS
        STA     LIMHI
        LDA     #LOINIT
        STA     LIMLO
        LDD     #SPFREQ   ;INITIALIZE SUPERPULSE FREQUENCY
        STD     SPULSE
        LDD     #POWFRQ   ;INITIALIZE POWER REGULATION FREQ.
        STD     CONFRQ
;
;       INITIALIZE PROGRAM VARIABLES
;
        LDD     #0        ;CLEAR CONTROL REGISTERS
        STD     YT
        STD     RT
        STD     UT
        STD     ET
        STD     ET1
        STD     ET2
        LDA     #$29      ;INITIALIZE STATUS REGISTER
        STA     STATUS
        LDD     #0        ;CLEAR PULSE, REPETITION DURATIONS
        STD     PULSE
;
        TFR     S,Y       ;SET UP INITIAL POWER TABLE
        LEAS    -62,S
        PSHS    Y         ;STORE POINTER TO POWER TABLE
        STS     ,Y        ;SAVE TOP OF STACK
        STS     STACK
;
        LEAX    POWTAB,PCR ;GET INDEX INTO POWER TABLE
IN1:    LDD     ,X++      ;GET POWER SETTING
        CMPA    #EOT      ;? END OF TABLE, JUMP
        BEQ     IN2
        STD     ,--Y      ;STORE POWER SETTING IN TABLE
        BRA     IN1       ;LOOP
;
IN2:    LDY     ,S        ;SET POINTER TO TOP OF STACK
;
;---------------------------------------
;
;       INITIALIZE HARDWARE
;
;       VIA1 DEFINTIONS
;
;       A - SIDE        INPUTS
;
;       PA0     COMBINER TEMP    0 = OK     1 = HIGH
;
;       PA1     RF AMP 1 TEMP    0 = OK     1 = HIGH
;
;       PA2     RF AMP 2 TEMP    0 = OK     1 = HIGH
;
;       PA3     WATER TEMP       0 = OK     1 = HIGH
```

```
;
;       PA4     WATER FLOW        0 = ON      1 = OFF
;
;       PA5     DOOR SWITCH       0 = CLOSED  1 = OPEN
;
;       PA6     FOOT SWITCH       0 = ON      1 = OFF
;
;       PA7     MON/OPR*          0=OPERATE   1=MONITOR
;
;       B - SIDE          OUTPUTS
;
;       PB0     RF OSC ENABLE     0 = ON      1 = OFF
;
;       PB1     SHUTTER           0 = OPEN    1 = CLOSED
;
;       PB2     COOLING SYSTEM    0 = ON      1 = OF
;
;       PB3     RF DRIVER         0 = ON      1 = OFF
;
;       PB4     ERROR1
;
;       PB5     ERROR2
;
;       PB6     ERROR3
;
;       PB7     ERROR4                 ALSO USED FOR SUPERPULSE
;
;       TIMERS
;
;       T2      WATCHDOG TIMER
;                       - TIMED INTERRUPT
;
;       T1      POWER REGULATION TIMER
;                       - CONTINUOUS INTERRUPTS
;
HDWARE: LDX     #VIA1     ;SET INDEX TO VIA1 BASE ADDRESS
        LDA     #$0F
        STA     ,X        ;I/O REGISTER B
        LDA     #$FF
        STA     2,X       ;DATA DIRECTION REGISTER B
        LDA     #$00
        STA     3,X       ;DATA DIRECTION REGISTER A
        LDA     #$40
        STA     11,X      ;AUXILIARY CONTROL REGISTER
;
;       ACIA1                   FRONT PANEL
;
;       9600 BAUD                 ]
;       INTERNAL CLOCK DIVIDER    ]  CONTROL REGISTER
;       7 DATA BITS               ]
;       1 STOP BIT                ]
;
;       DTR, RTS LOW              ]
;       INTERRUPT DISABLED        ]  COMMAND REGISTER
;       RECIEVER NORMAL MODE      ]
;       EVEN PARITY               ]
```

```
;
        LDX     #ACIA1      ;SET INDEX TO ACIA1 BASE ADDRESS
        STA     1,X         ;SOFTWARE RESET
        LDA     ,X
        LDA     #$3E
        STA     3,X         ;CONTROL REGISTER
        LDA     #$6B
        STA     2,X         ;COMMAND REGISTER
;
;       ACIA2                     TERMINAL/MODEM
;
;       4800 BAUD                ]
;       INTERNAL CLOCK DIVIDER   ] CONTROL REGISTER
;       7 DATA BITS              ]
;       1 STOP BIT               ]
;
;       DTR, RTS LOW             ]
;       INTERRUPT DISABLED       ] COMMAND REGISTER
;       RECIEVER NORMAL MODE     ]
;       EVEN PARITY              ]
;
        LDA     #$3C
        STA     ACIA2+3     ;CONTROL REGISTER
        LDA     #$6B
        STA     ACIA2+2     ;COMMAND REGISTER
;
;       PTM1                      RF CONTROL
;
;       CONNECT O2 -> G1
;
;       NOTE:   THE MAIN LOOP EXPECTS TO BE ABLE TO WRITE
;               DIRECTLY INTO CR1, SO CR20 SHOULD ALWAYS BE
;               LEFT 1 AFTER WRITING TO CR3
;
;       TIMER 1   OUTPUT DISABLED           ]  VARIABLE PULSE
;                 INTERRUPT DISABLED        ]    WIDTH
;                 16 BIT ONE-SHOT MODE      ]
;                 ENABLE CLOCK              ]
;
;       TIMER 2   OUTPUT ENABLED            ]  VARIABLE
;                 INTERRUPT DISABLED        ]    REPETITION
;                 16 BIT CONTINUOUS MODE    ]    PERIOD
;                 ENABLE CLOCK              ]
;
;       TIMER 3   OUTPUT ENABLED            ]  SUPERPULSE
;                 INTERRUPT DISABLED        ]    COUNTER
;                 DUAL 8 BIT CONTINUOUS     ]
;                 ENABLE CLOCK              ]
;
        LDX     #PTM1
        CLR     1,X         ;ENABLE WRITE TO CR3
        LDA     #$86
        STA     ,X          ;WRITE TO CR3
        LDA     #$83
        STA     1,X         ;WRITE TO CR2
        LDA     #$33
```

```
        STA     ,X          ;WRITE TO CR1
        LDD     #0
        STD     2,X         ;SET LATCHES
        STD     4,X
        LDX     SPULSE
        STD     6,X
;
;       PTM2                    TIMING FUNCTIONS
;
;       TIMER 1 OUTPUT ENABLED              ]  TRACE COMMAND
;               INTERRUPT DISABLED          ]    TIMER
;               DUAL 8 BIT ONE-SHOT MODE]
;               ENABLE CLOCK                ]
;
;       TIMER 2 OUTPUT ENABLED              ]  TIME ON/OFF
;               INTERRUPT ENABLED           ]    TIMER
;               16 BIT CONTINUOUS MODE      ]
;               EXTERNAL CLOCK              ]
;
;       TIMER 3 OUTPUT ENABLED              ]  0.1 SEC TIMER
;               INTERUPT DISABLED           ]
;               16 BIT CONTINUOUS MODE      ]
;               ENABLE CLOCK                ]
;
        LDX     #PTM2
        CLR     1,X         ;ENABLE WRITE TO CR3
        LDA     #$82
        STA     ,X          ;WRITE TO CR3
        LDA     #$A1
        STA     1,X         ;WRITE TO CR2
        LDA     #$A6
        STA     ,X          ;WRITE TO CR1
        LDD     #0
        STD     2,X         ;SET TIMER 1 TO ZERO
        STD     4,X         ;SET TIMER 2 TO ZERO
        LDD     #49999
        STD     6,X         ;SET TIMER 3 TO 0.1 SEC
;
;
;       START UP THE HARDWARE
;
START:  LDU     #VIA1       ;SET POINTER TO VIA1 - LEAVE ALONE!
        LDA     1,U         ;? - ENTER SYSTEM OR MONITOR
        BPL     IN5         ;JUMP TO SYSTEM
;
        CLRA                ;START THE MONITOR, RE-ENTER SYSTEM
        SWI                 ;    ON FALL-THROUGH
        FCB     MONITR
;
;       OPERATE MODE
;
IN5:    LDA     ,U          ;TURN ON RF, COOLING SYSTEM POWER
        ANDA    #$F3
        STA     ,U
        LDA     ACIA2+2     ;ENABLE TERMINAL INTERRUPT
        ANDA    #$FD
```

```
        STA     ACIA2+2
        LDD     TOTTIM    ;START WATCHDOG TIMER
        STB     8,U
        STA     9,U
        LDA     #$A0      ;ENABLE WATCHDOG TIMER INTERRUPT
        STA     14,U
        ANDCC   #$AF      ;UNMASK INTERRUPTS
        LBSR    LASOFF    ;SET LASER TO OFF CONDITION
;
;-------------------------------------
;
;       MAIN LASER CONTROL LOOP
;
;-------------------------------------
;
;       RESET WATCHDOG TIMER
;       CHECK ALL SYSTEM INTERLOCKS
;       GET STATUS INFORMATION FROM FRONT PANEL
;       RESPOND TO FOOT SWITCH CONTROL
;
;       main()  /* LASER CONTROL LOOP */
;       {
;           for (;;) {
;               reset time_out ;
;               if (interlock_bad)
;                   break ;
;               new_status == talk(get_status) ;
;               if (new_status == old_status) {
;                   if (old_status.mode == operate {
;                       if (foot_switch_on) {
;                           if (old_status.laser == off)
;                               turn_laser_on ;
;                       }
;                       elseif (old_status.laser == on)
;                           turn_laser_off ;
;                   }
;               }
;
;       INSTRUCTIONS INDEXED TO THE U REGISTER REFER TO THE
;       VIA - DON'T USE U FOR ANYTHING ELSE
;
MAIN:   LDD     TOTTIM    ;RESET WATCHDOG TIMER
        STB     8,U
        STA     9,U
        JSR     INTRLK    ;CHECK INTERLOCKS
        LBCS    SHTDWN    ;? INTERLOCKS BAD, SHUT DOWN
;
        LDA     #FPSTAT   ;REQUEST STATUS INFORMATION
        LBSR    TRANS
        CMPA    STATUS
        LBNE    CHANGE    ;? STATUS CHANGE, JUMP
        BITA    #$20
        LBNE    RET       ;? STANDBY, CONTINUE
        LDB     1,U       ;CHECK FOOT PEDAL
        BITB    #$40
        BNE     M0        ;? FOOT PEDAL NOT PRESSED, JUMP
```

```
        BITA    #$02
        LBNE    RET         ;? LASER ON, JUMP
        LBSR    LASON       ;TURN ON LASER
        LBRA    RET         ;CONTINUE
;
M0:     LDA     STATUS      ;CHECK IF LASER IS ON
        BITA    #$02
        LBEQ    RET         ;? LASER OFF, CONTINUE
        LBSR    LASOFF      ;TURN OFF LASER
        LBRA    RET         ;CONTINUE
;
;       UPDATE STATUS OF SYSTEM
;       SET DESIRED POWER LEVEL FOR LASER
;
;               else {
;                   old_status == new_status ;
;                   if (old_status.mode == operate) {
;                       while (foot_switch_on) {
;                           stop time_out ;
;                           display error ;
;                       }
;                       power == talk(get_power) ;
;                       set_point == *power ;
;
CHANGE: STA     STATUS      ;STORE NEW STATUS
        BITA    #$20
        LBNE    STNDBY      ;? STANDBY, JUMP
        LDA     1,U         ;CHECK FOOT PEDAL
        BITA    #$40
        BNE     M2          ;? FOOT SWITCH OFF, JUMP
;
        LDA     #$20        ;DISABLE WATCHDOG TIMER
        STA     14,U
        LDD     8,U         ;SAVE PRESENT TIMER COUNT
        PSHS    D
        LDB     #$70        ;INDICATE WHAT THE PROBLEM IS
        ORB     ,U
        STB     ,U
M1:     LDA     1,U         ;WAIT UNTIL FOOT SWITCH IS OFF
        BITA    #$40
        BEQ     M1
;
;       SET LASER PARAMETERS FOR OPERATION
;
M2:     PULS    D           ;RESET WATCHDOG TIMER COUNT
        STD     8,U
        LDA     #$A0        ;RE-ENABLE WATCHDOG TIMER INTERRUPT
        STA     14,U
        LDA     #FPPOW      ;REQUEST POWER SETTING
        LBSR    TRANS
        LDY     ,S          ;SET INDEX INTO POWER SETTING TABLE
        INCA                ;GET PROPER OFFSET
        ASLA
        CMPA    #62
        BLS     M3          ;? SETTING VALID, JUMP
        LDA     #$60
```

```
        LBRA    SHTDWN  ;SHUT DOWN SYSTEM
;
M3:     NEGA
        LDD     A,Y     ;GET SET POINT
        STD     RT      ;STORE SET POINT
;
;       SET SUPERPULSE PARAMETERS
;
;                       if (old_status.superpulse == on)
;                           set_superpulse ;
;
;       THE SUPERPULSE FEATURE IS FOR TESTING PURPOSES ONLY
;       THIS SECTION OF CODE IS DELETED WHEN THE SUPERPULSE
;       FEATURE IS NOT BEING USED
;
        LDB     ,U      ;PRE-LOAD OUTPUT REGISTER
        LDA     STATUS  ;CHECK FOR SUPERPULSE
        BITA    #$10
        BEQ     M7      ;? SUPERPULSE OFF, DISABLE TIMER
        ANDB    #$7F    ;ENABLE SUPERPULSE
        BRA     M8
;
M7:     ORB     #$80    ;DISABLE SUPERPULSE
M8:     STB     ,U
;
;       SET LASER EXPOSURE PARAMETERS
;
;                       if (old_status.exposure == pulsed) {
;                           width == talk(get_width) ;
;                           rate == talk(get_rate) ;
;                           if (width > 1/rate)
;                               break ;
;                       }
;
MODE:   LDA     STATUS  ;CHECK OPERATING MODE
        BITA    #$01
        LBNE    RET     ;? CONTINUOUS MODE, CONTINUE
        BITA    #$04
        BNE     PULSET  ;? PULSED MODE, SET PARAMETERS
        LDA     #$50
        LBRA    SHTDWN  ;IF NO OPERATING MODE, SHUT DOWN
;
PULSET: LDA     #FPPULS ;GET PULSE WIDTH
        LBSR    TRANS
        STA     PULSE   ;STORE PULSE WIDTH
        LDB     #100
        MUL
        PSHS    D       ;SAVE PULSE DURATION IN MICROSECS
        LDA     #FPRR   ;GET REPETITION RATE
        LBSR    TRANS
        STA     REPRAT
        LDX     #MATH   ;INITIALIZE REP RATE DIVISION
        LDD     #50000
        STB     ,X
        STA     ,X
        LDB     REPRAT
```

```
        CLRA
        STB     ,X
        STA     ,X
        LDA     #SDIV       ;START DIVISION
        STA     1,X
M4:     LDA     1,X         ;WAIT UNTIL MATH IS DONE
        BMI     M4
        LDA     ,X          ;GET RESULT
        LDB     ,X
        ASLB
        ROLA
        STD     PTM1+4      ;STORE REPETITION DURATION
        ASLB                ;GET FULL REPETITION DURATION
        ROLA
        SUBD    ,S          ;SUBTRACT PW FROM REP DURATION
        BHS     M5          ;? REP DURATION > PW, CONTINUE
        LDA     #$40        ;LOAD ERROR FLAG
        LBRA    SHTDWN      ;STOP
;
M5:     STD     PTM1+2      ;STORE PULSE WIDTH (ACTIVE LOW)
        LEAS    2,S         ;RECOVER TEMPORARY STORAGE
        LDA     #$B3        ;TRANSFER LATCHES
        STA     PTM1
        LBRA    RET         ;CONTINUE
;
;       ENSURE THE LASER IS OFF IN STANDBY MODE
;
;                       else
;                           turn_off_laser ;
;               }
;
STNDBY: JSR     LASOFF
;
;       SEND LASER POWER AND OPERATIONAL STATUS TO FR. PAN.
;
;               talk(give_power) ;
;               talk(Y(kT)) ;
;           }
;
RET:    LDA     STATUS      ;SAVE LIO STATUS FOR TRANSMISSION
        ANDA    #$02
        ASLA
        ASLA
        ASLA
        ASLA
        ASLA
        ORA     #CPPOW      ;SEND LASER POWER FLAG
        LBSR    TRANS
        LDD     YT          ;SEND LASER POWER
        LBSR    TRANS
        LBRA    MAIN        ;LOOP
;
;       SHUT DOWN SYSTEM
;
;           display_error_type ;
;           turn_off_laser ;
```

```
;           goto ASSIST09_monitor ;
;       }
;
SHTDWN: ORA     #$0F        ;DISPLAY SOURCE OF SHUTDOWN
        STA     VIA1        ; AND TURN OFF TRANSDUCERS
        JSR     LASOFF      ;TURN OFF LASER
        LDA     #$83        ;DISABLE TIMERS
        STA     PTM1+1
        LDA     #$33
        STA     PTM1
        LDA     ACIA2+2     ;DISABLE TERMINAL INTERRUPT
        ANDA    #$FD
        STA     ACIA2+2
        LDS     STACK       ;RESET STACK TOP
        SWI                 ;CALL MONITOR
        FCB     MONITR
;
        LBRA    START       ;RETURN TO START ON FALL THROUGH
;
;-----------------------------------------
;
;       INTERRUPT SERVICING ROUTINES
;
;       irq () /* interrupt servicing routine */
;       {
;           switch (irq_source) {
;               default :
;                   shut_down_system
;
IRQ:    LDA     ACIA2+1     ;POLL INTERRUPT SOURCES
        LBMI    MON         ;? TERMINAL INTERRUPT, JUMP
        LDA     VIA1+13
        BPL     IR0         ;? NOT VIA1 INTERRUPT, JUMP
        BITA    #$20
        LBNE    TIMOUT      ;? WATCHDOG TIMER, JUMP
        BITA    #$40
        LBNE    REGUL8      ;? POWER REGULATION INTERRUPT, JUMP
IR0:    LDA     #$30
        LBRA    SHTDWN      ;UNEXPECTED INTERRUPT - SHUT DOWN
;
;       TERMINAL INTERRUPT
;
;
;               case terminal :
;                   if (command == quit)
;                       shut_down_system ;
;                   break ;
;
MON:    BITA    #$07        ;CHECK FOR TRANSMISSION ERRORS
        BEQ     IR14        ;? NO ERRORS, JUMP
        LDA     ACIA2       ;CLEAR INTERRUPT AND RETURN
        RTI
;
IR14:   LDA     ACIA2       ;GET CHARACTER
        CMPA    #'Q'        ;CHECK FOR QUIT COMMAND
        BNE     IR15
        LDA     #$10
```

```
        LBRA    SHTDWN     ;SHUT DOWN SYSTEM
IR15:   RTI                ;IF NOT VALID COMMAND, IGNORE
;
;       WATCHDOG TIMER INTERRUPT
;
;               case watchdog_timer :
;                   shut_down_system ;
;
TIMOUT: LDA     #$7F       ;MASK OFF FURTHER INTERRUPTS
        STA     VIA1+13
        LDA     #$60
        STA     VIA1+14
        LDA     #$06       ;SHUT DOWN LASER
        LBRA    SHTDWN
;
;       POWER REGULATION INTERRUPT
;
;               case power_requlation :
;                   Y(kT) == convert_A/D() ;
;                   if (old_status.loop == open)
;                       D/A == R(kT) ;
;                   else {
;                       E(kT) == R(kT)-Y(kT) ;
;                       U(kT) == Kp*E(kT) ;
;                       linearize (U(kT)) ;
;                       D/A == U(kT) ;
;                   }
;                   break ;
;           }
;       }
;
REGUL8: LDA     VIA1+4     ;CLEAR INTERRUPT
        JSR     CONVRT     ;START A/D CONVERTER
        STD     YT         ;STORE Y(kT)
        LDA     STATUS     ;CHECK FOR OPEN OR CLOSED LOOP
        BITA    #$08
        BEQ     IR2        ;? CLOSED LOOP, GO TO CONTROL LOOP
        LDD     RT         ;GET DRIVE LEVEL AND SET IT
        STA     DTA
        RTI                ;RETURN
;
IR2:    LDX     #MATH      ;SET INDEX TO MATH PROCESSOR
        LDD     RT         ;GET SET POINT
        STB     ,X         ;ENTER INTO MATH PROCESSOR
        STA     ,X
        CLRA
        STA     ,X
        STA     ,X
        LDD     YT         ;GET FEEDBACK SIGNAL
        STB     ,X         ;ENTER INTO MATH PROCESSOR
        STA     ,X
        CLRA
        STA     ,X
        STA     ,X
        LDA     #DSUB      ;START DOUBLE PRECISION SUBTRACT
        STA     1,X
```

```
IR3:    LDA     1,X         ;WAIT FOR MATH TO FINISH
        BMI     IR3
        BITA    #$40
        BNE     MINUS       ;? -VE RESULT, JUMP
        LDA     ,X          ;GET RESULT
        LDA     ,X
        LDA     ,X
        LDB     ,X
        STD     ET          ;STORE FOR FUTURE USE
        STB     ,X          ;RE-ENTER INTO MATH PROCESSOR
        STA     ,X
        CLRA
        STA     ,X
        STA     ,X
        STA     ,X          ;ENTER Kp INTO MATH PROCESSOR
        LDD     KP
        STB     ,X
        STA     ,X
        CLRA
        STA     ,X
        LDA     #DMUL       ;START DOUBLE PRECISION MULTIPLY
        STA     1,X
IR4:    LDA     1,X         ;WAIT FOR MATH TO FINISH
        BMI     IR4
        BITA    #$02
        BNE     OVRFLW      ;? OVERFLOW, JUMP
        LDA     ,X          ;GET RESULT
        ADDA    LIMLO
        BVS     OVRFLW      ;? RESULT > 8 BITS, JUMP
        CMPA    LIMHI
        BHI     OVRFLW      ;? RESULT > HIGH LIMIT, JUMP
        STA     DTA         ;SEND RESULT TO D/A
        RTI                 ;RETURN FROM INTERRUPT
;
;       MATH OVERFLOW ROUTINE
;
OVRFLW: LDA     LIMHI       ;SET D/A LEVEL TO MAX OUTPUT
        STA     DTA
        RTI                 ;RETURN
;
;       -VE ERROR SIGNAL ROUTINE
;
MINUS:  LDA     LIMLO       ;SET D/A LEVEL TO MIN OUTPUT
        STA     DTA
        RTI                 ;RETURN
;
;-------------------------------------
;
;       SUBROUTINES
;
;-------------------------------------
;
;       TRANS   SENDS DATA TO THE FRONT PANEL
;
;       A - PASSES THE DATA TO BE TRANSMITTED
;           RETURNS THE RESPONSE FROM THE FRONT PANEL
```

```
;
;       talk(data)
;       {
;           do {
;               while (line_busy)
;                   continue ;
;               send data ;
;               while (no_response)
;                   continue ;
;           } while (response == not_valid) ;
;           return (response) ;
;       }
;
TRANS:  PSHS    A           ;SAVE DATA
S1:     LDA     ACIA1+1     ;GET STATUS REGISTER
        BITA    #$10
        BEQ     S1          ;? NOT READY TO TRANSMIT, LOOP
S2:     LDA     ,S
        STA     ACIA1       ;SEND DATA
S3:     LDA     ACIA1+1     ;GET STATUS REGISTER
        BITA    #$08
        BEQ     S3          ;? NO DATA RECIEVED, LOOP
        BITA    #$07
        BNE     S2          ;? BAD TRANSMISSION, REPEAT
        PULS    A           ;RESET STACK
        LDA     ACIA1       ;GET DATA
        RTS                 ;RETURN
;
;       CONVRT  WAITS FOR A/D CONVERSION TO FINISH AND
;               RETURNS THE VALUE
;
;       D - RETURNS THE A/D CONVERSION VALUE
;
;       convert_A/D()
;       {
;           start_conversion ;
;           while (converter == busy)
;               continue ;
;           return (hex_value) ;
;       }
;
CONVRT: PSHS    CC          ;SAVE REGISTERS
        ORCC    #$50        ;MASK INTERRUPTS DURING CONVERSION
        LDA     #4
        STA     ATD         ;START CONVERSION
S6:     DECA                ;WAIT FOR CONVERSION TO FINISH
        BNE     S6
        LDA     ATD         ;GET CONVERSION VALUE
        LDB     ATD+1
        PULS    CC,PC       ;RETURN
;
;       WAIT    THIS ROUTINE PROVIDES FOR A TIMED LOOP
;
;       X - PASSES THE NUMBER OF MILLISECONDS OF WAIT TIME
;           RETURNS CLEARED
;
```

```
;       A - RETURNS CLEARED
;
;       wait(time)
;       {
;           while (time) {
;               wait one millisecond ;
;               time-- ;
;           }
;       }
;
WAIT:   CMPX    #0
        BNE     S5          ;? ZERO LOOP TIME, RETURN
        RTS
S5:     LEAX    -1,X        ;DECREASE COUNTER AND WAIT 1 MS
        LDA     #196        ;1 MS LOOP
        BRN     S5
S4:     DECA
        BNE     S4
        BRA     WAIT        ;NOW WAIT FOR N-1 MS
;
;       TURN LASER ON
;
;       A,B - VOLATILE
;
;       turn_laser_on()
;       {
;           if (old_status.exposure == continuous)
;               initialize continuous operation ;
;           elseif (old_status.exposure == pulsed)
;               initialize pulsed operation ;
;           else
;               shut_down_system
;       }
;
LASON:  LDA     STATUS      ;CHECK OPERATING MODE
        BITA    #$01
        BNE     CONT        ;?CONTINUOUS MODE, START CONTINUOUS
        BITA    #$04
        BNE     PULSED      ;? PULSED MODE, START PULSED
        LDA     #$50
        LBRA    SHTDWN      ;IF NO OPERATING MODE, SHUT DOWN
;
CONT:   LDA     #$33        ;DISABLE PULSE OUTPUT
        STA     PTM1
        LDA     STATUS      ;INDICATE LASER ON
        ORA     #$02
        STA     STATUS
        LDA     VIA1        ;TURN ON OSCILLATOR
        ANDA    #$FE
        STA     VIA1
        LDA     #$32        ;START TIMERS, OUTPUT MASKED
        STA     PTM1
        LDD     CONFRQ      ;RESET CONTROL TIMER
        STB     VIA1+4
        STA     VIA1+5
        LDA     #$C0        ;ENABLE INTERRUPT
```

```
         STA      VIA1+14
         RTS      —          ;RETURN
;
PULSED:  LDA      STATUS     ;INDICATE LASER ON
         ORA      #$02
         STA      STATUS
         LDD      RT         ;SET OUTPUT LEVEL
         STA      DTA
         LDA      VIA1       ;TURN ON OSCILLATOR
         ANDA     #$FE
         STA      VIA1
         LDA      #$B2       ;START TIMERS, OUTPUT ENABLED
         STA      PTM1
         RTS                 ;RETURN
;
;        TURN LASER OFF
;
;        A,B - VOLATILE
;
;        turn_laser_off()
;        {
;            turn off laser, re-initialize power regulation ;
;        }
;
LASOFF:  LDA      VIA1       ;TURN OFF OSCILLATOR
         ORA      #$01
         STA      VIA1
         LDA      #$33       ;DISABLE TIMERS
         STA      PTM1
         CLRA                ;SET D/A LEVEL TO ZERO
         STA      DTA
         LDA      STATUS     ;INDICATE LASER OFF
         ANDA     #$FD
         STA      STATUS
         LDD      #0         ;CLEAR CONTROL REGISTERS
         STD      UT
         STD      ET
         STD      ET1
         STD      ET2
         STD      YT
         LDA      #$40       ;DISABLE CONTROL INTERRUPT
         STA      VIA1+14
         RTS                 ;RETURN
;
;        INTRLK  CHECK INTERLOCKS
;
;        A - RETURNS ERROR CODE, IF ANY
;
;        CCR - BIT C IS SET IF ANY INTERLOCK HAS WRONG VALUE
;                    CLEARED IF ALL INTERLOCKS ARE OK
;
;
INTRLK:  PSHS     B          ;SAVE B
         LDB      #-1        ;PRE-SET INTERLOCK COUNTER
         LDA      VIA1+1     ;CHECK INTERLOCKS
         BNE      INT0       ;? ANY BAD, JUMP
         PULS     B          ;RETRIEVE B
```

```
        ANDCC   #$FE        ;SET OK FLAG
        RTS                 ;RETURN
;
INT0:   INCB                ;INCREMENT INTERLOCK COUNTER
        RORA
        BCC     INT0        ;? THIS INTERLOCK OK, LOOP
        TFR     B,A         ;SHIFT INTERLOCK COUNTER INTO A
        PULS    B           ;RETRIEVE B
        ORCC    #$01        ;SET ERROR FLAG
        RTS                 ;RETURN
;
;---------------------------------------
;
;       POWER REGULATION SET POINT TABLE
;
;       THIRTY-ONE SET POINTS, EACH ONE CORRESPONDING TO THE
;       HEX VALUE OF LASER OUTPUT POWER EXPECTED AT THAT
;       POWER SETTING
;
;
POWTAB: DW      $0000
        DW      $0880
        DW      $1110
        DW      $1990
        DW      $2220
        DW      $2AA0
        DW      $3330
        DW      $3BB0
        DW      $4440
        DW      $4CC0
        DW      $5550
        DW      $5DD0
        DW      $6660
        DW      $6EE0
        DW      $7770
        DW      $7FF0
        DW      $8880
        DW      $9110
        DW      $9990
        DW      $A220
        DW      $AAA0
        DW      $A330
        DW      $BBB0
        DW      $B440
        DW      $CCC0
        DW      $C550
        DW      $DDD0
        DW      $D660
        DW      $EEE0
        DW      $E770
        DW      $FFF0
;
        DB      EOT     ;END OF TABLE MARKER
;
;
        END
```

APPENDIX II - FRONT PANEL PROGRAM LISTING

```
;----------------------------------------
;
;       FRONT PANEL SOFTWARE
;
;----------------------------------------
;
;       HARDWARE EQUATE TABLE
;
;       THIS DEFINES THE LOCATIONS OF THE 68701 REGISTERS
;
RAMST   EQU     $80
DDR1    EQU     $00
DDR3    EQU     $04
DDR4    EQU     $05
DATA    EQU     $02
STROBE  EQU     $06
SWITCH  EQU     $07
P3CSR   EQU     $0F
RMCR    EQU     $10
TRCSR   EQU     $11
RDR     EQU     $12
TDR     EQU     $13
RECR    EQU     $14
EPROM   EQU     $F800
;
;       DISPLAY VARIABLE EQUATE TABLE
;
;       THIS DEFINES THE ORGANIZATION OF THE DISPLAY MEMORY
;       THE MEMORY ALLOCATON MUST REMAIN IN THIS ORDER
;
        ORG     RAMST
DISP    EQU     $               ;LOCATE BEGINNING OF DISPLAY RAM
BCDINT  RMB     1               ;INTENSITY DATA (BCD)
OUTPOW  RMB     1               ;BAR GRAPH DATA (BINARY)
BCDPOW  RMB     1               ;POWER SET POINT (BCD)
BCDRR   RMB     1               ;REPETITION RATE (BCD)
BCDPW   RMB     1               ;PULSE WIDTH (BCD)
STATUS  RMB     1               ;STATUS
BINPOW  RMB     1               ;POWER SET POINT (BINARY)
BINRR   RMB     1               ;REPETITION RATE (BINARY)
BINPW   RMB     1               ;PULSE WIDTH (BINARY)
BININT  RMB     1               ;INTENSITY DATA (BINARY)
;
;       PROGRAM VARIABLE MEMORY ALLOCATION
;
SW      RMB     1
PRESSD  RMB     1
CNTRL   RMB     1
WORD    RMB     1
RECEIV  RMB     2
DIVRAM  RMB     6
;
        ORG     EPROM
;
```

```
;       SWITCH TABLE
;
;       THIS DEFINES WHICH SUBROUTINE IS TO BE EXECUTED WHEN
;       THE RELEVANT KEY IS PRESSED
;
SWTAB:  FDB     ERROR
        FDB     ERROR
        FDB     POW1
        FDB     POW10
        FDB     ERROR
        FDB     CONT
        FDB     SPULSE
        FDB     PULSE
        FDB     PW1
        FDB     PW10
        FDB     RR1
        FDB     RR10
        FDB     HI
        FDB     LO
        FDB     RDY
        FDB     STBY
;
;       TRANSMIT DATA TABLE
;
;       THIS SETS WHICH DATA IS TO BE TRANSMITTED
;
TXTAB:  FCB     STATUS-DISP
        FCB     BINPW-DISP
        FCB     BINRR-DISP
TXEND:  FCB     BINPOW-DISP
;
;       RECEIVE DATA TABLE
;
;       THIS SETS WHICH REGISTER THE INCOMING DATA IS TO BE
;       STORED IN
;
RXTAB:  FCB     STATUS-DISP
        FCB     BININT-DISP
RXEND:  FCB     OUTPOW-DISP

;-------------------------------------
;
;
;       INITIALIZATION SEQUENCE
;
;       THIS INITIALIZATION SEQUENCE IS CALLED AFTER EVERY
;       RESET
;
;       PORT 1 = DATA : OUTPUT
;       PORT 3 = DISPLAY MUX : OUTPUT
;       PORT 4 BITS 0-3 = SWITCH OUTPUT
;              BITS 4-7 = SWITCH INPUT
;       SC2 = PORT 3 OUTPUT STROBE
;       STATUS = CONTINUOUS, LO RANGE, STANDBY
;       DISPLAY RAM = CLEARED
;
```

```
;
INIT:   LDAA    #$FF        ;PORT1, PORT 3 - OUTPUTS
        STAA    DDR1
        STAA    DDR3
        LDAA    #$0F        ;PORT 4 - HALF OUTPUT, HALF INPUT
        STAA    DDR4
        LDAA    #$10
        STAA    P3CSR
        LDAA    #$05        ;INITIALIZE SERIAL PORT
        STAA    RMCR
        LDAA    #$1A
        STAA    TRCSR
        LDAA    #$29        ;STATUS = CONT, LO, STBY
        STAA    STATUS
        LDAA    #$00
        STAA    $08
        LDS     #$00FF
        CLR     DISP        ;CLEAR DISPLAY REGISTERS
        CLR     DISP+1
        CLR     DISP+2
        CLR     DISP+3
        CLR     DISP+4
        CLR     DISP+6
        CLR     DISP+7
        CLR     DISP+8
        CLR     DISP+9
        CLR     CNTRL
        CLR     PRESSD
        CLI                 ;ENABLE INTERRUPTS

;-------------------------------------
;
;       MAIN PROGRAM
;
;       UPDATE DISPLAYS
;       CHECK KEYS TO SEE IF ANY ARE PRESSED
;       IF A KEY IS PRESSED, EXECUTE THE APPROPRIATE
;       SUBROUTINE, AND WAIT BEFORE CHECKING KEYS AGAIN
;
;       main() /* Front Panel Program */
;       {
;           for (;;) {
;               display_data() ;
;               if (switch_pressed) {
;                   update_data ;
;                   if (1st_press)
;                       wait 500 ms ;
;                   else
;                       wait 250 ms ;
;               }
;           }
;       }
;
KEYCK:  JSR     STORE       ;UPDATE THE DISPLAYS
        LDX     #SWTAB      ;SET INDEX TO SWITCH TABLE
        LDAA    #$F7        ;PREPARE TO PULL ONE OUTPUT LOW
```

```
KC1:    CLRB                ;RESET LINE COUNTER
        STAA    SWITCH      ;SET OUTPUT LOW
        NOP
        LDAA    SWITCH      ;GET INPUT LINES
        STAA    SW          ;STORE INPUT LINES
KC2:    LSL     SW
        BCC     CHANGE      ;? LINE LOW - GO TO CHANGE ROUTINE
        INCB                ;INCREMENT LINE COUNTER
        INCB
        CMPB    #8
        BCS     KC2         ;? NOT ALL INPUTS CHECKED, LOOP
        ASRA                ;SET NEXT OUTPUT LINE LOW
        BCS     KC3         ;? NOT ALL OUTPUTS PULLED LOW, JUMP
        CLR     PRESSD      ;FLAG NO KEY PRESSED
        BRA     KEYCK       ;LOOP
;
KC3:    ABX                 ;NO - CHECK NEXT SET
        BRA     KC1
;
CHANGE: ABX                 ;ADD OFFSET TO TABLE INDEX
        LDX     0,X         ;GET ADDRESS OF SUBROUTINE
        JSR     0,X         ;EXECUTE SUBROUTINE
        JSR     STORE       ;UPDATE DISPLAYS
        TST     PRESSD
        BEQ     CH1         ;? FIRST TIME KEY PRESSED, JUMP
        LDX     #500        ;WAIT FOR 500 ms
        BRA     CH2
;
CH1:    LDX     #$250       ;WAIT FOR 250 ms
CH2:    JSR     WAIT
        JMP     KEYCK       ;LOOP BACK TO BEGINNING

;-----------------------------------
;
;       INTERRUPT PROCESSING
;
;       INTERRUPTS ARE GENERATED BY THE SERIAL DATA PORT.
;       IF THE DATA CONTAINS A TRANSMISSION ERROR, A REQUEST
;       FOR RE-TRANSMISSION IS SENT BACK.
;       IF THE CPU IS SENDIN A CONTROL WORD, THE MICRO IS
;       CONFIGURED TO RECIEVE THE DATA AND A CONFIRMATION OF
;       RECEPTION OF THE CONTROL WORD IS SENT BACK TO THE
;       CPU.IF THE CPU IS SENDING DATA, THE MICRO STORES THE
;       DATA IN THE APPROPRIATE PLACE AND CONFIRMS DATA
;       RECIEVED. IF THE CPU IS REQUESTING DATA, THE
;       APPROPRIATE DATA IS SENT TO THE CPU
;
;       irq() /* Interrupt Driven Communication Protocol */
;       {
;           if (data_received != ok) {
;               transmit error flag ;
;               return ;
;           }
;
POLL:   LDAA    TRCSR       ;GET THE SERIAL CONTROL REGISTER
        BITA    #$40
```

```
        BNE     IR0         ;? TRANSMISSION NOT OK, JUMP
        BITA    #$80
        BEQ     RET         ;? NOT RECEIVE REGISTER FULL, JUMP
        JSR     PARCHK      ;CHECK PARITY OF DATA
        BCC     CON         ;? PARITY OK, CONTINUE
IR0:    LDAA    #$01        ;SEND ERROR FLAG
        JSR     TRANS
RET:    CLI                 ;CLEAR INTERRUPT AND RETURN
        RTI
;
;           elseif {data_received != control_word) {
;               store received data in display memory ;
;               transmit ok flag ;
;               return ;
;           }
;
CON:    LDAA    RDR         ;GET BYTE FROM SERIAL PORT
        LDAB    CNTRL
        BEQ     TXD         ;? CONTROL WORD, JUMP
        LDAA    #$81        ;SEND OK FLAG
        JSR     TRANS
        LDX     RECEIV      ;GET POINTER TO DATA OFFSET
        LDAB    0,X         ;GET OFFSET
        LDX     #DISP       ;GET POINTER TO DISPLAY RAM
        ABX                 ;ADD OFFSET
        STAA    0,X         ;STORE DATA IN RAM
        CLR     CNTRL       ;CLEAR CONTROL WORD FLAG
        BRA     RET         ;RETURN
;
;           elseif (transmit_data_to_CPU) {
;               send requested information to CPU ;
;               return ;
;           }
;
TXD:    STAA    WORD        ;STORE CONTROL WORD FOR FUTURE USE
        COM     CNTRL       ;SIGNAL CONTROL WORD RECIEVED
        BITA    #$40
        BNE     SETCON      ;? DATA TO BE RECEIVED, JUMP
        LDX     #TXTAB      ;SET OFFSET TABLE POINTER
T1:     CPX     #TXEND
        BGE     RET         ;? ALL VALUES CHECKED, RETURN
        LSR     WORD        ;SHIFT CONTROL WORD
        BCS     GO          ;? THIS DATA WANTED, SEND DATA
        INX                 ;INCREMENT POINTER AND LOOP
        BRA     T1
;
GO:     LDAB    0,X         ;GET OFFSET TO DATA REGISTER
        LDX     #DISP       ;GO TO DISPLAY RAM
        ABX                 ;ADD OFFSET
        LDAA    0,X         ;GET DATA
        JSR     PARCHK      ;DO PARITY CHECK
        BCC     G1          ;? PARITY OK, SEND DATA
        ORAA    #$80        ;SET PARITY BIT
G1:     JSR     TRANS       ;SEND DATA
        BRA     RET         ;RETURN
;
```

```
;           else {
;               transmit ok flag ;
;               set Laser In Operation status ;
;               set registers to receive data ;
;               return ;
;           }
;       }
;
SETCON: LDAA    #$81        ;SEND OK FLAG
        JSR     TRANS
        BITA    #$20
        BNE     LIO1        ;? LIO FLAG SET, JUMP
        LDAB    STATUS      ;TURN OFF LIO LIGHT
        ANDB    #$FD
        STAB    STATUS
        BRA     LIO2
;
LIO1:   LDAB    STATUS      ;TURN ON LIO LIGHT
        ORAB    #$02
        STAB    STATUS
LIO2:   LSL     WORD        ;SHIFT OUT CONTROL BITS
        LSL     WORD
        LSL     WORD
        LDX     #RXTAB      ;GET RECEIVE DATA OFFSET POINTER
CON1:   CPX     #RXEND
        BGE     RET         ;? ALL DATA CHECKED, RETURN
        LSL     WORD
        BCS     CON2        ;? THIS DATA WANTED, JUMP
        INX                 ;POINT TO NEXT LOCATION
        STX     RECEIV
        BRA     CON1        ;LOOP
;
CON2:   STX     RECEIV      ;STORE APPROPRIATE DISPLAY POINTER
        CLI                 ;CLEAR INTERRUPT AND RETURN
        RTI

;-----------------------------------------
;
;       SUBROUTINES
;
;       STATUS SUBROUTINES CHANGE ONE OR MORE BITS IN THE
;       STATUS REGISTER.
;
;       A - VOLATILE FOR ALL STATUS SUBROUTINES
;
STBY:   LDAA    STATUS      ;CHANGE STATUS TO STANDBY
        ORAA    #$20
        STAA    STATUS
        RTS

RDY:    LDAA    STATUS      ;CHANGE STATUS TO READY
        ANDA    #$DF
        STAA    STATUS
        RTS

HI:     LDAA    STATUS      ;CHANGE RANGE TO HI
```

```
        ANDA    #$F7
        ORAA    #$20
        STAA    STATUS
        RTS

LO:     LDAA    STATUS    ;CHANGE RANGE TO LO
        ORAA    #$28
        STAA    STATUS
        RTS

PULSE:  LDAA    STATUS    ;CHANGE TO PULSE MODE
        ORAA    #$24
        ANDA    #$FE
        STAA    STATUS
        RTS

SPULSE: LDAA    STATUS    ;CHANGE TO SUPER PULSE MODE
        ORAA    #$20
        EORA    #$10
        STAA    STATUS
        RTS

CONT:   LDAA    STATUS    ;CHANGE TO CONTINUOUS MODE
        ORAA    #$21
        ANDA    #$FB
        STAA    STATUS
        RTS
;
;       INCREMENT DISPLAY RAM SUBROUTINES
;
;       THESE SUBROUTINES INCREMENT THE DISPLAY RAM BY THE
;       APPROPRIATE AMOUNT AND CHECK THAT THE NEW VALUE IS
;       WITHIN BOUNDS FOR THAT DISPLAY
;
;       A,B,X - VOLATILE FOR ALL INCREMENT SUBROUTINES
;

;
;       INCREMENT PULSE WIDTH BY 1
;
PW1:    LDAA    STATUS    ;GET STATUS
        BITA    #$04
        BEQ     P1        ;? CONTINUOUS MODE, DON'T INCREMENT
        LDAA    BCDPW     ;INITIALIZE INC1 REGISTERS
        LDAB    BINPW
        LDX     #BCDPW
        JSR     INC1      ;INCREMENT REGISTERS
        STAA    BCDPW     ;STORE NEW VALUES
        STAB    BINPW
P1:     JMP     STBY      ;GO TO STANDBY MODE
;
;       INCREMENT PULSE WIDTH BY 10
;
PW10:   LDAA    STATUS    ;GET STATUS
        BITA    #$04
        BEQ     P2        ;? CONTINUOUS MODE, DON'T INCREMENT
```

```
        LDAA    BCDPW    ;INITIALIZE INC10 REGISTERS
        LDAB    BINPW
        LDX     #BCDPW
        JSR     INC10    ;INCREMENT REGISTERS
        STAA    BCDPW    ;STORE NEW VALUES
        STAB    BINPW
P2:     JMP     STBY     ;GO TO STANDBY MODE
;
;       INCREMENT REPETITION RATE BY 1
;
RR1:    LDAA    STATUS   ;GET STATUS
        BITA    #$04
        BEQ     R1       ;? CONTINUOUS MODE, DON'T INCREMENT
        LDAA    BINRR    ;GET OLD REPETITION RATE
        BEQ     R10      ;? REP RATE = 0, DON'T DO DIVISION
        STAA    DIVRAM+5 ;STORE DIVISOR
        LDX     #1000    ;STORE DIVIDEND
        STX     DIVRAM+2
        CLR     DIVRAM   ;CLEAR QUOTIENT AND BUFFER
        CLR     DIVRAM+1
        CLR     DIVRAM+4
        JSR     DIV      ;DO DIVISION -> 1000/(REP RATE)
        LDD     DIVRAM   ;GET QUOTIENT
        TSTA
        BNE     R10      ;? QUOTIENT > 8 BITS, INCREMENT
        CMPB    BINPW
        BLO     R3       ;? QUOTIENT < PULSE WIDTH, DON'T
R10:    LDAA    BCDRR    ;INITIALIZE INC1 REGISTERS
        LDAB    BINRR
        LDX     #BCDRR
        JSR     INC1     ;INCREMENT REGISTERS BY 1
        STAA    BCDRR    ;STORE NEW VALUES
        STAB    BINRR
R1:     JMP     STBY     ;GO TO STANDBY MODE
;
R3:     JMP     ERROR    ;SIGNAL THAT INCREMENT CANT BE DONE
;
;       INCREMENT REPETITION RATE BY 10
;
RR10:   LDAA    STATUS   ;GET STATUS
        BITA    #$04
        BEQ     R2       ;? CONTINUOUS MODE, DON'T INCREMENT
        LDAA    BINRR    ;GET OLD REP RATE
        BEQ     R20      ;? REP RATE = 0, DON'T DO DIVISION
        STAA    DIVRAM+5 ;STORE DIVISOR
        LDX     #1000    ;STORE DIVIDEND
        STX     DIVRAM+2
        CLR     DIVRAM   ;CLEAR QUOTIENT AND BUFFER
        CLR     DIVRAM+1
        CLR     DIVRAM+4
        JSR     DIV      ;DIVIDE - 1000/(REP RATE)
        LDD     DIVRAM   ;GET QUOTIENT
        TSTA
        BNE     R20      ;? QUOTIENT > 8 BITS, INCREMENT
        CMPB    BINPW
        BLO     R3       ;? QUOTIENT < PULSE WIDTH, DON'T
```

```
R20:    LDAA    BCDRR     ;INITIALIZE INC10 REGISTERS
        LDAB    BINRR
        LDX     #BCDRR
        JSR     INC10     ;INCREMENT REGISTERS BY 10
        STAA    BCDRR     ;STORE NEW VALUES
        STAB    BINRR
R2:     JMP     STBY      ;GO TO STANDBY MODE
;
;       INCREMENT POWER SET POINT BY 1
;
POW1:   LDAA    BCDPOW    ;INITIALIZE INC1 REGISTERS
        LDAB    BINPOW
        LDX     #BCDPOW
        JSR     INC1      ;INCREMENT REGISTERS BY 1
        CMPA    #$30
        BLO     P3        ;? POWER < 30, STORE NEW VALUE
        LDAA    #$30      ;SET POWER TO 30
        LDAB    #30
P3:     STAA    BCDPOW    ;STORE NEW VALUES
        STAB    BINPOW
        JMP     STBY      ;GO TO STANDBY MODE
;
;       INCREMENT POWER SET POINT BY 10
;
POW10:  LDAA    BCDPOW    ;INITIALIZE INC10 REGISTERS
        LDAB    BINPOW
        LDX     #BCDPOW
        JSR     INC10     ;INCREMENT REGISTERS BY 10
        CMPA    #$30
        BLS     P4        ;? POWER < 30, STORE NEW VALUES
        ANDA    #$0F      ;SET 10'S DIGIT TO 0
        TAB
P4:     STAA    BCDPOW    ;STORE NEW VALUES
        STAB    BINPOW
        JMP     STBY      ;GO TO STANDBY MODE
;
;       INCREMENT REGISTERS BY 1
;
;       THE VALUES TO BE INCREMENTED ARE PASSED IN THE
;       ACCUMULATORS. THE INCREMENTED VALUES ARE RETURNED
;       IN THE SAME ACCUMULATORS.
;
;       A - BCD VALUE
;       B - HEX VALUE
;       X - POINTER TO BCD VALUE
;
INC1:   ANDA    #$0F      ;MASK OFF 10'S DIGIT
        INCA              ;INCREMENT REGISTERS BY 1
        INCB
        CMPA    #10
        BLO     I1        ;? NEW VALUE < 10, CONTINUE
        SUBA    #10       ;ROLL AROUND FROM 9 TO 0
        SUBB    #10
I1:     PSHB              ;SAVE B
        LDAB    0,X       ;GET OLD 10'S DIGIT
```

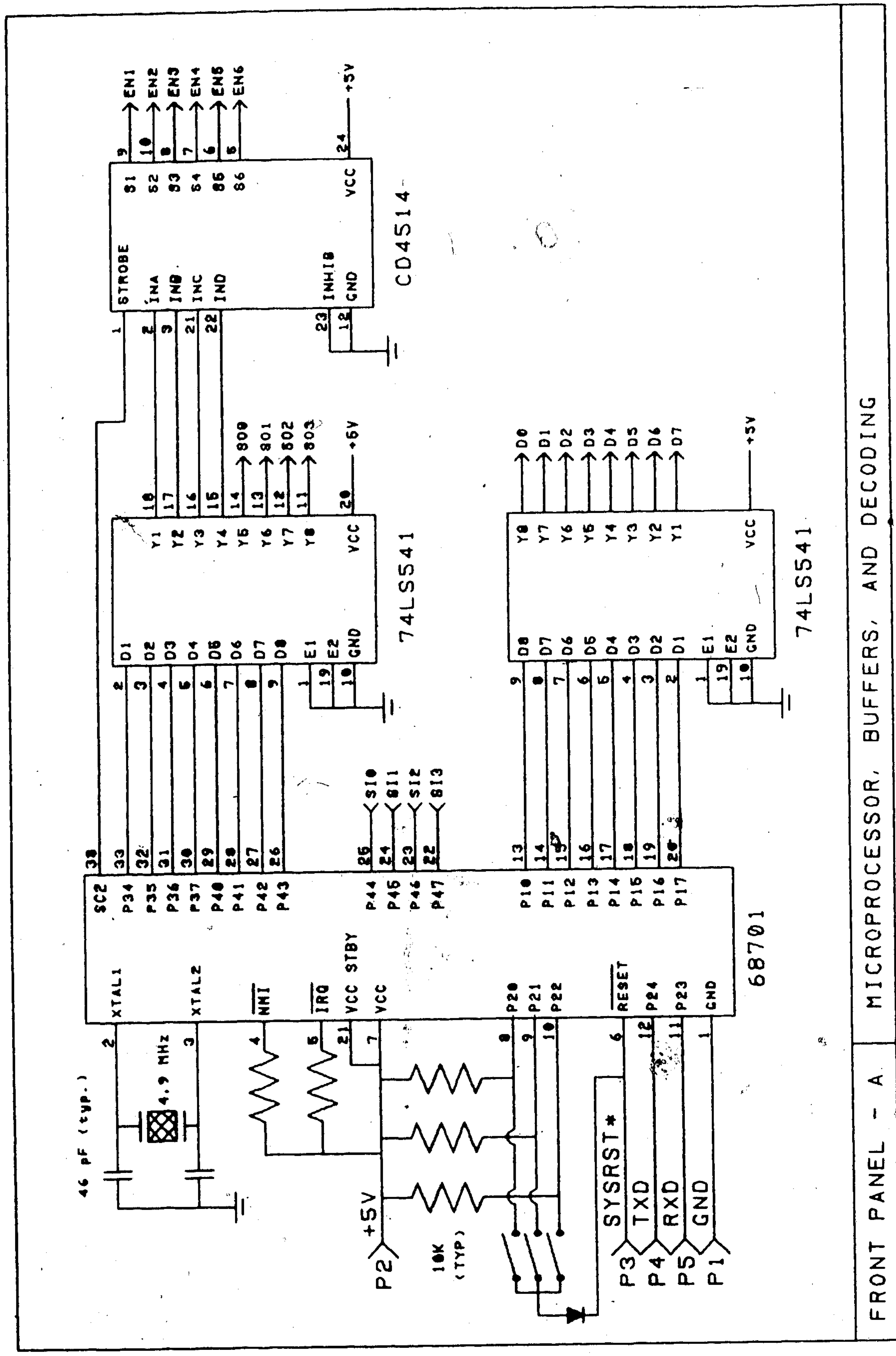
```
         ANDB    #$F0
         ABA               ;MERGE 10'S AND 1'S
         PULB              ;GET B
         RTS               ;RETURN

;
;        INCREMENT REGISTERS BY 10
;
;        THE VALUES TO BE INCREMENTED ARE PASSED IN THE
;        ACCUMULATORS. THE INCREMENTED VALUES ARE RETURNED
;        IN THE SAME ACCUMULATOR
;
;        A - BCD VALUE
;        B - HEX VALUE
;        X - POINTER TO BCD VALUE
;
INC10:   ANDA    #$F0      ;MASK OFF 1'S DIGIT
         ADDA    #$10      ;INCREMENT 10'S DIGIT
         ADDB    #10
         CMPA    #$A0
         BLO     I2        ;? NEW VALUE < 100, CONTINUE
         SUBA    #$A0      ;ROLL AROUND 10'S DIGIT
         SUBB    #100
I2:      PSHB              ;SAVE B
         LDAB    0,X       ;GET OLD 1'S DIGIT
         ANDB    #$0F
         ABA               ;MERGE 10'S AND 1'S
         PULB              ;GET B
         RTS               ;RETURN

;
;        STORE DISPLAY DATA
;
;        THIS SUBROUTINE LATCHES THE INFORMATION IN THE
;        DISPLAY RAM ONTO THE DISPLAYS ON THE FRONT PANEL.
;
;        A,B,X - VOLATILE
;
STORE:   LDAB    #$10
         LDX     #DISP     ;LOAD INDEX TO DISPLAY RAM
ST1:     CLR     STROBE    ;DISABLE DATA BUS
         LDAA    0,X       ;GET DISPLAY DATA
         CPX     #OUTPOW
         BNE     ST3       ;? NOT BAR GRAPH DATA, CONTINUE
         ASLA              ;SHIFT BAR GRAPH DATA TO 8 BITS
ST3:     STAA    DATA      ;STORE DATA ON DATA BUS
         STAB    STROBE    ;LATCH INTO DISPLAY
         CPX     #STATUS   ;ALL REGISTERS STORED?
         BEQ     ST2       ;YES-RETURN
         ADDB    #$10      ;INCREMENT POINTERS
         INX
         BRA     ST1       ;LOOP
;
ST2:     RTS               ;RETURN

;
```

```
;
;        WAIT - A TIMED LOOP OF 1 mS MULTIPLES
;
;        X - PASSES THE NUMBER OF MILLISECONDS TO WAIT
;            RETURNS CLEARED
;
;        A - VOLATILE
;
WAIT:    LDAA    #$F4       ;LOAD 1 mS LOOP
W1:      DECA
         BNE     W1         ;? NOT FINISHED, LOOP
         DEX                ;DECREMENT # OF MILLISECONDS
         BNE     WAIT       ;? MORE TIME LEFT, LOOP
         RTS                ;RETURN
;
;        DIV - DIVIDE A 16 BIT NUMBER BY AN 8 BIT NUMBER
;
;        PARAMETERS ARE PASSED IN RAM AREA
;
;        DIVRAM       QUOTIENT - 2 BYTES, INITIALLY ZERO
;        DIVRAM+2     DIVIDEND - 2 BYTES
;        DIVRAM+4     BUFFER   - INITIALLY ZERO
;                                RETURNS REMAINDER
;        DIVRAM+5     DIVISOR  - 1 BYTE
;
DIV:     LDAB    #16
D1:      ASL     DIVRAM+3 ;SHIFT DIVIDEND
         ROL     DIVRAM+2
         ROL     DIVRAM+4
         ASL     DIVRAM+1 ;SHIFT QUOTIENT
         ROL     DIVRAM
         LDAA    DIVRAM+4 ;GET DIVIDEND BUFFER
         CMPA    DIVRAM+5 ;TEST SUBTRACTION
         BLO     D2       ;? CAN'T SUBTRACT, LOOP
         SUBA    DIVRAM+5 ;DO SUBTRACTION
         STAA    DIVRAM+4 ;STORE RESULT IN BUFFER
         INC     DIVRAM+1 ;INCREMENT QUOTIENT
D2:      DECB             ;DECREMENT COUNT
         BNE     D1       ;? NOT DONE, LOOP
         RTS
;
;        TRANS - TRANSMIT DATA TO CPU
;
;        A - PASSES DATA TO BE TRANSMITTED
;            RETURNS UNCHANGED
;
TRANS:   PSHA               ;SAVE A
         LDAA    TRCSR      ;LOAD SERIAL STATUS REGISTER
         BITA    #$20
         BEQ     TRANS      ;? TDR NOT EMPTY, WAIT
         PULA               ;GET A
         STAA    TDR        ;SEND DATA
         RTS                ;RETURN

;
```

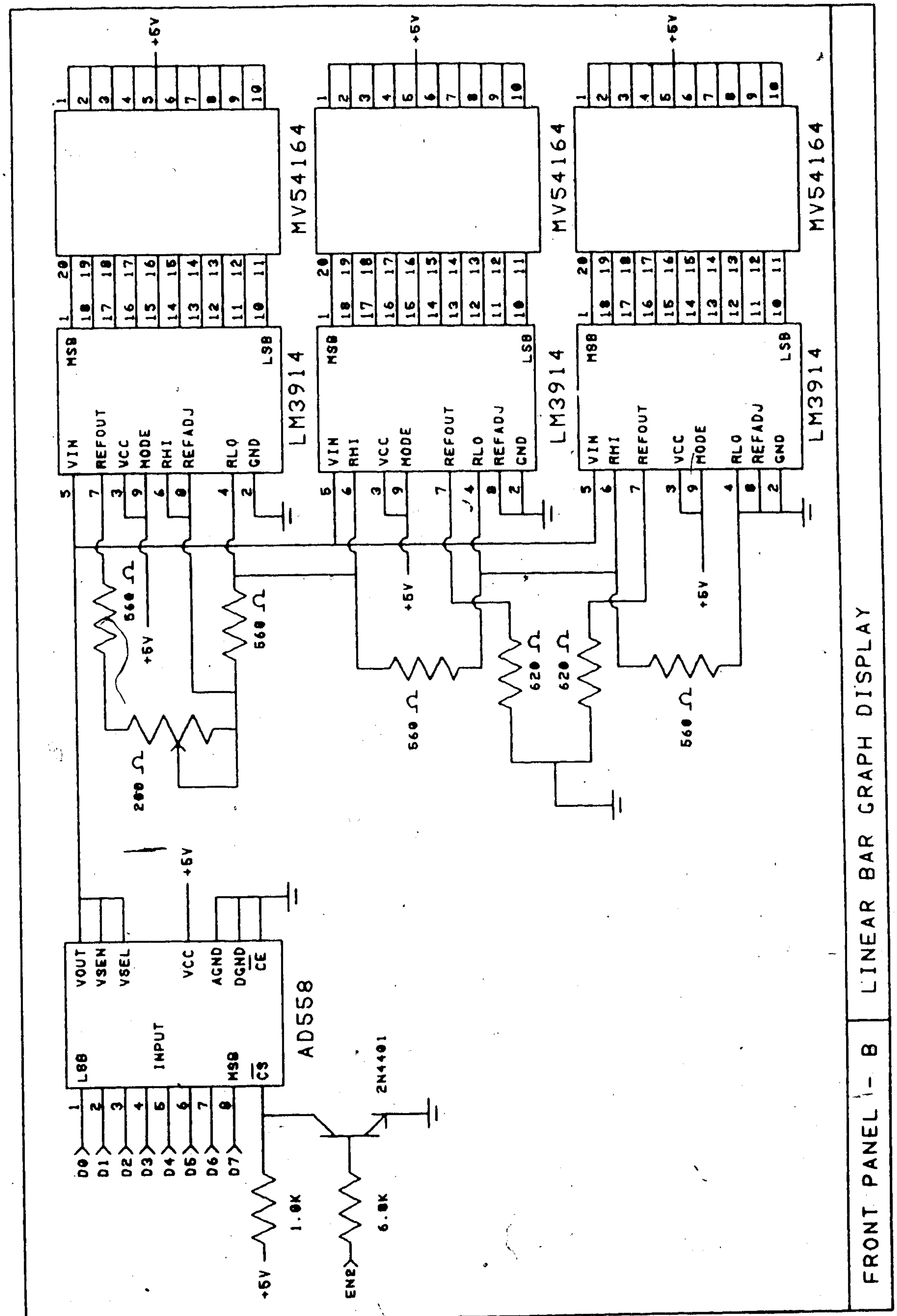
```
;       PARCHK - EVEN PARITY CHECK
;
;       A - PASSES THE DATA TO BE CHECKED
;           RETURNS UNCHANGED
;
;       CCR - BIT C IS SET IF PARITY IS NOT OK
;                      CLEARED IF PARITY IS OK
;
;       B,X - VOLATILE
;
PARCHK: CLRB                ;CLEAR PARITY FLAG
        CLC                 ;CLEAR CARRY BIT
        LDX     #8          ;SET COUNTER
PAR1:   ROLA
        BCC     PAR2        ;? BIT CLEAR, JUMP
        COMB                ;FLIP PARITY FLAG
PAR2:   DEX                 ;DECREMENT COUNTER
        BNE     PAR1        ;? NOT FINISHED, LOOP
        TSTB
        BEQ     PAR3        ;? EVEN # OF BITS, JUMP
        SEC                 ;SET CARRY BIT
        RTS                 ;RETURN
;
PAR3:   CLC                 ;CLEAR CARRY BIT
        RTS                 ;RETURN

;
;       ERROR TRAPPING ROUTINE
;
;       ON ERROR RETURN TO MAIN PROGRAM
;
ERROR:  RTS

;
;       INTERRUPT VECTORS
;
        ORG     $FFF0
        FDB     POLL
        FDB     INIT
        FDB     INIT
        FDB     INIT
        FDB     INIT
        FDB     INIT
        FDB     INIT
        FDB     INIT
;
;
        END
```

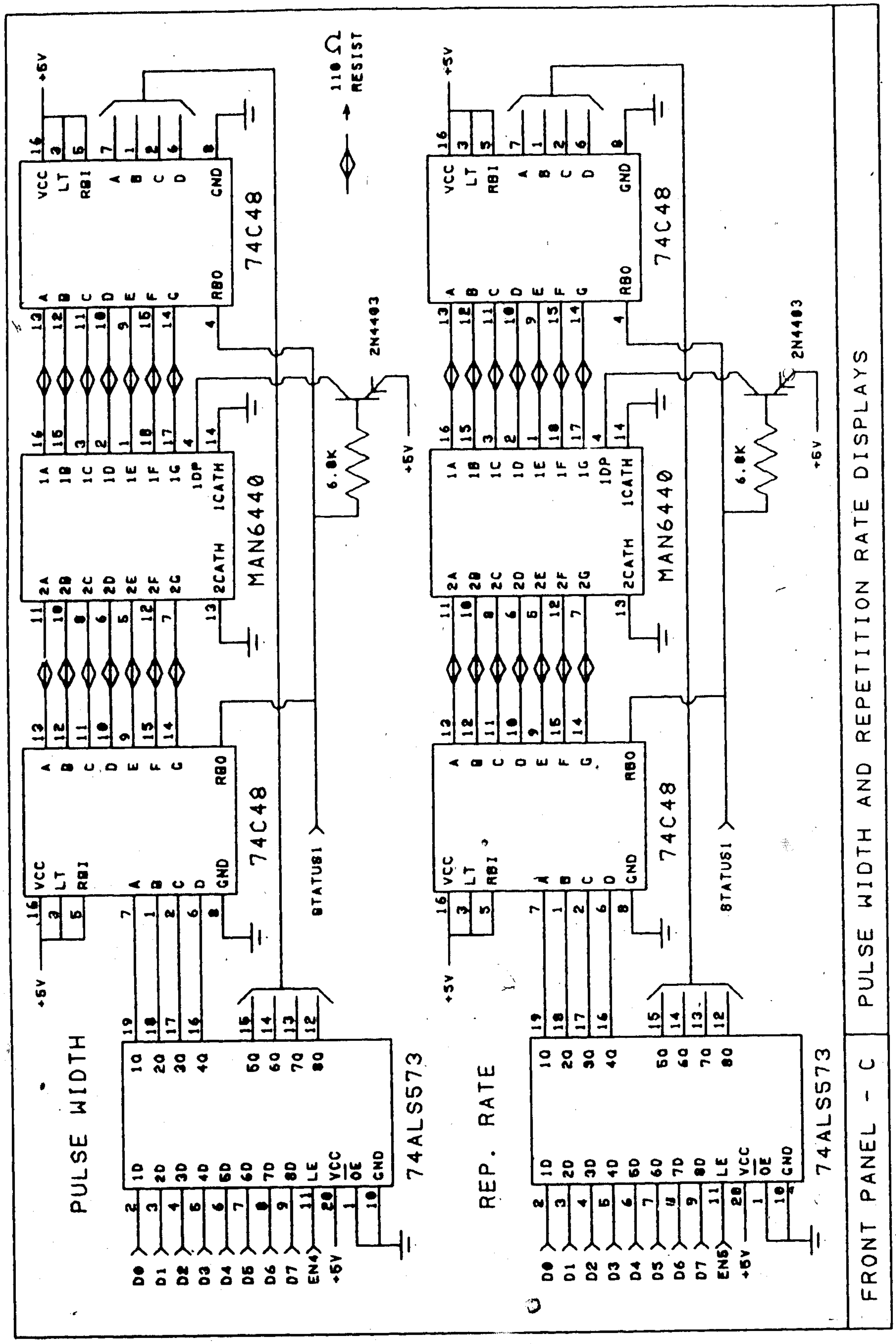
APPENDIX III - PC BOARD SCHEMATICS

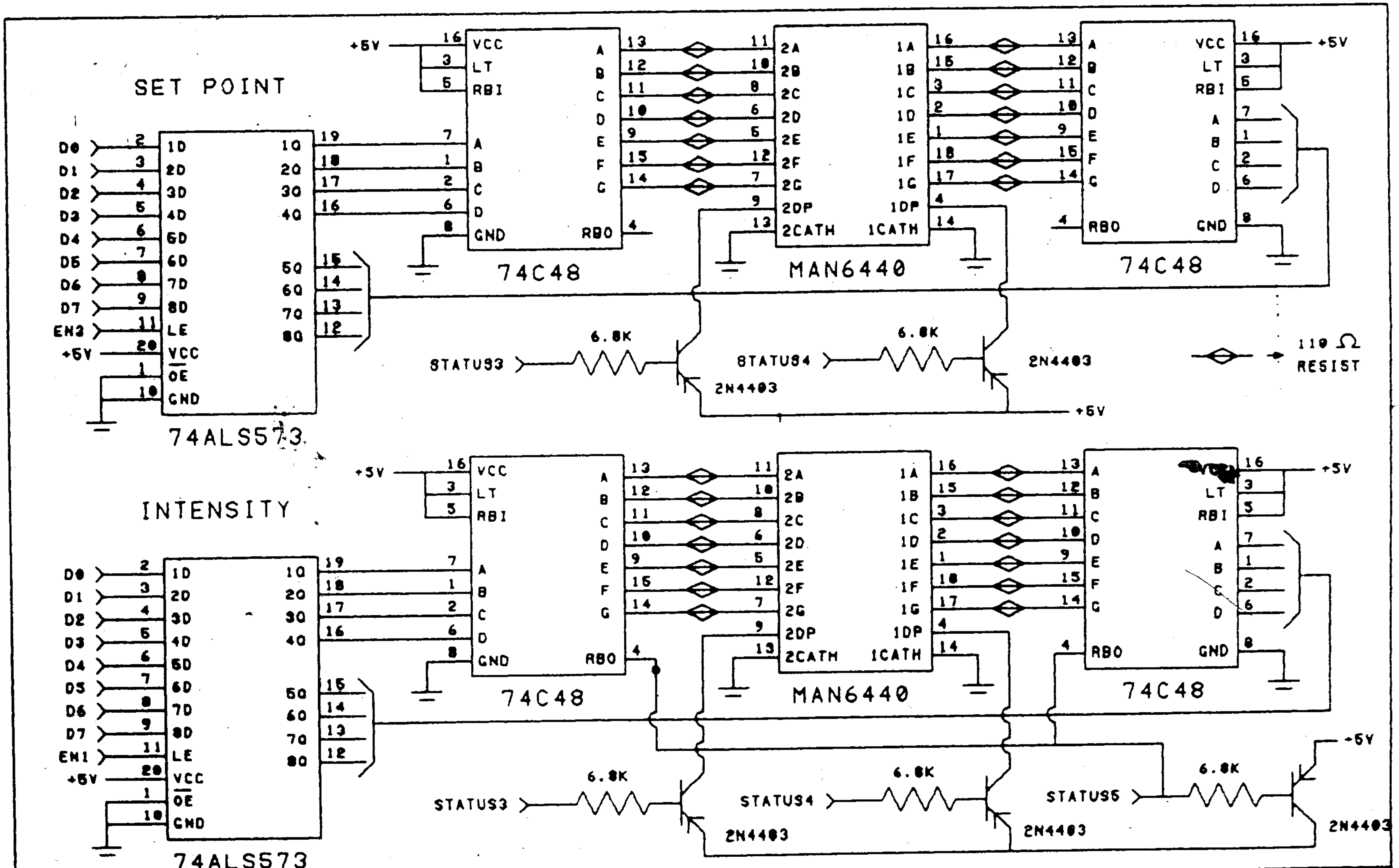
On the following pages are the schematic diagrams for the front panel, the I/O board, and the signal conditioning board.



CD4514
74LS541
74LS541
68701
4.9 MHz
46 pF (typ.)
10K (TYP)
+5V
P2
SYSRST *
TXD
RXD
GND
P3
P4
P5
P1
EN1
EN2
EN3
EN4
EN5
EN6
D0
D1
D2
D3
D4
D5
D6
D7
FRONT PANEL - A
MICROPROCESSOR, BUFFERS, AND DECODING

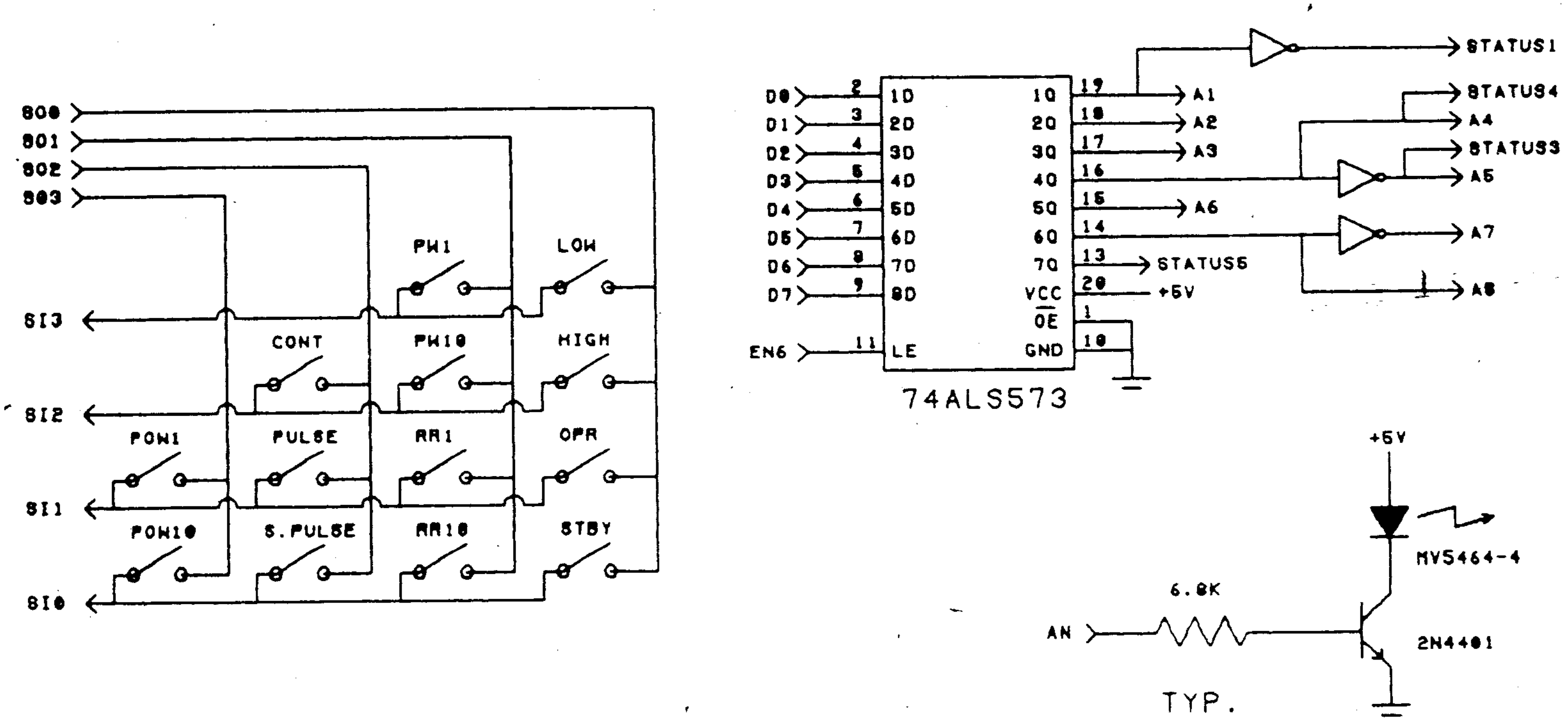

FRONT PANEL - B
LINEAR BAR GRAPH DISPLAY
AD558
VOUT
VSEN
VSEL
VCC
AGND
DGND
CE
LSB
INPUT
MSB
CS
D0
D1
D2
D3
D4
D5
D6
D7
+5V
EN2
1.0K
6.8K
2N4401
LM3914
VIN
REFOUT
VCC
MODE
RHI
REFADJ
RLO
GND
MSB
LSB
MV54164
560 Ω
200 Ω
620 Ω


FRONT PANEL - C
PULSE WIDTH AND REPETITION RATE DISPLAYS
PULSE WIDTH
REP. RATE
74ALS573
74C48
MAN6440
2N4403
6.8K
110 Ω RESIST
STATUS1
+5V
D0 D1 D2 D3 D4 D5 D6 D7
EN4
EN5
VCC
LT
RBI
RBO
GND
1CATH
2CATH
1DP
LE
OE

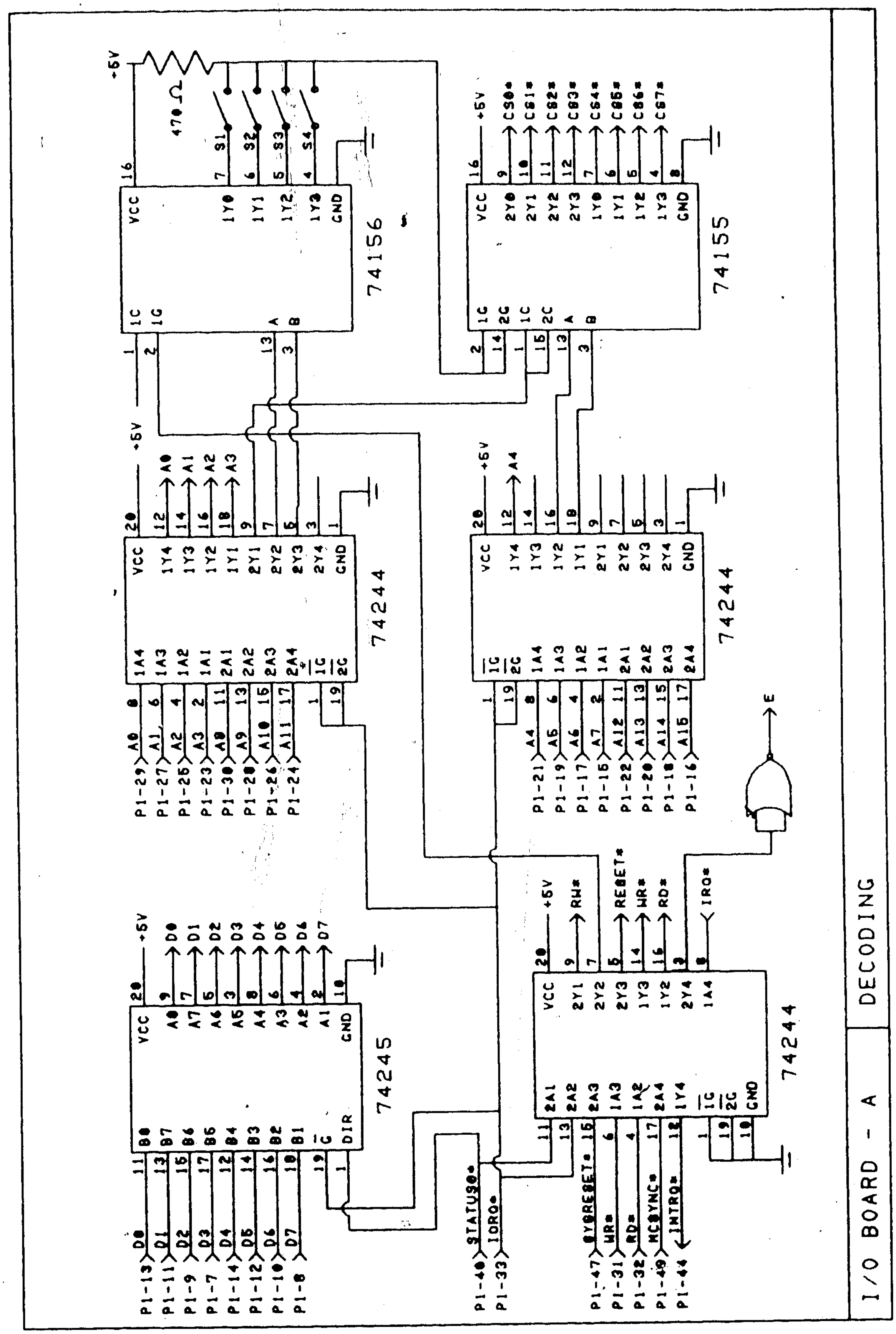


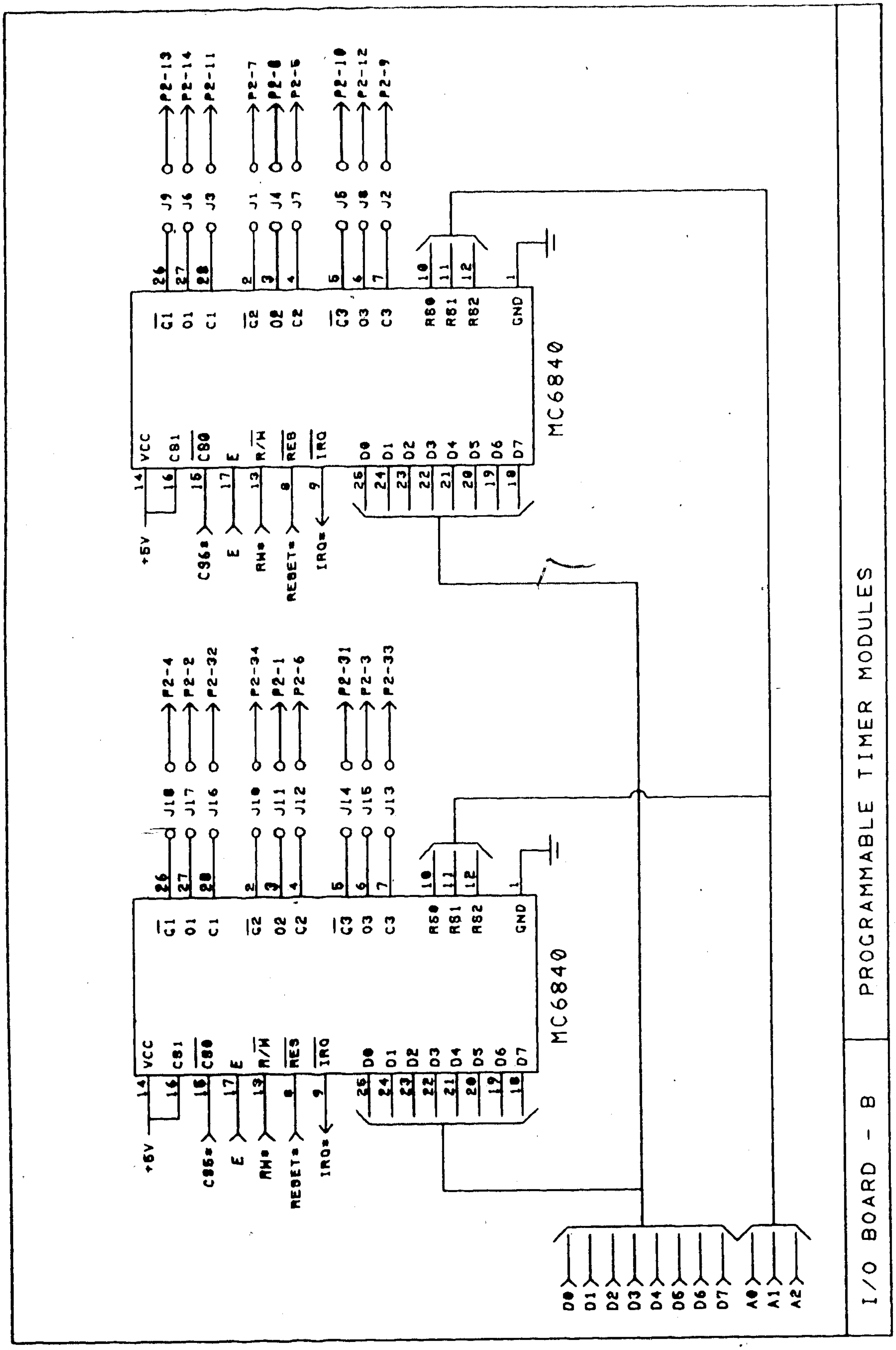
FRONT PANEL - D

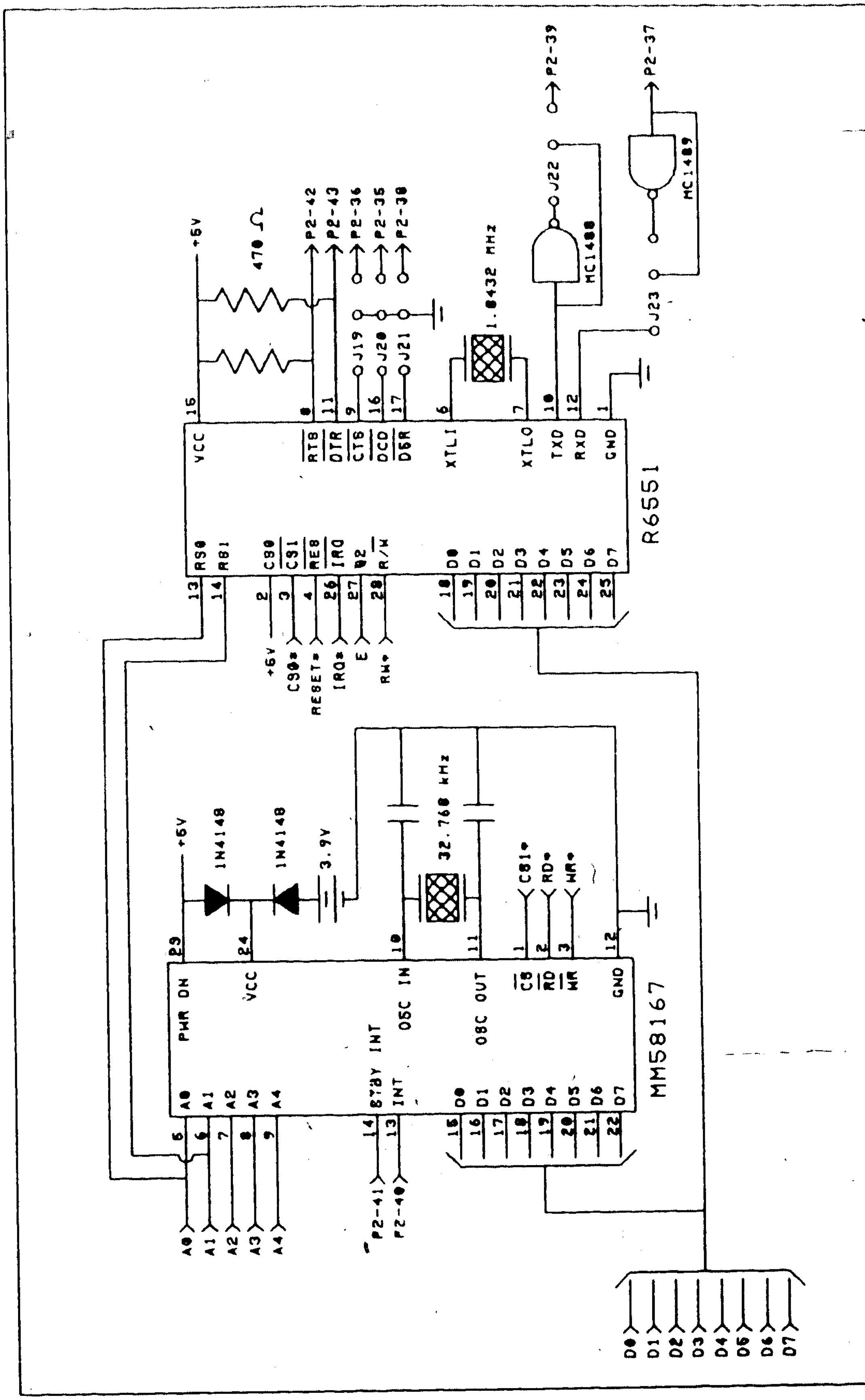
POWER SET POINT AND INTENSITY DISPLAYS



FRONT PANEL - E | SWITCH MATRIX AND STATUS DISPLAY

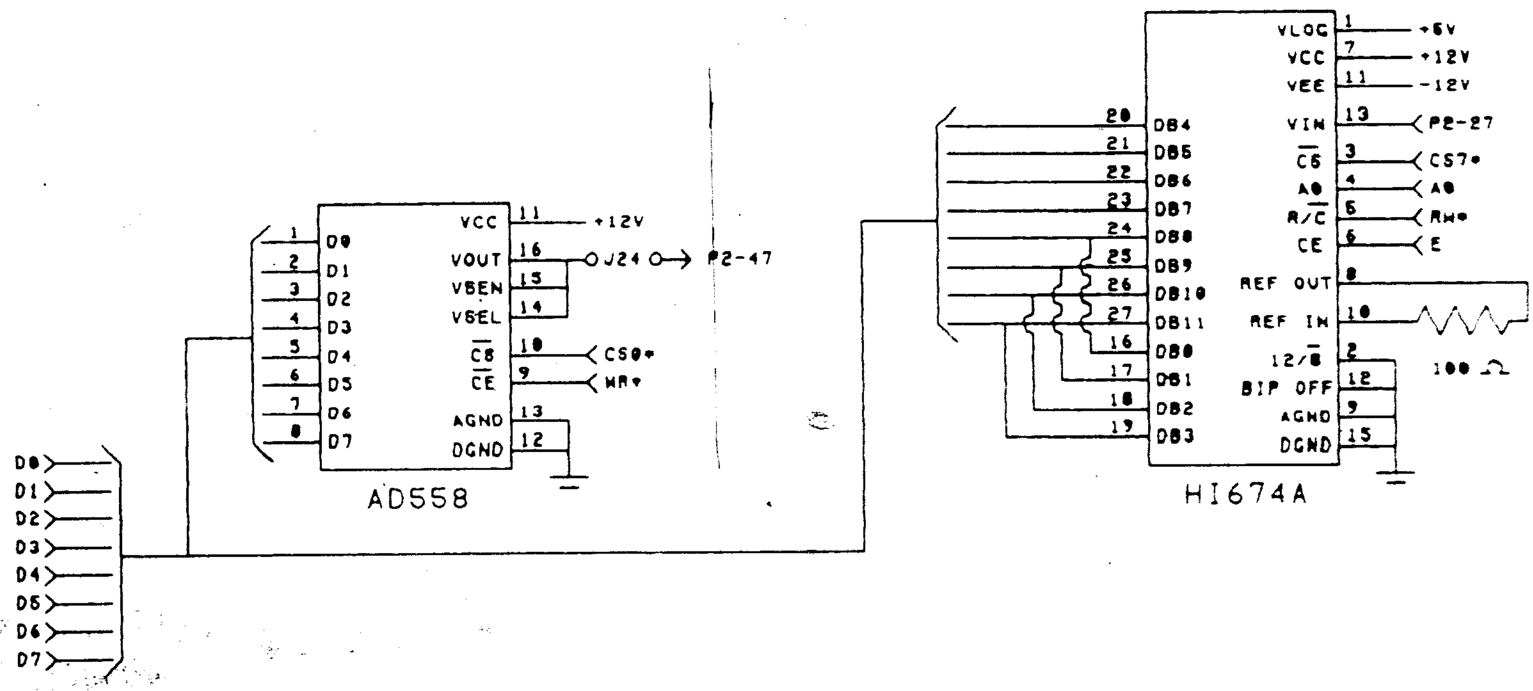

74156
74155
74244
74244
74245
74244
I/O BOARD - A
DECODING


MC6840
MC6840
VCC
CB1
CB0
E
R/W
RES
IRQ
D0
D1
D2
D3
D4
D5
D6
D7
G1
O1
C1
G2
O2
C2
G3
O3
C3
RS0
RS1
RS2
GND
+5V
CS6*
CS5*
E
RW*
RESET*
IRQ*
J1
J2
J3
J4
J5
J6
J7
J8
J9
J10
J11
J12
J13
J14
J15
J16
J17
J18
P2-13
P2-14
P2-11
P2-7
P2-8
P2-5
P2-10
P2-12
P2-9
P2-4
P2-2
P2-32
P2-34
P2-1
P2-6
P2-31
P2-3
P2-33
A0
A1
A2
I/O BOARD - B
PROGRAMMABLE TIMER MODULES



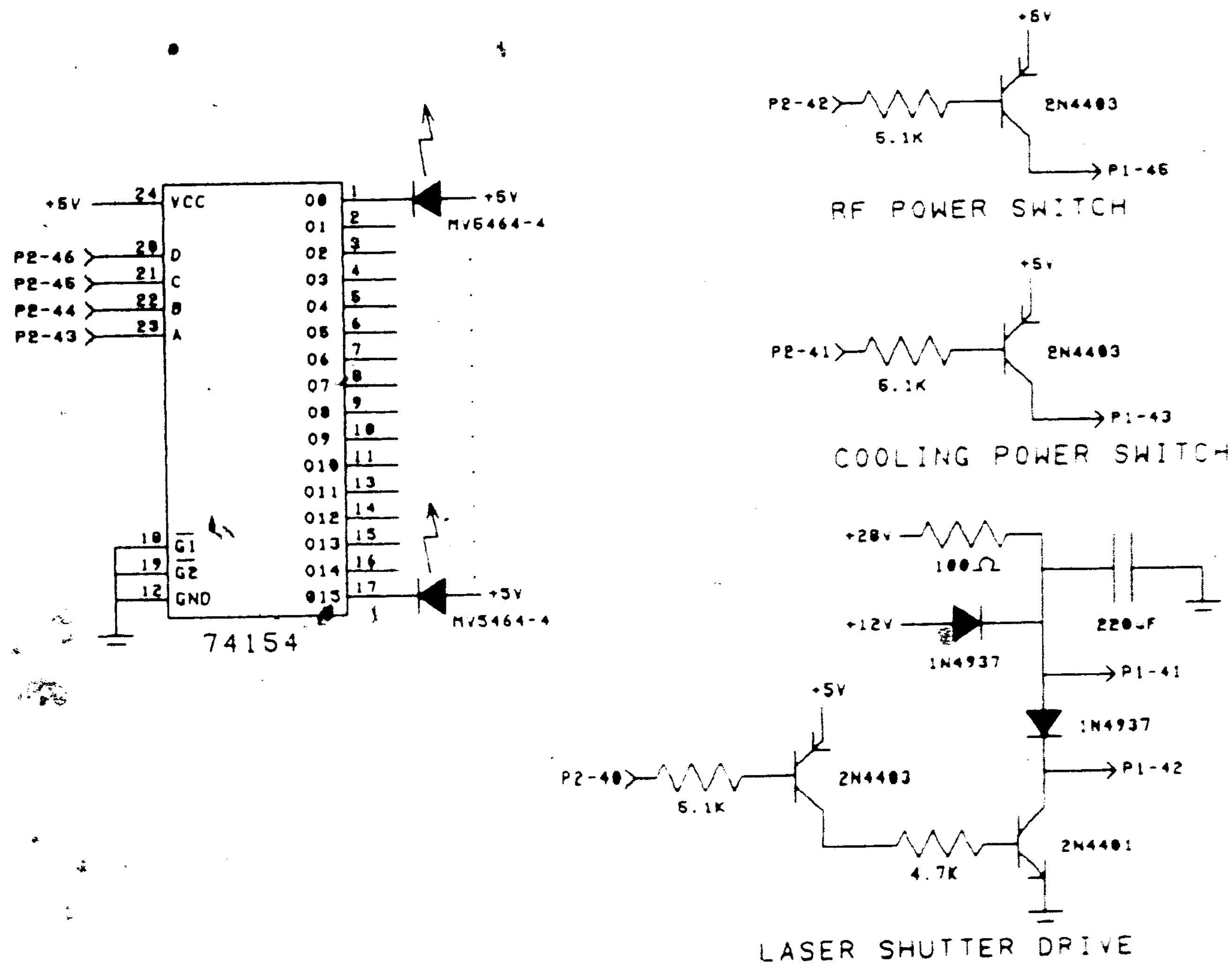
I/O BOARD - C

ACIA AND REAL TIME CLOCK

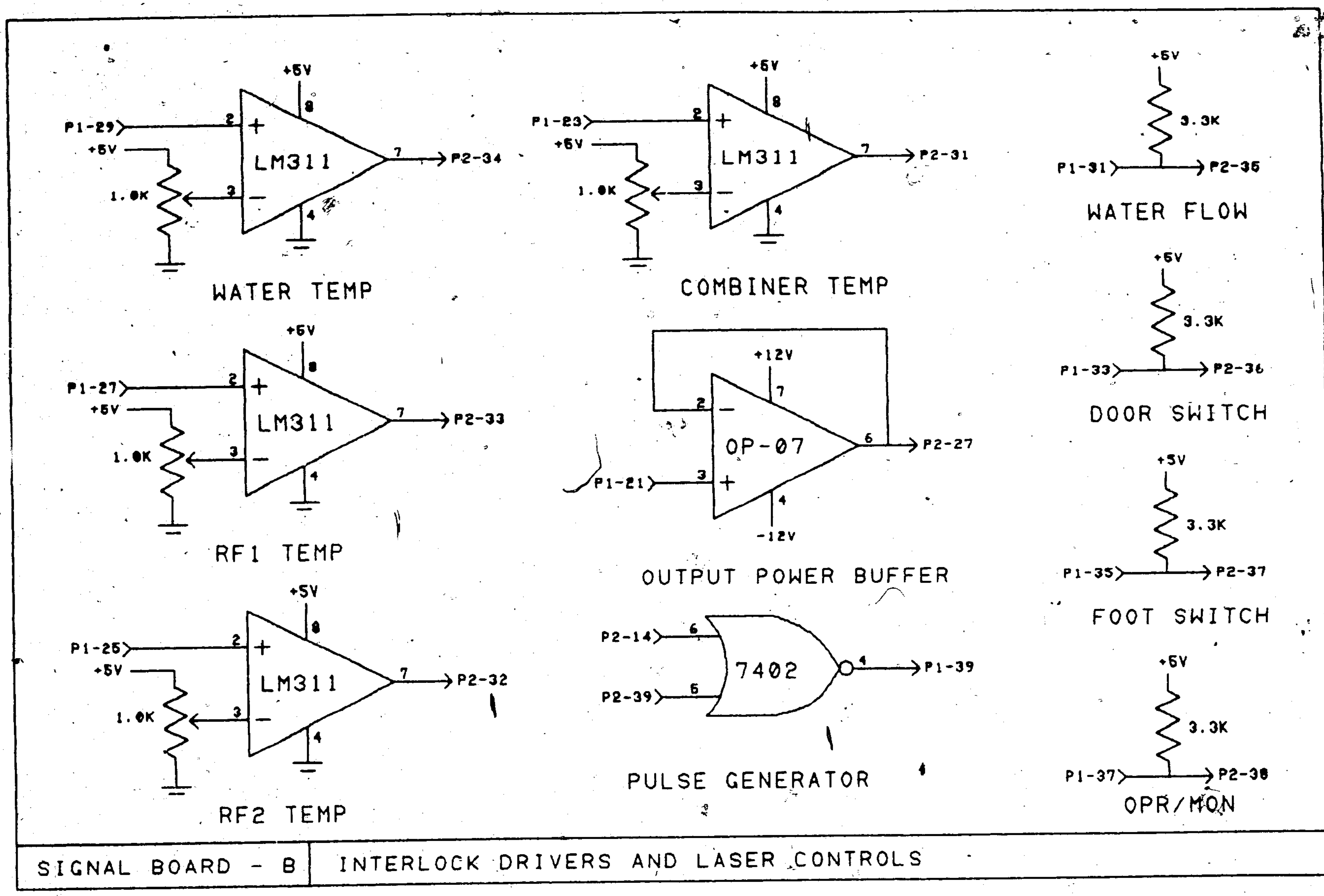


I/O BOARD - D

A-D AND D-A CONVERTERS



SIGNAL BOARD - A | ERROR DISPLAY AND CURRENT SWITCHES.



+5V
P1-29
+5V
1.0K
LM311
P2-34
WATER TEMP
P1-23
+5V
1.0K
LM311
P2-31
COMBINER TEMP
+5V
3.3K
P1-31
P2-35
WATER FLOW
+5V
P1-27
+5V
1.0K
LM311
P2-33
RF1 TEMP
+12V
OP-07
P1-21
P2-27
-12V
OUTPUT POWER BUFFER
+5V
3.3K
P1-33
P2-36
DOOR SWITCH
+5V
3.3K
P1-35
P2-37
FOOT SWITCH
+5V
P1-25
+5V
1.0K
LM311
P2-32
RF2 TEMP
P2-14
P2-39
7402
P1-39
PULSE GENERATOR
+5V
3.3K
P1-37
P2-38
OPR/MON
SIGNAL BOARD - B
INTERLOCK DRIVERS AND LASER CONTROLS