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SUMMARY

A microcomputer serves as a programmable interface between high frequency transient recorders and a digital incremental tape recorder An interactive program stored in the microcomputer permits the operator to enter various experimental parameters in response to queries from the system. The microcomputer then stores both the experimental parameters and the raw digital data on tape for later processing by a general purpose computer.

I. INTRODUCTION

As a result of recent technological advances, transient recorders (or waveform recorders) are now commercially available which permit one to acquire, digitize, and store high frequency transient signals in digital form. These instruments are quite flexible with various pre- and post-trigger options and variable sampling rates which in many cases extend to several hundred MHz.

Although the transient signal may be viewed on an oscilloscope with the aid of the transient recorder's D/A (digital to analog) converter, the principal advantage of the transient recorders lie in their ability to capture and digitize transient signals for later analysis on a digital computer Let us assume for the moment that one has the capability to transfer the digitized data from the transient recorder to a computer, where the data resides as a series of numbers, known as a time series. At this point, one is in a position to analyze the

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raw time series data by utilizing one or more powerful techniques from the well developed field of digital time series analysis [1]. Digital time series analysis is concerned with the extraction of desired information from a background of noise and unwanted signals The techniques are primarily statistical and include, for example, digital spectral analysis based on the fast-Fourier-transform [2], correlation analysis, generation of probability density functions and their moments, bispectral analysis (useful in analyzing data associated with nonlinear systems), and so on.

Given the capability of present-day transient recorders to digitize and store high frequency transient (and steady-state) data, and given the capability to apply powerful digital time series analysis techniques once the data is safely stored in the computer, the experimentalist is still faced with the problem of transferring the digitized data from the memory of the transient recorder to the digital computer. This problem is further complicated by the fact that computer programs which perform digital time series analysis not only require the raw time series data, but also calibration and experimental data such as voltage range settings on the transient recorder, sampling intervals, pre-amp gains of conditioning electronics between the experiment and the transient recorders, etc. This type of information is necessary if the results of the digital time series analysis are to be presented in terms of absolute physical units rather than arbitrary or relative units. It also is desirable that archival information, such as the date, experimental run number, experimental conditions, etc., be stored with the raw time series data and calibration data. It is the objective of this paper to describe a relatively inexpensive, simple, and flexible system that allows: (1) the transfer of experimental data from one or more transient recorders to a digital computer, (2) the entry of calibration data, and (3) the entry of important archival data.

At this point we pause to describe the specific project that motivated the work reported herein. The NASA Lewis Bumpy Torus [3] experiment employs a modified Penning discharge to produce and heat a plasma in a confining toroidal magnetic field. The strong radial electric field associated with the Penning discharge, along with the strong toroidal magnetic field, gives rise to a diversity of $E \times B$ phenomena such as rotating waves and spokes, which in turn manifest themselves as space-time fluctuations of the plasma density and potential. The objective of this work is to develop and apply a plasma fluctuation diagnostic tool based on digital spectral analysis techniques that allows one to investigate and establish the connection between wave and spoke-generated fluctuations, and radial transport across the confining magnetic fields. Since the digital spectral analysis approach described in Ref. 4 seemed to offer the best way of attacking this problem, a system had to be developed that would permit plasma density and potential fluctuation data to be digitized at frequencies up to 10 MHz, stored in permanent form along with selected experimental and archival data, and transferred to a general purpose computer. Additional objectives included keeping the system as flexible as possible while keeping the cost of both hardware and software as low as possible.

The overall approach we decided upon is shown in Fig. 1 and is discussed in detail in Sections II and III. Although the approach was developed in response to the objectives cited in the previous paragraph, it is quite general in nature and should prove useful to anyone who wishes to develop an inexpensive but flexible system for transferring data from one or more transient recorders to a digital computer. Biomation 8100 transient recorders were selected since they have a maximum sampling rate of 100 MHz. As Fig. 1 indicates, the heart of the system consists of a DEC LSI-11 microcomputer with 4k of memory. In selecting a microcomputer, we basically opted for the advantages of programmed logic versus hardwired logic; the advantages including flexibility, modularity, and expandibility. As Fig. 1 indicates, we decided to store the digital data on magnetic tape using a Kennedy 1600R incremental tape recorder. For the application considered here, incremental tape recorders possess ideal characteristics in that they are capable of preparing "computer compatible" tapes from sources of data operating at random or non-standard rates. By "computer compatible," we mean that the tapes produced by the incremental recorder can be read by standard computer tape drives as if they had been written by the computer itself. This feature means that we avoid the associated hardware and software costs that would be involved if we interfaced the LSI-11 directly to a larger computer on which the data is to be analyzed. Cost-wise the incremental recorder is relatively inexpensive since it operates at relatively low speeds and does not require any extensive and expensive memories. Utilizing a tape recorder for storage also results in the system being both more portable and self-contained.

Several advantages arise as a result of using the programmed logic of a microcomputer such as the DEC LSI-11 in the system of Fig. 1. For example, one can make use of the computing capability of the LSI-11 to do some preprocessing of the data before transferring it to magnetic tape. Such preprocessing of the data is often invaluable in making a decision to record a particular set of data or to discard it. A further advantage lies in the fact that both archival and experimental information can be entered on a keyboard by an operator and stored on magnetic tape. An interactive program stored in the LSI-11 prompts the operator to enter all requested information. This program can be modified and tailored to fit any given experimental situation. The expandibility of the system is also an important advantage For example, the system can be easily expanded to handle more transient recorders with minor modifications in hardware and software; the memory can be expanded which would permit more extensive preprocessing of the data; and various peripherals, such as floppy disks, can be easily added. A final example of the programmed logic approach lies in the fact that one has flexibility in formatting the digital tape. This is important where one may be using two or more different digital computers to read and process the data

II SYSTEM DESCRIPTION AND IMPLEMENTATION

Figure 1 shows a block diagram of the overall system. The heart of the system, an LSI-11 microcomputer, controls a Kennedy 1600R 7-track digital tape recorder and multiple Biomation 8100 A/D converters. In addition, the LSI-11 prompts the operator via the terminal and receives system parameter information via the keyboard An example of the prompting signals is given in Table I. Observing the LSI-11 as it controls the data acquisition for a typical experimental run aids in understanding the system operation.

First, the operator arms and triggers the Biomation transient recorders. At this point, the memory in the Biomations contains simultaneously sampled data from the experiment. Then the operator sits down at the console and the interactive program residing in the LSI-11, via the terminal, asks him to type in the date, run number and various experimental parameters such as, in our case, the anode voltage, anode current, magnetic field and pressure, all in appropriate units. Then the LSI-11 asks the operator for the front panel selections on the individual Biomations such as the input range setting, sample interval, gain, etc. Next, the LSI-11 writes the information on tape in the format shown in Fig. 2.

Each experimental run occupies one file on tape with four records per file. The first record contains the experimental data interactively entered by the operator. Each following record contains the numeric data from one Biomation after it has been converted to the appropriate format for the large computer used.

When the LSI-11 completes the data recording, it stops the tape deck and prompts the operator for the next experimental run.

A. DATA HANDLING HARDWARE

Figure 3 is a schematic block diagram of the data handling system A schematic diagram of the system is included as Appendix A. Figure 4 is an overall photograph of the hardware described in this paper. On the left-hand side of Fig. 4 is the hydraulically actuated probe assembly, which allows an array of three or more probes to be inserted and withdrawn from the plasma in times as short as 3/10 of a second The equipment on the bench at the left contains the dc power supply which biases the Langmuir probe, the amplifiers and filters for each of the three channels, and a signal generator and oscillator used for calibration purposes. The equipment rack on the left contains the three analog to digital converters, the oscilloscope used to display the stored data, and, at the top, the time delay generator used to trigger the biomation with a signal from the hydraulically actuated probe. The equipment rack on the right contains the magnetic tape unit, the LSI 11 microcomputer, and other necessary auxiliary equipment including power supplies, blowers, and a tape interface unit. In the foreground is the interactive terminal, the printer of which keeps a hard copy log of the system operation, and the keyboard of which provides the command and control function.

This data handling system is quite flexible, and it is capable of obtaining simultaneous signals from virtually any type of fluctuating phenomena. Its intended application, taking plasma-related data from the NASA Lewis Bumpy Torus experiment [3, 5], placed certain constraints on its design. The hot, dense plasma from which this system was designed to take measurements is subject to very strong electrostatic potential fluctuations, the RMS magnitude of which sometimes exceeds 1 kV [5]. The high plasma densities achieved in this steady-state plasma have made it necessary to probe the plasma for periods less than 1 second in order to avoid damage to the probes. The violent electrostatic potential fluctuations in the plasma give rise to three phenomena which may affect a data handling system. These include arcing to the probe and resulting large voltages and currents on the probe input circuit, intense rf emission from the plasma which can be picked up by inadequately shielded equipment in the vicinity of the plasma, and occasional large amplitude potential fluctuations which can saturate or even damage electronic components in the data handling system

Interference from rf plasma emission was eliminated by taking ordinary rf shielding precautions, including the use of coaxial cable and the placement of all components in shielded instrument racks. Dealing with voltage transients, whether due to arcing or low probability extremes of the fluctuating electrostatic potential, presented somewhat more of a problem, since the precautions required to deal with voltage spikes often lead to degradation of the frequency or amplitude response of the system. It was found, for example, that FET input stages to some instruments were not rugged enough to stand up to voltage transients, and the FET input circuits required replacement on an almost daily basis. For this reason, all components between the capacitive probes and the analog-to-digital conversion units were the older vacuum tube technology, which are much less sensitive to occasional voltage transients. The inputs of the analog-to-digital converters were protected by the vacuum tube instrumentation preceding them.

The individual components of the data handling system in Fig. 3 will now be described. The capacitive probes used in this investigation are of a type originally reported by Schmidt [6] and are identical in their geometry and frequency response characteristics with the capacitive probes described by Roth and Krawczonek [7]. The Langmuir probes used in this study were similar in their geometry and frequency response characteristics to the Langmuir probes reported in Ref. 7. The present application required a few minor modifications relative to the characteristics reported in Ref. 7. These include the strengthening of the probes by a stainless steel sleeve slipped over the outer diameter of the probes, the use of epoxy to cement this sleeve to the body of the probes and to reinforce all joints in the probes, and the use of a 0.025 cm rather than a 0.0025 cm wire at the tip of the Langmuir probe.

The probe assembly used is shown in Fig. 5, which illustrates the placement of the two capacitive and one Langmuir probes which were used to take simultaneous density and potential fluctuations in the plasma. The nature of this research into measurement of the frequency dependence of the transport in the plasma is described in Refs. 4 and 8. Figure 6 is a photograph of the hydraulically actuated probe assembly. At the right is the probe assembly shown in Fig. 5 and a long shaft leading to the aluminum airlock and the hydraulic actuation mechanism on the left-hand side of the photograph. The two cathode followers for the capacitive probes are shown on the lower left-hand side of the photograph, attached to the wood frame of the airlock support. RG 195/U teflon coaxial cable was used to connect the probes to the vacuum feedthrough and subsequently to the cathode followers. This teflon coaxial cable was chosen because of its low outgassing in the vacuum system and to minimize the total capacity of the system. The cables are connected to the probes by General RF fittings which were chosen because of their small size and relatively small mechanical inertia. At the exterior end of the probe shaft, near the left side of the photograph, is a vacuum connector which has built-in vacuum-tight coaxial feedthroughs which are used to feed the signal through the atmospherevacuum interface. Outside the vacuum system, standard BNC connectors are used throughout the rest of the system.

The next component of the data handling system is the cathode followers. These cathode followers are less sensitive to voltage transients than FET follower probes. These probes are rated by their manufacturer to have a flat frequency response beyond 300 MHz. They were used at frequencies below 10 MHz in this experiment. These probes saturate at a 1.5 volt input with a 10x attenuator, and their maximum output is 150 mV into a 50 ohm termination. The Langmuir probe is normally operated in the ion saturation regime in order to obtain a signal proportional to the plasma number density fluctuations. It is connected to a Harrison Model 6516A dc bias supply which is rated at 0 to 3000 volt dc at 6 milliamps. The positive side of this bias supply went to ground through a 1000 ohm resistor. The dc voltage appearing across this resistor is proportional to the average number density.

Tektronix Model 1121 amplifiers were used for all three probe circuits, and each had a flat frequency response to at least 10 MHz. Their maximum output was 2 volts peak-to-peak into a 93 ohm load, and they were terminated with RG 71/U (93 ohm) cables on their output side. The nominal frequency range of these amplifiers was from 5 Hz to 30 MHz.

Kron-Hite model 3200 filters in the low pass mode were used in the three probe circuits. Their frequency was set equal to the frequency corresponding to the sampling interval, which was in turn equivalent to twice the Nyquist frequency for the data being sampled. These filters have a maximum input of 3 volts RMS and a maximum output of 1.4 volts peak-to-peak. They are terminated to RG 58/U (50 ohm) cables.

The analog signals from the filters are converted into digital form by three Biomation model 8100 units which are capable of sampling up to 2048 data points at equal sampling intervals. The upper frequency capability is about 10 MHz, and for the plasma-physics investigations, sampling intervals from 1 to 5 microseconds have been used. The time base of the Biomation units 2 and 3 are slaved to that of Biomation number 1 so that all three units operate on the same time base. The three Biomations were simultaneously triggered by a signal from a time delay generator which in turn was triggered by a bounceless switch on the probe assembly when it was actuated into the plasma at the desired radial location The time delay generator was set to sample the plasma about 150 msec into the 300 msec total dwell time of the probes in the plasma. A triggering signal from the time delay generator traveled to the trigger input of the three Biomation units through three cables of equal length. The triggers were found to be simultaneous to much less than one sampling interval, as will be shown in the discussion of the calibration procedure.

The simultaneously obtained signals stored in each of the three Biomations can be examined on an oscillographic display before it is transferred to the LSI-11 unit for recording on magnetic tape. This provision was extremely helpful in monitoring the quality of the data, and in assuring that only data without obvious defects were recorded on the tape for further analysis. This analog display of the actual signal was particularly helpful in looking for signal clipping at either the top or bottom of the waveform, or for data that were anomalous because of changes in the experiment, arcing, or other instrumental problems.

This interactive data acquisition system requires several hardware interfaces between the LSI-11 microcomputer and its peripherals, the Kennedy tape deck, the terminal, and the Biomation 8100's. These are shown in the schematic diagram of Appendix A. The Biomations each have three address lines (outputs from the DRV-11 parallel interface) to select the Biomation, a Command pulse to read the Biomation data, eight data lines (inputs to the LSI-11), and a FLAG signal which indicates that the Biomation is ready. The terminal needs simply a serial interface, a DLV-11.

The Kennedy tape deck, however, has many different functions which must be performed. The tape unit must read and write data and file gaps on tape. Since the DRV-11 parallel interface's control status register (CSR) has two read/write control bits, CSR0 and CSR1, these bits are used to select the function performed by the tape deck. Other signals used for this purpose include the DATA TRANSMITTED (DX), a pulse generated when the LSI-11 reads from the DRV-11's INPUT BUFFER (INBUF), and the NEW DATA READY (NDR), pulse generated when the LSI-11 writes to the DRV-11's OUTPUT BUFFER (OUTBUF). The state of CSR1, CSR0 define the tape mode and the DX and NDR pulses provided the start pulses Table II shows the tape functions selected by these control signals.

Figure 7 shows the block diagram of the hardware interface between the tape unit and the LSI-11. The GAP DETECT OUTPUT signal, generated when the tape deck encounters a gap while reading data, goes to the LSI-11 data input bit, number 7. The software uses this fact when reading the tape to differentiate between true data and an encountered gap.

The CSR0 and CSR1 from the DRV-11 are controlled via software Using these signals to control the demultiplexor is an easy way to implement the tape controller When the LSI-11 writes to the DRV-11, it generates a NEW DATA READY pulse. CSR0 and CSR1 then route this pulse to the proper one-shot to generate the pulse required by the tape deck as a WRITE/STEP COMMAND, and EOF WRITE or an EOR WRITE When the tape interface is in mode 1, that is, CSR0 equal 1 and CSR1 equal 0, the NEW DATA READY pulse is steered to the TAPE WRITE output pin as a negative pulse. The falling edge of this pulse sets the write enable (WENB) flip-flop and resets the load forward enable (LD FWD ENB H) and reverse enable (REV ENB H) flip-flops in mode selector The rising edge of this negative pulse then triggers the WRITE/STEP COMMAND H which causes the tape deck to write one six-bit character. The pulse also generates the tape write ready (TPWRDY), which when steered by CSR0 and CSR1 through the MUX appears as RQST A H. RQST A H then shows up in the DRV-11 control status register (CSR) and the software tests this bit until the write sequencehas finished.

Writing an EOR or EOF follows much the same sequence When the interface is in mode 2, that is, CSR0 equal 0, CSR1 equal 1, the command signals steer the NEW DATA READY pulse to the output pin EOR W where it again appears as a 1 μsec negative pulse. The negative edge again sets the WENB and resets LD FWD ENB H and REV ENB H in mode selector. But the rising edge now triggers one shot, generating EOR W H which causes the tape deck to generate a 3/4 inch gap and a longitudinal check character (LCC) When in mode 2, the control signals steer the gap in progress (GIP) signal generated by the tape deck to RQST A H. When in mode 3, that is, CSR0 equal 1; CSR1 equal 1, the command sequence follows the same pattern except that the data pulse generates a $3\frac{1}{2}$ inch EOF mark on tape.

The sequence of events when the interface is in the read mode is somewhat different. When the CPU reads from the DRV-11's receive buffer, it generates a data transmitted (DATA X-MITTED) pulse. When the interface is in mode 1, the control signals steer the pulse to the output pin, tape read reset (TP RDRST). This negative pulse sets the read enable (RDEN H) and the load forward enable (LD FWD ENB H) in mode selector. This pulse also resets the tape read (TPRD) which was set either by a clock pulse or a gap detect pulse both of which the tape deck generates when reading a magnetic tape. The controls signals also steer the TPRD H signal through the MUX to RQST BH, a bit in the CSR which the software tests to detect either a new data character or a tape gap. When in mode 2, the control signals steer the DATA X-MITTED pulse to the TP STOP pin which simply stop the tape drive by resetting LD FWD ENB H and REV ENB H in mode selector. When in mode 3, the DATA X-MITTED pulse sets the REV ENB H signal which, when the LD FWD ENB H signal is set, moves the tape drive in reverse for reading purposes.

Notice that when the tape interface is in mode 0, that is, CSR0 equal 0, CSR1 equal 0, this resets the LD FWD ENB and REV ENB signals which causes the tape drive to stop. This means that the LSI-11 instruction, RESET, will disable the tape interface by resetting CSR0 and CSR1.

B. SOFTWARE ASPECTS OF THE SYSTEM

The programs written for the LSI-11 must control the Kennedy digital tape deck, display character strings to prompt the operator, receive experimental data the operator entered via the keyboard, and read the data stored in the Biomations. The complete program will be found in Appendix B. Certain utility routines which are useful in debugging programs and the overall system are listed in Appendix C.

The Kennedy 1600R digital tape deck incrementally records data at a $0 \rightarrow 300$ character/sec rate and continuously (not incrementally) reads data at 1000 characters/sec. To record data, the tape deck must be in the write mode at which time a 50 microsecond pulse on the WRITE/STEP line initiates a single step by the stepping motor and enables the write amplifier. A 50 microsecond pulse also initiates the EOF and EOR file gap commands in the unit. The procedure to read data is somewhat simpler. When the signal input LD FWD is true, the stepping motor enters a slew mode and steps at 1000 characters/sec. The internal read amplifiers then produce the data output signals accompanied by a clock pulse. Due to the slow writing speed, the time required to write the 2048 8-bit Biomation data bytes is approximately 14 seconds. Since the Biomation may be read at rates approaching 2×10^6 bytes/sec, the time required to read a Biomation is approximately 1 mS. Since the time difference between reading a Biomation and writing the data on tape is so large and since the Biomations must be read one at a time, the control policy consists of reading the 2048 data bytes from a Biomation, converting the bytes to one's complement form, then writing the bytes onto tape.

As the operator uses this system, the interactive program software prompts him by printing a block of characters which ask him to enter various experimental parameters, as shown in Table I. After all the necessary experimental data and the additional comments are typed in by the operator, this portion is recorded onto the magnetic tape followed by EOR mark.

Next, the system software reads the Biomation data, determines the minimum and maximum values and the number of times they occur. This information is printed out on the terminal, and is invaluable in terms of adjusting the input voltage range settings of the transient recorder to utilize the dynamic range of the A/D converter while at the same time avoiding saturation or clipping effects

Next, the system software converts the data from 2's complement to 1's complement, and writes the data on tape followed by an EOR. This sequence repeats for each Biomation. Then an EOF is written on tape and the system returns to the beginning of the program, and is ready for the experiment. A simplified version of the interactive program flowchart is shown in Fig. 8.

Since the LSI-11 instruction set is from the DEC PDP-11 family, we may take advantage of this most powerful and comprehensive instruction repertoire. The basic design philosophy lies in utilizing the LSI-11 instruction set to minimize the hardware effort. The instruction "Trap" [5] is used exclusively to enhance the flexibility and modularity of the system in writing the above program. That is, each independent control function constitutes one subroutine and is called by TRAP INSTRUCTION. For example, "Subroutine 0" outputs one character (6 bits) onto the magnetic tape in write mode and "Subroutine 3" writes either the end of record (EOR) mark or the end of file (EOF) on the magnetic tape and so forth. There are 40 different subroutines which include some utility routines necessary for developing the programs The main program is just the appropriate arrangement of these subroutines, and is listed in Appendix B. It is very easy to modify the program according to the different experimental environment just by rearranging these elementary different control functions (i e., subroutines in the software) It is also worthwhile to note that the above program uses only 4 K memory.

The data tape made with the above procedure is read and analyzed by a CDC 6600 computer. The program to process the experimental data is written in FORTRAN. This program is divided into two main parts; the first part is to read all the experiment parameters typed in by an operator and also the three sets of numeric data from the three different Biomation units. The parameters must also be converted into floating-point numbers because these values are used to generate the various spectra in the absolute physical scale in the second part of this program. ASC II (used in LSI-11) is also converted into Display Code (used in CDC 6600) to print all the typed-in experiment parameters and some comments. This is also done in the first part of the program The second part generates all the spectra necessary for the time-series analysis (i.e., auto power spectra, phase spectra and transport spectra, etc.). Some notes on the LSI-11 which are useful in this present application are given in Appendix D. Some operating instructions for the overall system are included in Appendix E.

III. CALIBRATION OF OVERALL SYSTEM

To insure that the entire data acquisition and processing system is functioning properly, it is necessary to calibrate the overall "system." In this context "system" refers to conditioning electronics, transient recorders, LSI-11, digital tape recorder, tape read programs, and data analysis programs on the general purpose computer.

For the system discussed in this paper, the calibration checkout is influenced very much by the applications of the system. As mentioned in the introduction, the overall system was developed to provide insight into fluctuation induced plasma transport across a confining magnetic field An essential aspect of this work involves the ability to measure the amplitude, frequency ω, and wavenumber k of each wave present in the fluctuation spectrum [4]. This can be done using classical FFT digital spectral analysis techniques [6]. Specifically, the (mean square) amplitude and frequency of each wave can be determined from the auto-power spectrum of each channel. To determine $k(\omega)$, the fluctuations are monitored at two (or more) spatial points and the phase of the cross-power spectrum between these two signals is computed. Since the value of the phase spectrum is numerically equal to the phase difference between the signals in the two channels, it is also equal to the phase shift a wave undergoes in propagating between the two spatial points. Since the computer generated phase shift is also equal to $k(\omega)\,\Delta x$, where Δx is the known distance of propagation, one can determine $k(\omega)$ directly from the phase spectrum [8].

In the approach cited above the amplitude response of each channel must be calibrated, otherwise the wave amplitudes will be in error. With respect to the measurement of $k(\omega)$, there must be no differential phase shift between channels introduced by the system, otherwise, a system differential phase shift will be added (or subtracted) to that associated with the propagating wave, thus resulting in incorrect measurements of $k(\omega)$. In other words, for this type of application, we do not care what the phase characteristics of each channel are; the important point is that they be as identical as possible.

To test the amplitude and phase response of the overall system extending from input to the conditioning electronics to the general purpose computer output, we apply known deterministic test signals to each channel. The same signal is applied to each channel through equal lengths of coaxial cable. Signals such as triangular waves and square waves are commonly used since they are rich in harmonics Knowing the peak-to-peak amplitude of the square-wave at the input to each channel, one can compute the mean square amplitude of each harmonic and compare this with the output of the auto-power spectrum which is calibrated in absolute physical units. When good agreement exists, we can then be confident that the amplitude response of each channel is correct and that, furthermore, the scaling information entered via the interactive program has been correctly read and utilized by the analysis program.

To check the differential phase response, the phase of the cross-power spectrum between channels is computed. If each channel has an identical phase response, then the phase of the cross-power spectrum will be zero at the fundamental and harmonics of the periodic wave.

Shown in Fig. 9 are the results of applying a square wave input to the three channels We only show the auto-power spectrum of Channel 1 since the auto-power spectra of Channels 2 and 3 are essentially identical. The absolute values of mean square amplitudes of the fundamental and the harmonics are in good agreement with those computed from the known amplitude of the input square wave. For the particular application which motivated this project, the phase spectrum between Channels 1 and 2, and Channels 1 and 3 are very important. Shown in Fig. 9 are the corresponding phase spectra, and we note that the phase spectrum is nearly zero at the fundamental and its harmonics. The actual differential phase shift is not identically zero, but may be safely neglected when it is small compared to the phase shift introduced by the propagating wave(s).

It has been our experience that by using identical electronics in each channel, the differential phase shift can be reduced to negligible values. It is also important that all three transient recorders be triggered and sampled simultaneously If the samples of one transient recorder are delayed τ seconds with respect to another, then a phase shift $\varphi = \omega\tau$ will be introduced. This linear phase shift is fairly easy to detect using the calibration procedure outlined in the previous paragraph. In fact, we had exactly this problem until we utilized the external clock features of the Biomation to lock the sampling times of each to a master clock.

The use of periodic deterministic test signals is a very powerful system diagnostic test. It is our practice to carry out such tests at the beginning and end of each data session. When the amplitude and phase response check out, this gives us confidence in the proper operation of the system. If, on the other hand, there is some problem indicated by either the amplitude or phase response, then it is not necessary to discard all the experimental data, since the tests indicate in a quantitative way the degree of amplitude and/or phase error, and thus appropriate corrections can be programmed into the data analysis programs. For example, this must be done when one cannot achieve perfect identical phase characteristics for two channels.

CONCLUSIONS

In concluding we would like to stress the features of this system which uses a microcomputer as a programmable interface. First, we comment on the ease with which it can be expanded. All the programs described in this paper utilize less than 4 K of memory. Expansion of the memory up to 28 K is possible and will permit detailed preprocessing of the data. Furthermore, the addition of peripherals such as a floppy disk may be easily added. Second, we stress the flexibility of such an approach. The interactive program may be easily rewritten and tailored to any specific application. Furthermore, the format in which the data is written on magnetic tape may be easily changed in order to be compatible with a variety of computer systems. Lastly, by utilizing an incremental digital tape recorder we avoid the hardware and software expense of interfacing directly to a large, general purpose computer system. Also, the inclusion of the digital tape recorder renders the system more portable and self-contained.

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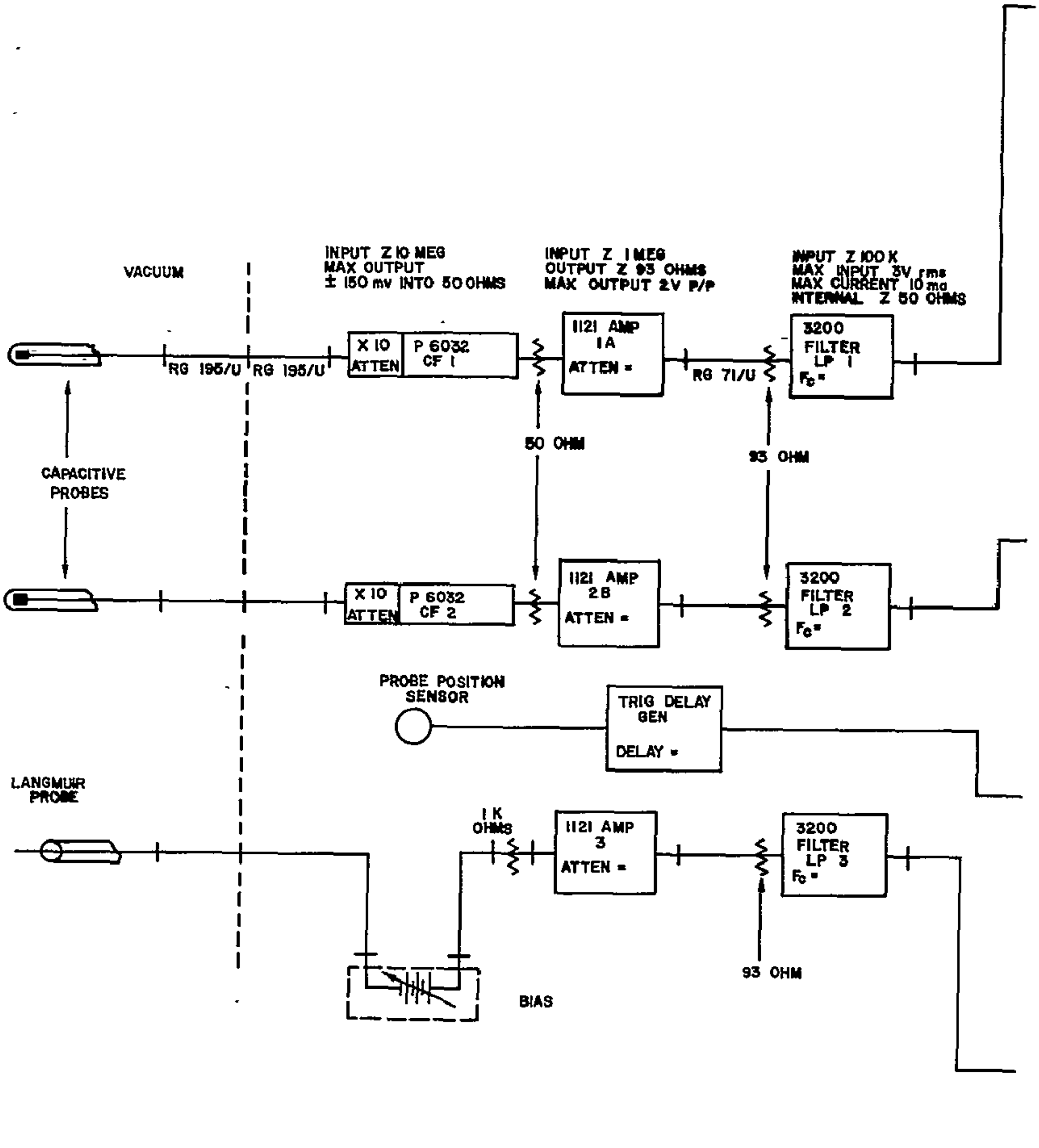
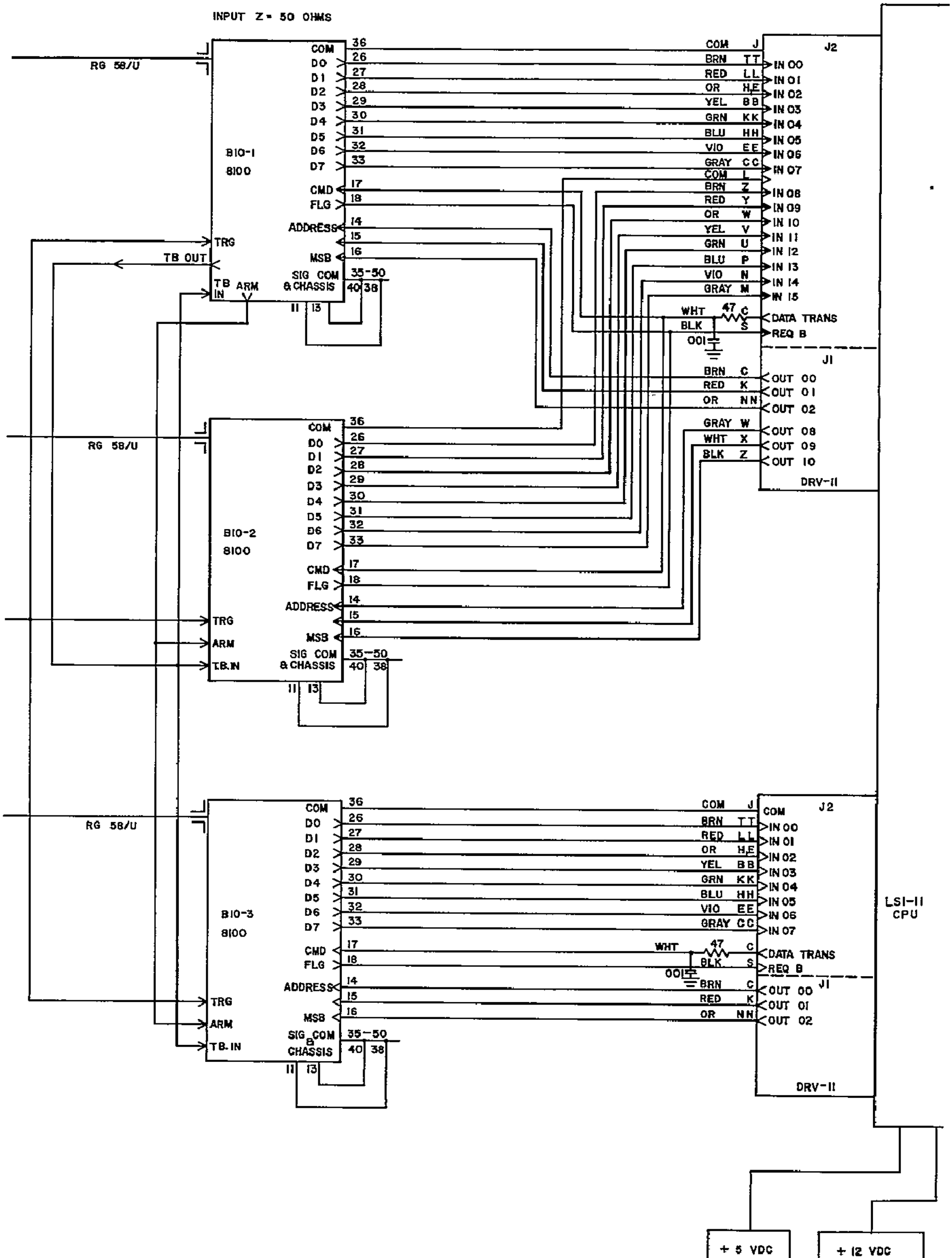
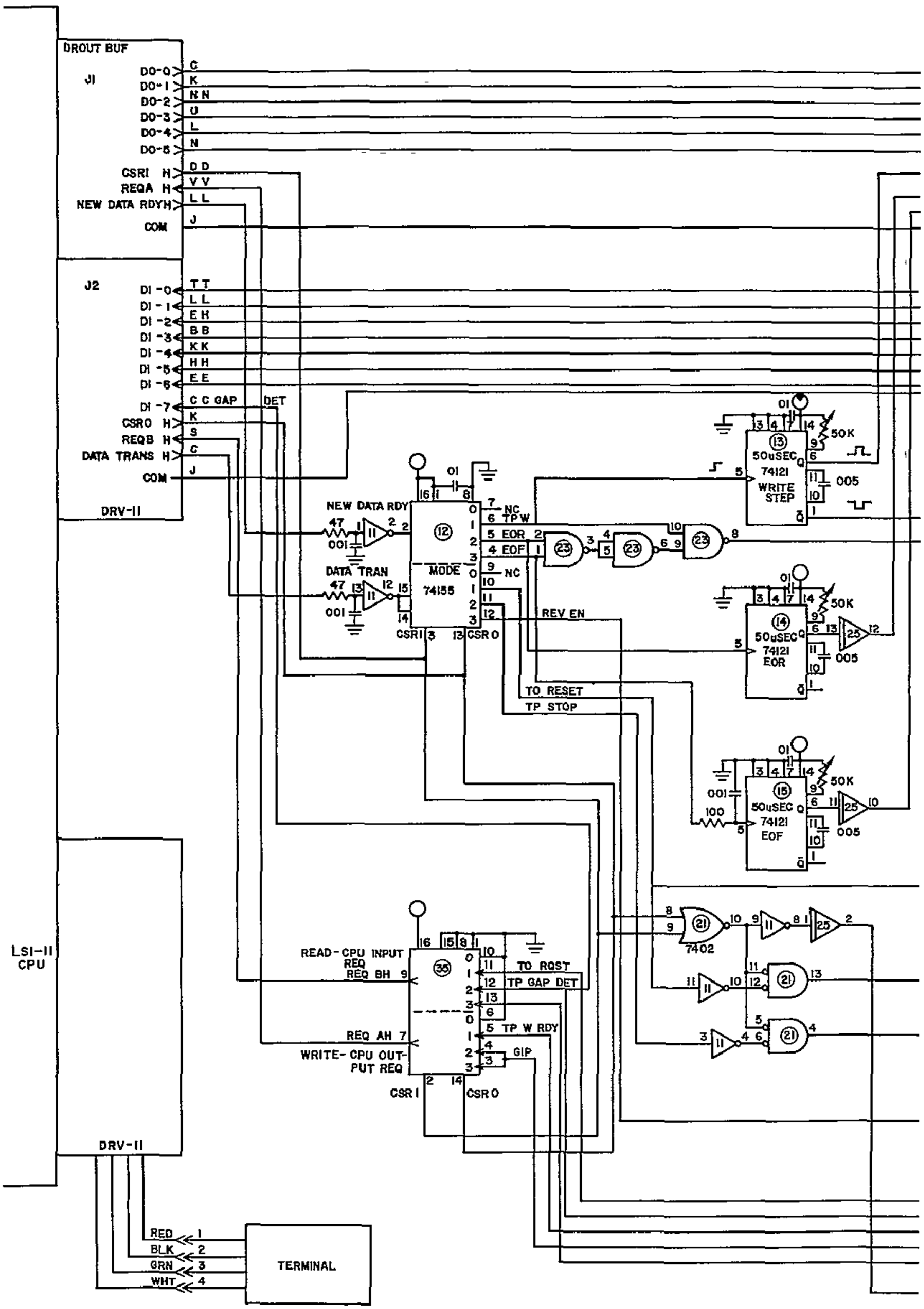
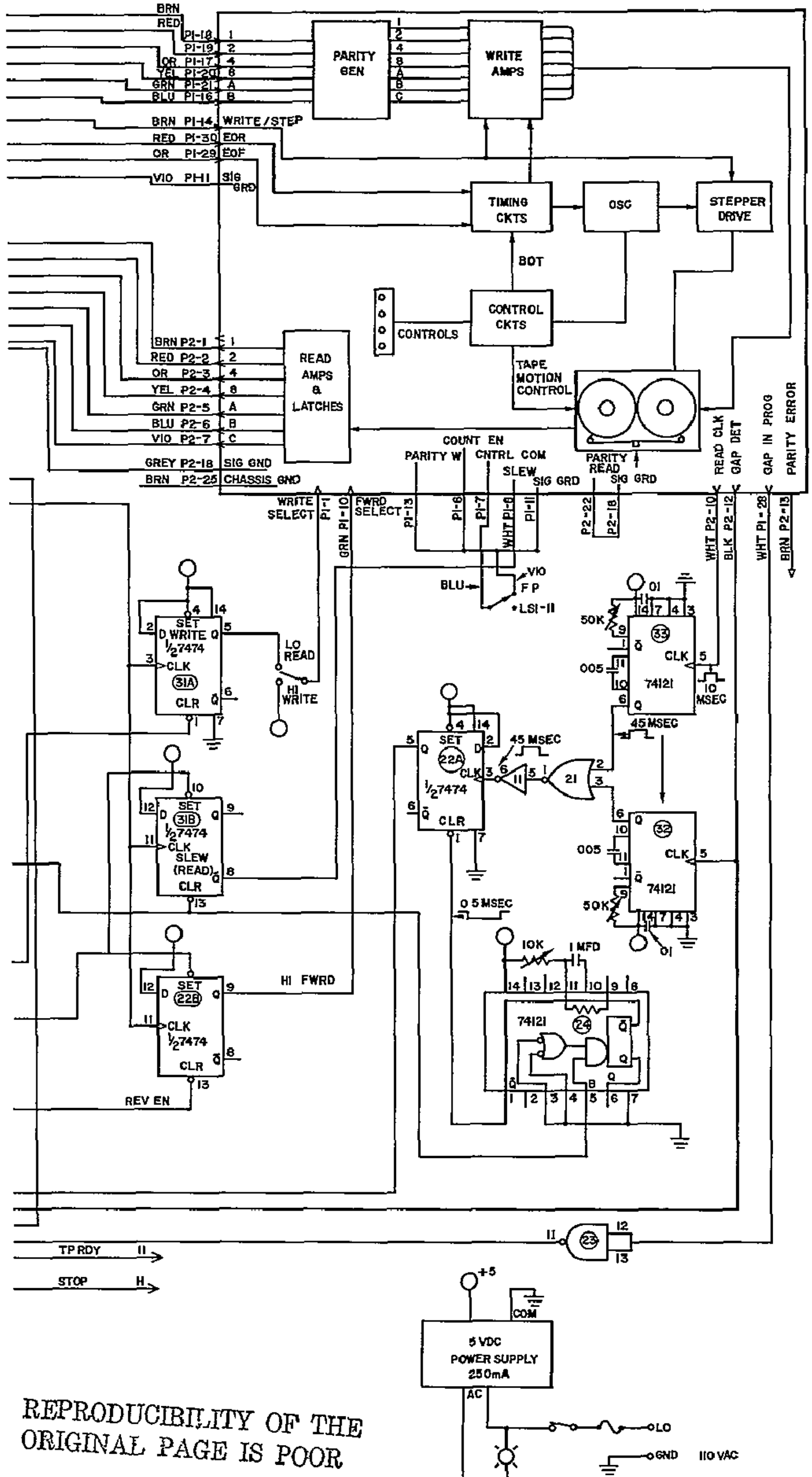
APPENDIX A




INPUT Z = 50 OHMS
RG 58/U
BIO-1
8100
BIO-2
8100
BIO-3
8100
COM
D0
D1
D2
D3
D4
D5
D6
D7
CMD
FLG
ADDRESS
MSB
TRG
TB OUT
TB IN
ARM
SIG COM & CHASSIS
35-50
40
38
11
13
J2
J1
IN 00
IN 01
IN 02
IN 03
IN 04
IN 05
IN 06
IN 07
IN 08
IN 09
IN 10
IN 11
IN 12
IN 13
IN 14
IN 15
DATA TRANS
REQ B
OUT 00
OUT 01
OUT 02
OUT 08
OUT 09
OUT 10
DRV-11
WHT
BLK
47
.001
BRN
RED
OR
YEL
GRN
BLU
VIO
GRAY
LSI-11 CPU
+ 5 VDC
+ 12 VDC



DROUT BUF
J1
DO-0
DO-1
DO-2
DO-3
DO-4
DO-5
CSRI H
REQA H
NEW DATA RDY H
COM
J2
DI -0
DI -1
DI -2
DI -3
DI -4
DI -5
DI -6
DI -7
CSRO H
REQB H
DATA TRANS H
COM
DRV-11
C
K
N N
U
L
N
D D
V V
L L
J
T T
L L
E H
B B
K K
H H
E E
C C GAP
DET
K
S
C
J
LSI-11 CPU
NEW DATA RDY
47
001
DATA TRAN
MODE
74155
NC
TPW
EOR
EOF
NC
REV EN
CSR1
CSR0
TO RESET
TP STOP
01
50K
50uSEC
74121
WRITE STEP
005
74121
EOR
74121
EOF
100
7402
READ-CPU INPUT REQ
REQ BH
REQ AH
WRITE-CPU OUTPUT REQ
TO RQST
TP GAP DET
TP W RDY
GIP
CSR 1
CSR 0
DRV-11
RED
BLK
GRN
WHT
TERMINAL



PARITY GEN
WRITE AMPS
WRITE/STEP
EOR
EOF
SIG GRD
TIMING CKTS
OSC
STEPPER DRIVE
BOT
CONTROL CKTS
CONTROLS
READ AMPS & LATCHES
TAPE MOTION CONTROL
BRN P2-1
RED P2-2
OR P2-3
YEL P2-4
GRN P2-5
BLU P2-6
VIO P2-7
GREY P2-18 SIG GND
BRN P2-25 CHASSIS GND
BRN PI-14
RED PI-30
OR PI-29
VIO PI-1
COUNT EN
PARITY W
CNTRL COM
SLEW
SIG GRD
PARITY READ
WRITE SELECT
FWRD SELECT
READ CLK
GAP DET
GAP IN PROG
PARITY ERROR
WHT P2-10
BLK P2-12
WHT PI-28
BRN P2-13
BLU
VIO
F P
LSI-II
LO READ
HI WRITE
SET
WRITE
1/2 7474
CLK
CLR
31A
31B
SLEW (READ)
22A
22B
HI FWRD
REV EN
45 MSEC
10 MSEC
0.5 MSEC
50K
005
74121
10K
1 MFD
TP RDY
STOP
+5
COM
5 VDC POWER SUPPLY 250mA
AC
LO
GND
HI
110 VAC

APPENDIX B

This Appendix is concerned with the overall Final Interactive Program. This program is built up from 32 individual subroutines. Each of the subroutines are described in detail in this Appendix. Where appropriate flow charts are also included.

TRAP HANDLER

MNEMONIC	ADDRESS	MACHINE CODE	
MOV R0,-(R6)	500	010046	
MOV 2(R6),R0		016600	2
MOVB -2(R0),R0		116000	177776
BIC #177400,R0		042700	177400
ASL R0		6300	
JSR PC, @ 530(R0)		4770	530
MOV(SP)+,R0		12600	
RTT		6	

PURPOSE:

This program calls a subroutine upon execution of the LSI-11 instruction

TRAP n

where n is the subroutine number.

COMMENTS:

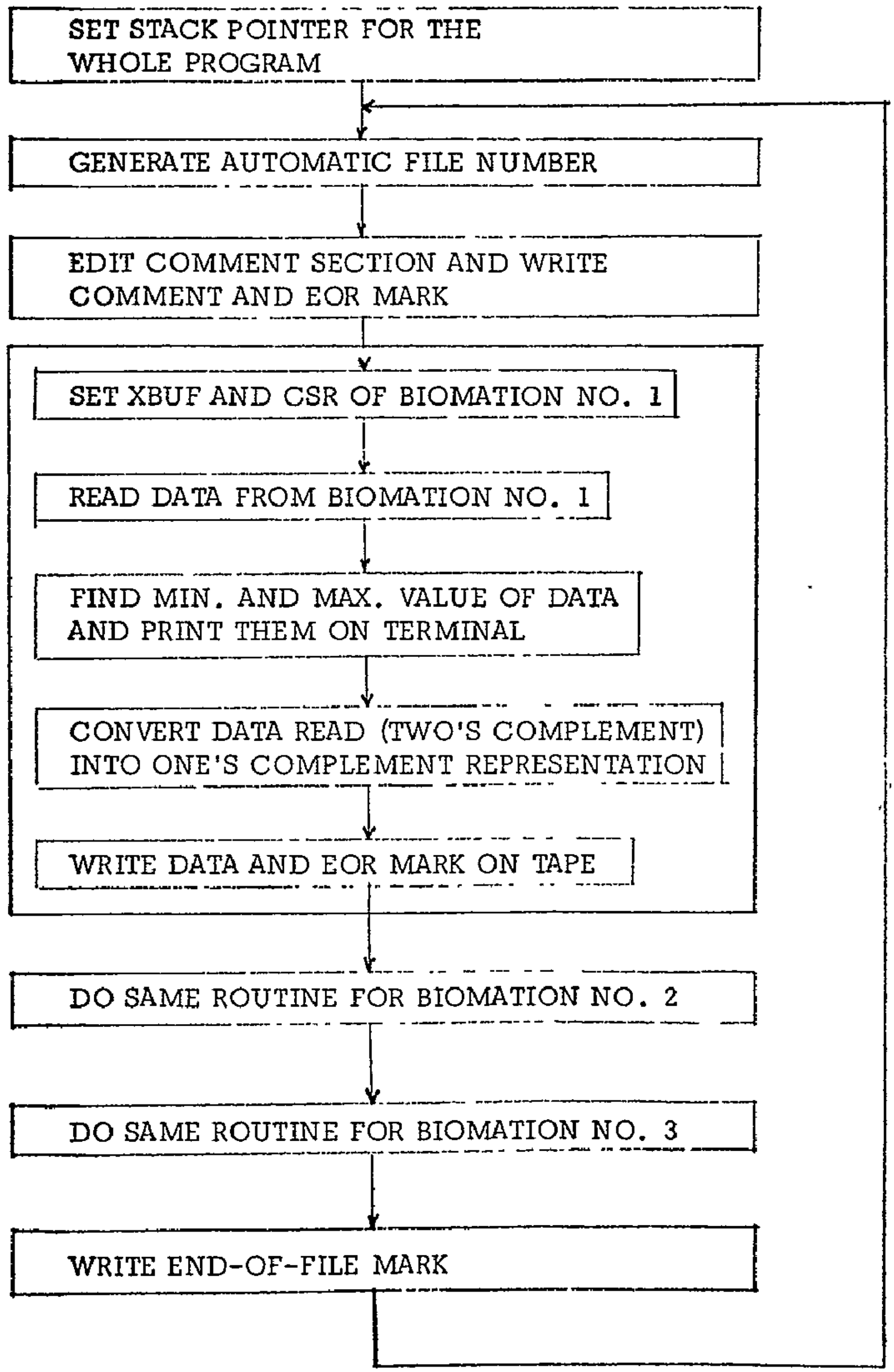
i) None of the subroutines called with the TRAP instruction may use R0 to pass parameters because R0 is changed the TRAP HANDLER.

ii) The subroutine starting addresses are listed in ascending order in consecutive memory locations starting at 530.

iii) The TRAP PC and SR are in locations 34 and 36.

SUBROUTINE STARTING ADDRESSES USED WITH THE TRAP HANDLER

MEMORY LOCATION	CONTENTS	SUB.NO.	SUB.TITLE
530	1000	0	OUTPUT TAPE CHARACTER
532	1030	1	OUTPUT TAPE BYTE
534	1070	2	OUTPUT TAPE BLOCK
536	1110	3	TAPE GAP WRITE
540	1140	4	TAPE EOR WRITE
542	1160	5	TAPE EOF WRITE
544	1200	6	INPUT CHARACTER - TTY
546	1220	7	INPUT CHARACTER + TTY
550	1230	10	OUTPUT CHARACTER - TTY
552	1240	11	OUTPUT CHARACTER + TTY
554	1250	12	MOVE BLOCK
556	1300	13	COUNT BYTES
560	1320	14	OUTPUT CR, LF - TTY
562	1350	15	INTERACTIVE PROGRAM
564	1510	16	DELETE SPACES
566	1600	17	FIND BLOCK START
570	1630	20	OUTPUT CHARACTER STRING
572	1650	21	INTERACTIVE PROGRAM II
574	2050	22	ADDITIONAL COMMENTS ROUTINE
576	2170	23	OUTPUT COMMENT RECORD
600	2300	24	WRITE BIOMATION DATA
602	2330	25	BCD TO ASCII CONVERTER
604	2350	26	BINARY TO ASCII CONVERTER
606	2510	27	SEARCH DATA
610	2630	30	PRINT MAX and MIN VALUES
612	2730	31	READ BIOMATION DATA
614	2770	32	ONE'S COMPLEMENT
616	3040	33	READ BIOMATION DATA II
620	3110	34	TEST INPUT CHARACTER
622	3200	35	TEST INPUT CHARACTER II
624	3240	36	DELAY LOOP
626	3276	37	GENERATE SAWTOOTH WAVE
630	4200	40	READ BIO. 1 WITH DELAY (TEST ROUTINE)
632	4250	41	READ BIO. 2 WITH DELAY (TEST ROUTINE)
634	4320	42	AUTOMATIC FILE NUMBER



FINAL PROGRAM

FINAL PROGRAM

MNEMONIC	ADDRESS		MACHINE CODE
MOV #13776, R6	3400/	12706	
		13776	
MOVB @#5047, R3		113703	
		5047	
SWAB R3		303	
BISB @#5050, R3		153703	
		5050	
MOV R3, -(R6)		10346	
TRAP 42		104442	
TRAP 23		104423	
MOV #167762, R5		12705	167762
MOV #167760, R4		12704	167760
TRAP 31		104431	
MOV #4, R5		12705	4
TRAP 17		104417	
TRAP 20		104420	
TRAP 27		104427	
TRAP 30		104430	
TRAP 6		104406	
TRAP 32		104432	
MOV #167762, R5		12705	167762
MOV #167760, R4		12704	167760
TRAP 33		104433	
MOV #6, R5		12705	6
TRAP 17		104417	
TRAP 20		104420	
TRAP 27		104427	
TRAP 30		104430	
TRAP 6		104406	
TRAP 32		104432	
MOV #167752, R5		12705	167752
MOV #167750, R4		12704	167750
TRAP 31		104431	
MOV #10, R5		12705	10
TRAP 17		104417	
TRAP 20		104420	
TRAP 27		104427	
TRAP 30		104430	
TRAP 6		104406	
TRAP 32		104432	
TRAP 5		104405	
BR .-33		725	

SUBROUTINE 0

OUTPUT TAPE CHARACTER

MNEMONIC	ADDRESS	MACHINE CODE	
TSTB@#167770	1000	105737	167770
BPL.-1		100375	
MOV R1,-(R6)		10146	
MOV #1000,R1		12701	1000
SOB R1,.		77101	
MOVB R5,@#167772		110537	167772
MOV(R6)+,R1		12601	
RTS,PC		207	

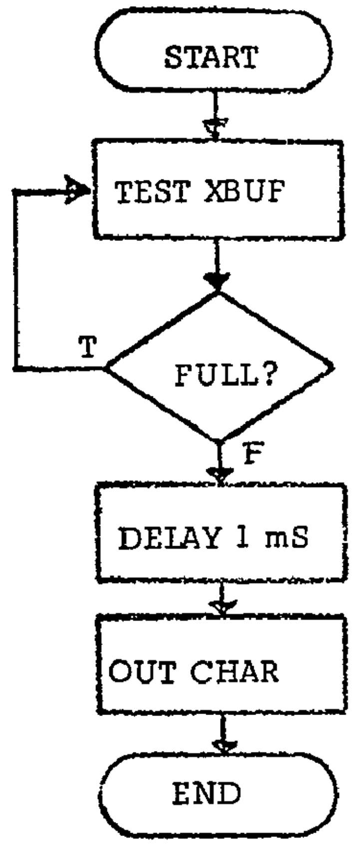
PURPOSE:

This subroutine outputs one character (6 bits) onto magnetic tape.

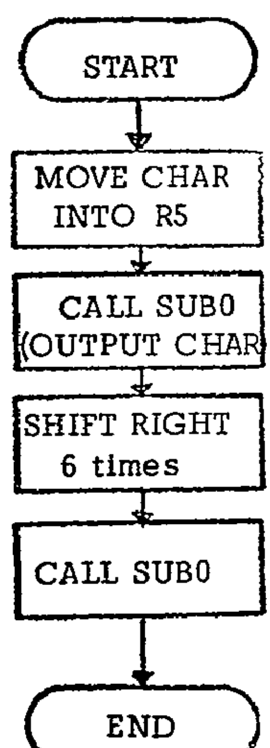
COMMENTS:

i) Assumes character in lower byte of R5.

ii) Assumes tape in write mode (mode 1).



SUBROUTINE 0



SUBROUTINE 1

SUBROUTINE 1

OUTPUT TAPE BYTE

MOV R5, -(R6)	1030	10546	
MOVB (R1), R5		111105	
MOV R1, -(R6)		10146	
MOV R5, -(R6)		10546	
MOV #6, R1		12701	6
ASRB R5		106205	
SOB R1, .-1		77102	
TRAP 0		104400	
MOVB (R6)+, R5		112605	
TRAP 0		104400	
MOV (R6)+, R1		12601	
MOV (R6)+, R5		12605	
RTC, PC	1062	207	

ASSUME: tape in write mode.
address of byte in R1.

1st Char.	7	7	7	7	7	6
2nd Char.	5	4	3	2	1	0

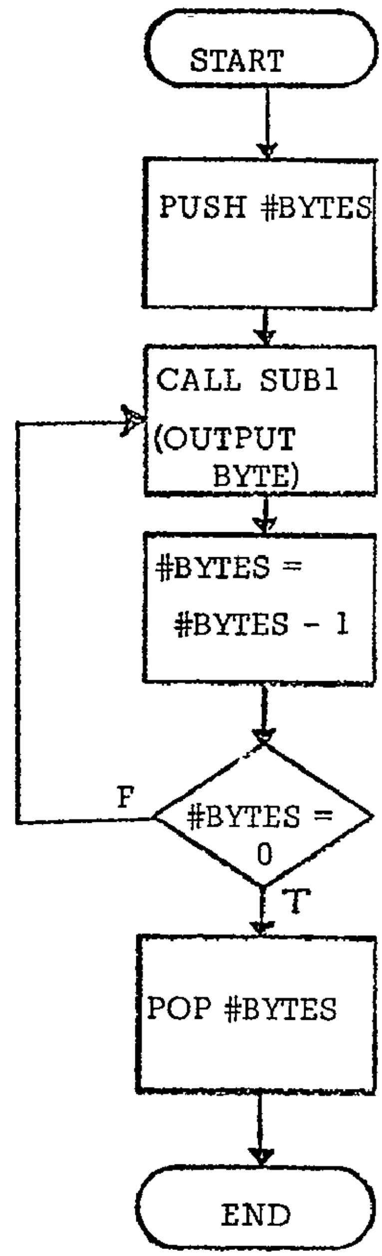
PURPOSE:

This subroutine outputs one 8-bit byte (two 6-bit characters) onto tape. The first character consists of the two most significant bits with the sign bit extended. The second character consists of the six least significant bits.

COMMENTS:

i) Assumes tape in write mode.

ii) Assumes address of the byte in R1.



SUBROUTINE 2

SUBROUTINE 2

OUTPUT TAPE BLOCK

MNEMONIC	ADDRESS	MACHINE CODE
MOV R2,-(R6)	1070	10246
NOP		240
TRAP 1		104401
INC R1		5201
SOB R2,.-2		77203
MOV(R6)+,R2		12602
RTS,PC		207

PURPOSE:

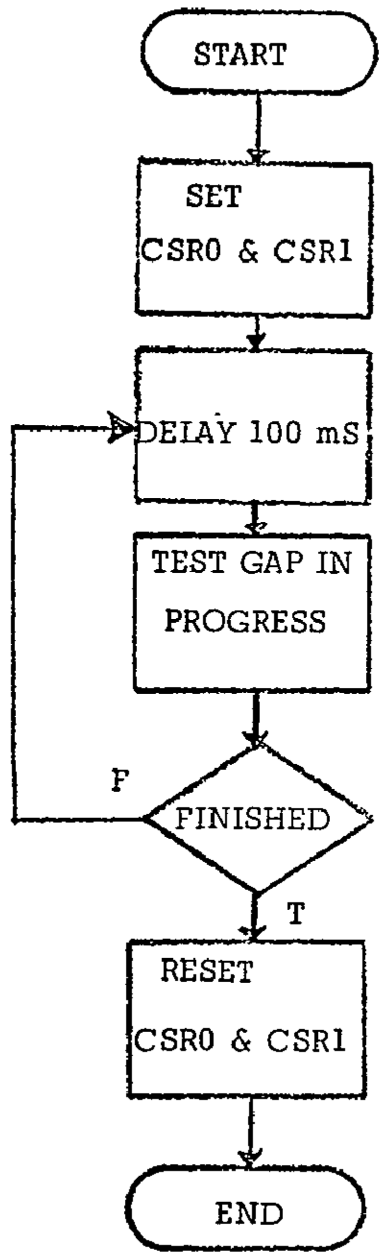
This subroutine outputs a block of memory onto tape.

COMMENTS:

i) Assumes the tape in write mode.

ii) Assumes starting address in R1.

iii) Assumes number of bytes in R2.



SUBROUTINE 3

SUBROUTINE 3

GAP WRITE

MNEMONIC	ADDRESS	MACHINE CODE	
MOV R5,@#167770	1110	10537	167770
MOV #177777,R5		12705	177777
MOV R5,@#167772		10537	167772
SOB,R5,.		77501	
TSTB@#167770		105737	167770
BPL.-1		100375	
RESET		5	
RTS,PC		207	

PURPOSE:

This subroutine writes either an EOR or EOF on tape.

COMMENTS:

i) To write EOR, put 2 into R5 then call the subroutine.

ii) To write EOF, put 3 in R5.

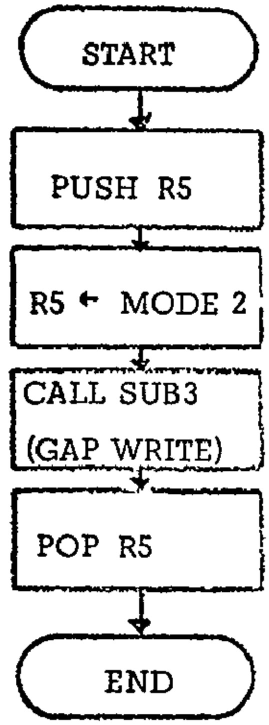
SUBROUTINE 4

END OF RECORD WRITE

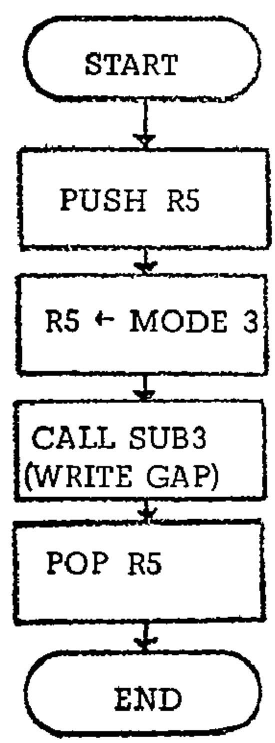
MNEMONIC	ADDRESS	MACHINE CODE	
MOV R5,-(R6)	1140	10546	
MOV #2,R5		12705	2
TRAP 3		104403	
MOV (R6)+,R5		12605	
RTS,PC		207	

PURPOSE:

This subroutine writes an EOR on tape.



SUBROUTINE 4



SUBROUTINE 5

SUBROUTINE 5

END OF FILE WRITE

MNEMONIC	ADDRESS	MACHINE CODE	
MOV R5,-(R6)	1160	10546	
MOV#3,R5		12705	3
TRAP 3		104403	
MOV (R6)+,R5		12605	
RTS, PC		207	

PURPOSE:

This subroutine writes an EOF on tape.

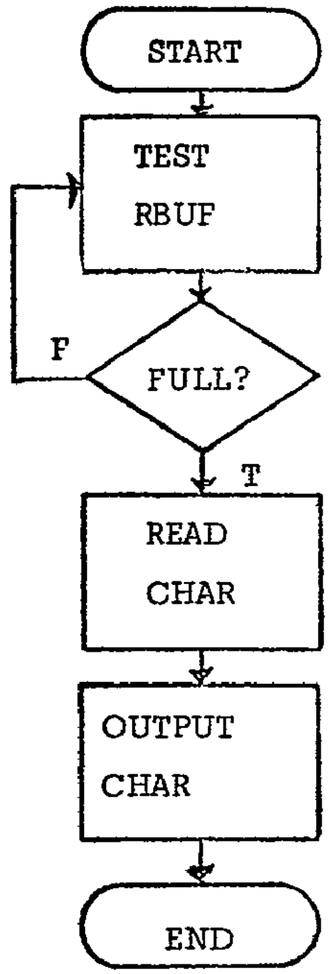
SUBROUTINE 6

INPUT CHARACTER - TTY

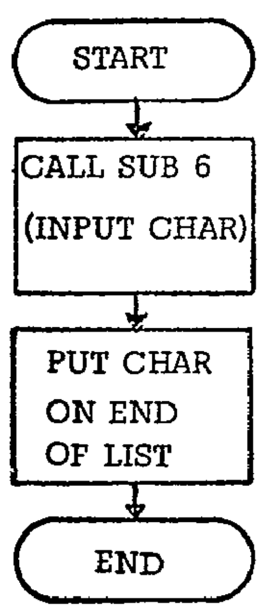
MNEMONIC	ADDRESS	MACHINE CODE		
TSTB@#177560	1200	105737	177560	
BPL.-1		100375		
TRAP 10		104410		
MOVB@#177562,@#177566		113737	177562	177566
RTS,PC		207		

PURPOSE:

This subroutine reads an ASCII character from the keyboard and echo prints it.



SUBROUTINE 6



SUBROUTINE 7

SUBROUTINE 7

INPUT CHARACTER + TTY

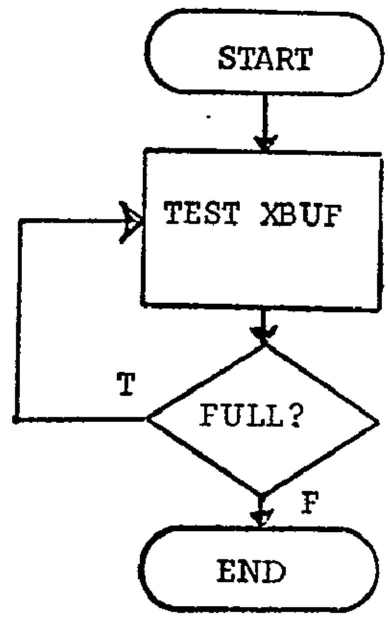
MNEMONIC	ADDRESS	MACHINE CODE	
TRAP 6	1220	104406	
MOVB@#177562,(R2)+		113722	177562
RTS,PC		207	

PURPOSE:

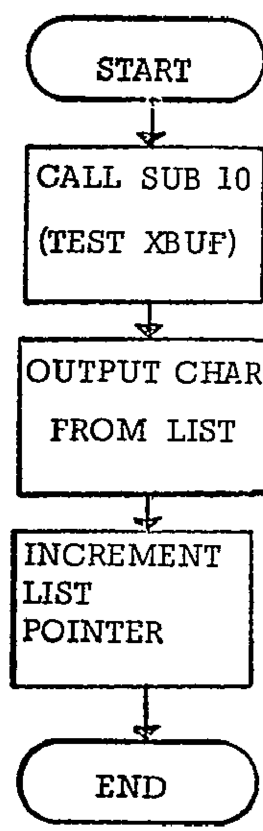
This subroutine reads a character from keyboard and puts it in the address specified by R2. It then increments R2.

COMMENTS:

1) Used to input a character string.



SUBROUTINE 10



SUBROUTINE 11

SUBROUTINE 10

OUTPUT CHARACTER - TTY

MNEMONIC	ADDRESS	MACHINE CODE	
TSTB@#177564	1230	105737	177564
BPL.-1		100375	
RTS		207	

PURPOSE:

This subroutine tests the TTY until it is ready to print another character.

SUBROUTINE 11

OUTPUT CHARACTER + TTY

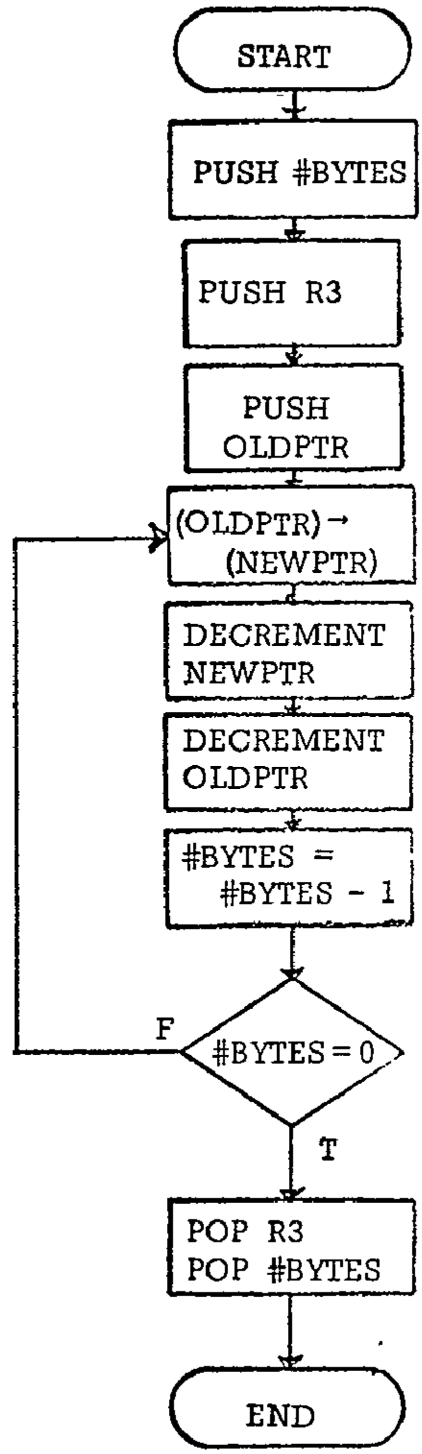
MNEMONIC	ADDRESS	MACHINE CODE	
TRAP 10	1240	104410	
MOVB(R2)+,@#177566		112237	177566
RTS, PC		207	

PURPOSE:

This subroutine prints the ASCII character whose address is in R2, then increments R2.

COMMENTS:

1) Used to print a character string.



SUBROUTINE 12

SUBROUTINE 12

MOVE BLOCK

MNEMONIC	ADDRESS	MACHINE CODE
ADD R1,R2	1250	60102
MOV R1,-(R6)		010146
MOV R3,-(R6)		010346
MOV R2,R3		010203
MOVB -(R2),(R3)		114213
DEC R3		5303
SOB R1,.-2		77103
MOV (R6)+,R3		12603
MOV (R6)+,R1		12601
RTS,PC		207

PURPOSE:

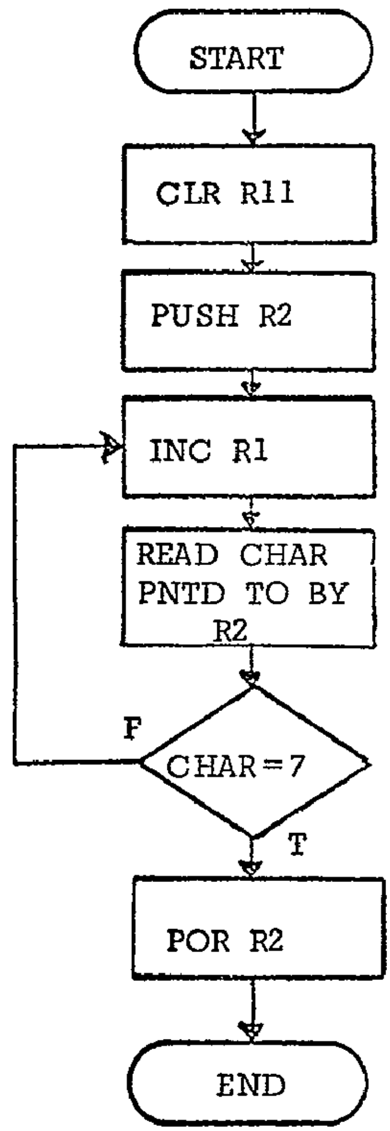
This subroutine moves memory byte by byte forward in memory.

COMMENTS:

i) Assumes starting address in R2.

ii) Assumes number of bytes in R1.

iii) Used to insert a character into a list.



SUBROUTINE 13

SUBROUTINE 13

COUNT BYTES

MNEMONIC	ADDRESS	MACHINE CODE	
CLR R1	1300	5001	
MOV R2,-(R6)		10246	
INC R1		5201	
CMPB (R2)+,#7 (BEL)		122227	7
BNE.-2		1374	
MOV(R6)+,R2		012602	
RTS,PC		207	

PURPOSE:

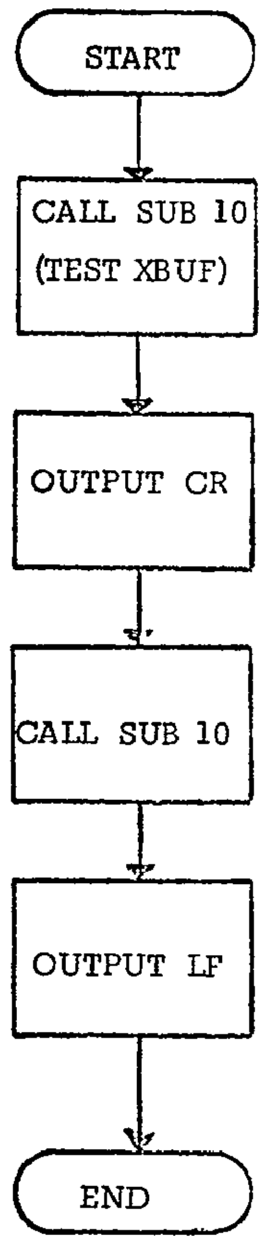
This subroutine counts the number of bytes from the current position in the list (pointer in R2), to the end character.

COMMENTS:

i) List pointer in R2.

ii) End of list character is CTRL G (ASCII 007) on keyboard.

iii) Used to find the length of the remainder of the list.



SUBROUTINE 14

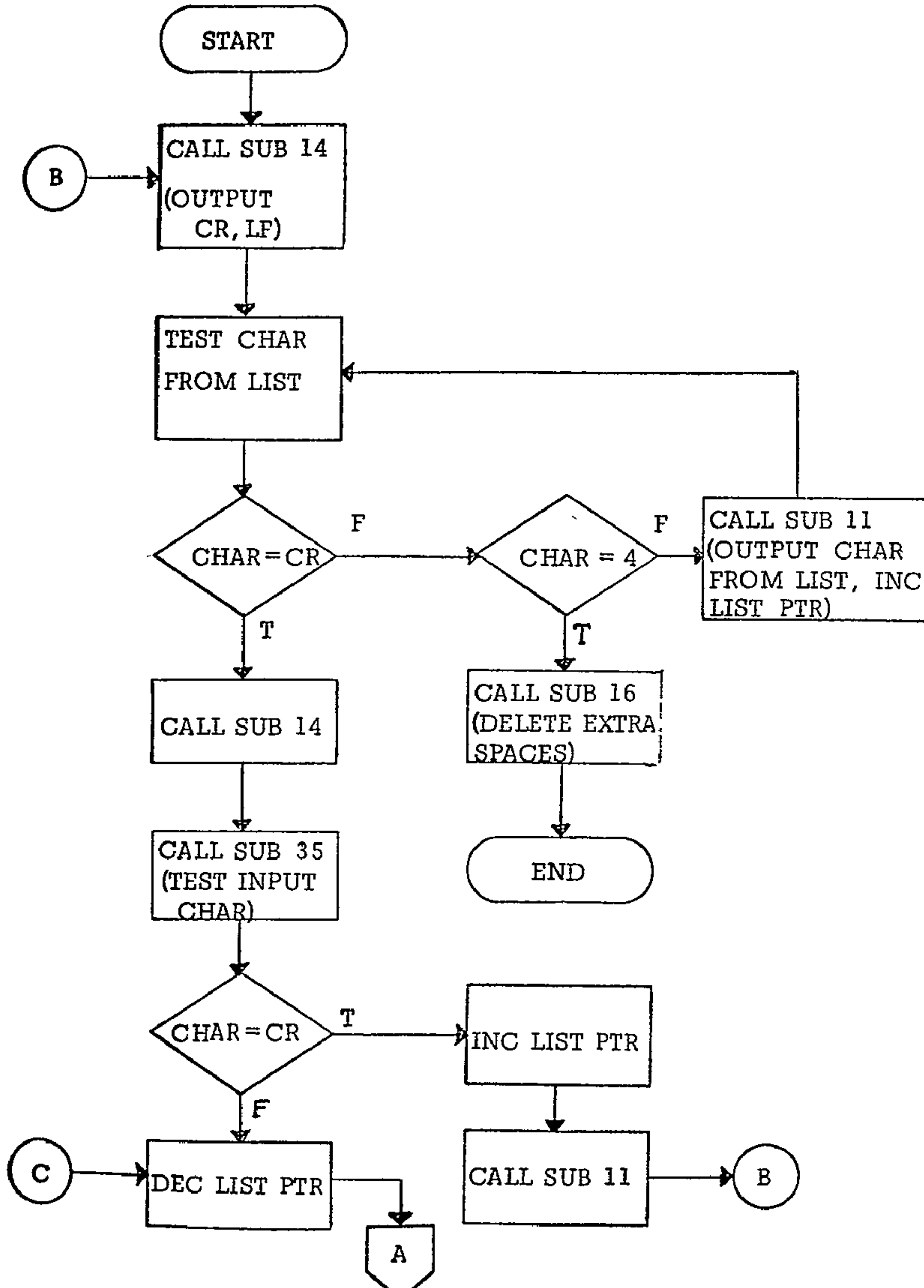
SUBROUTINE 14

OUTPUT CR, LF TO TTY

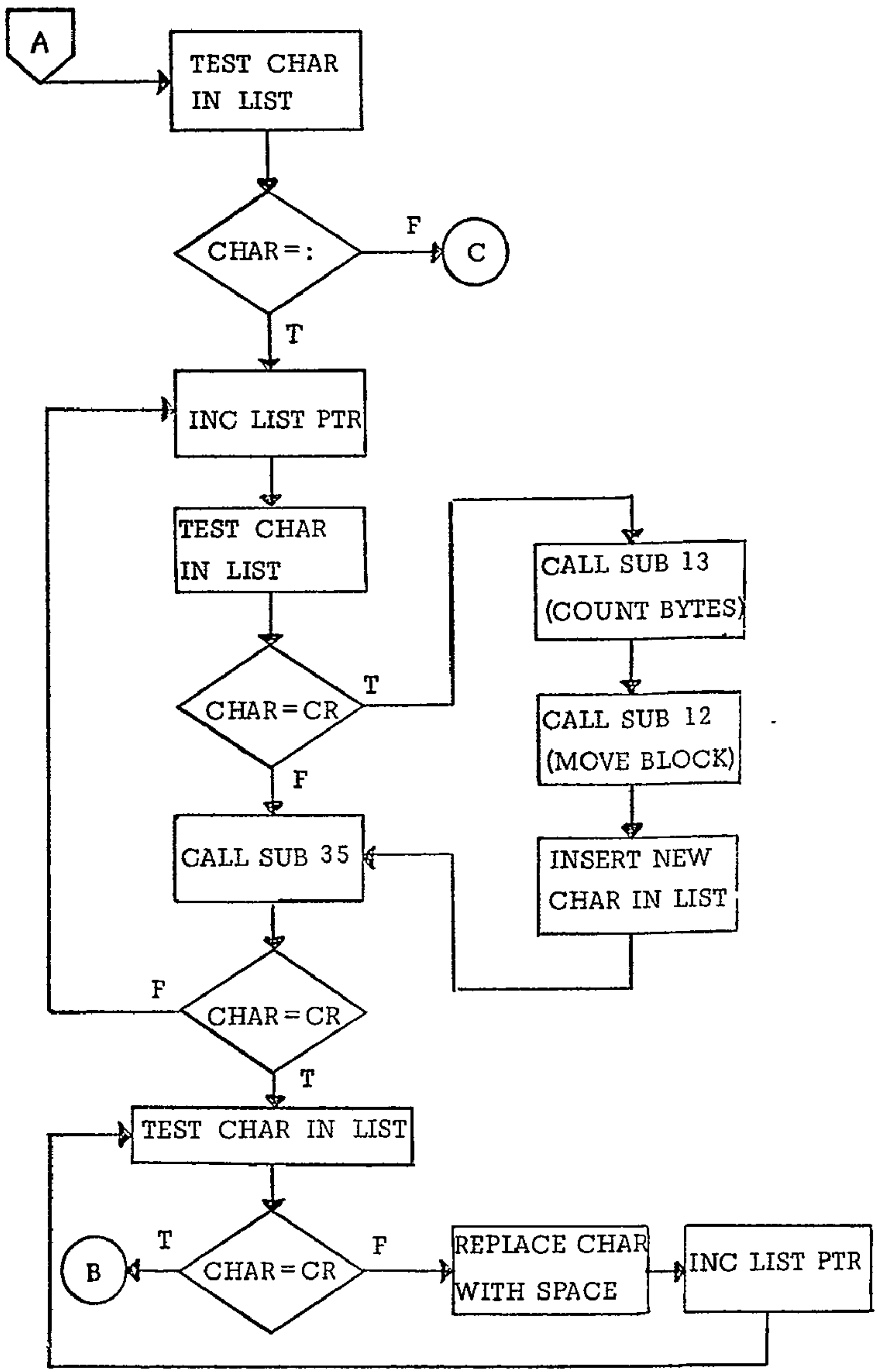
MNEMONIC:	ADDRESS	MACHINE CODE		
TRAP 10	1320	104410		
MOVB#15,@#177566		112737	15	177566
TRAP 10		104410		
MOVB#12,@#177566		112737	12	177566
RTS,PC		207		

PURPOSE:

This subroutine outputs a CR, LF to TTY.



SUBROUTINE 15 p. 1



SUBROUTINE 15 (Continued)

SUBROUTINE 15

INTERACTIVE PROGRAM

MNEMONIC	ADDRESS	MACHINE CODE		
TRAP 14	1350	104414		
CMPB(R2),#15		121227	15	
BEQ,.+7		1407		
CMP B(R2),#4		121227	4	
BNE.+3		1002		
TRAP 16		104416		
RTS,PC		207		
TRAP 11		104411		
BR.-7		766		
BR.+19		440		
CMPB@#177562,#15		123727	177562	15
BNE.+4		1003		
INC R2		5202		
TRAP 11		104411		
BR.-6		767		
CMPB -(R2),#72(:)		124227	72	
BNE.-1		1375		
INC R2		5202		
INC R2		5202		
CMPB(R2),#15		121227	15	
BNE.+3		1002		
TRAP 13		104413		
TRAP 12		104412		
MOVB@#177562,(R2)+		113722	177562	
TRAP 35		104435		
CMPB@#177562,#15		123727	177562	15
BEQ.+2		1401		
BR.-8		763		
CMPB(R2),#15		121227	15	
BEQ.+3		1403		
MOVB#40,(R2)+		112722	40	
BR.-3		772		
BR.-20		744		
TRAP 14		104414		
TRAP 35		104435		
BR.-22		735		

SUBROUTINE 15 (Continued)

PURPOSE:

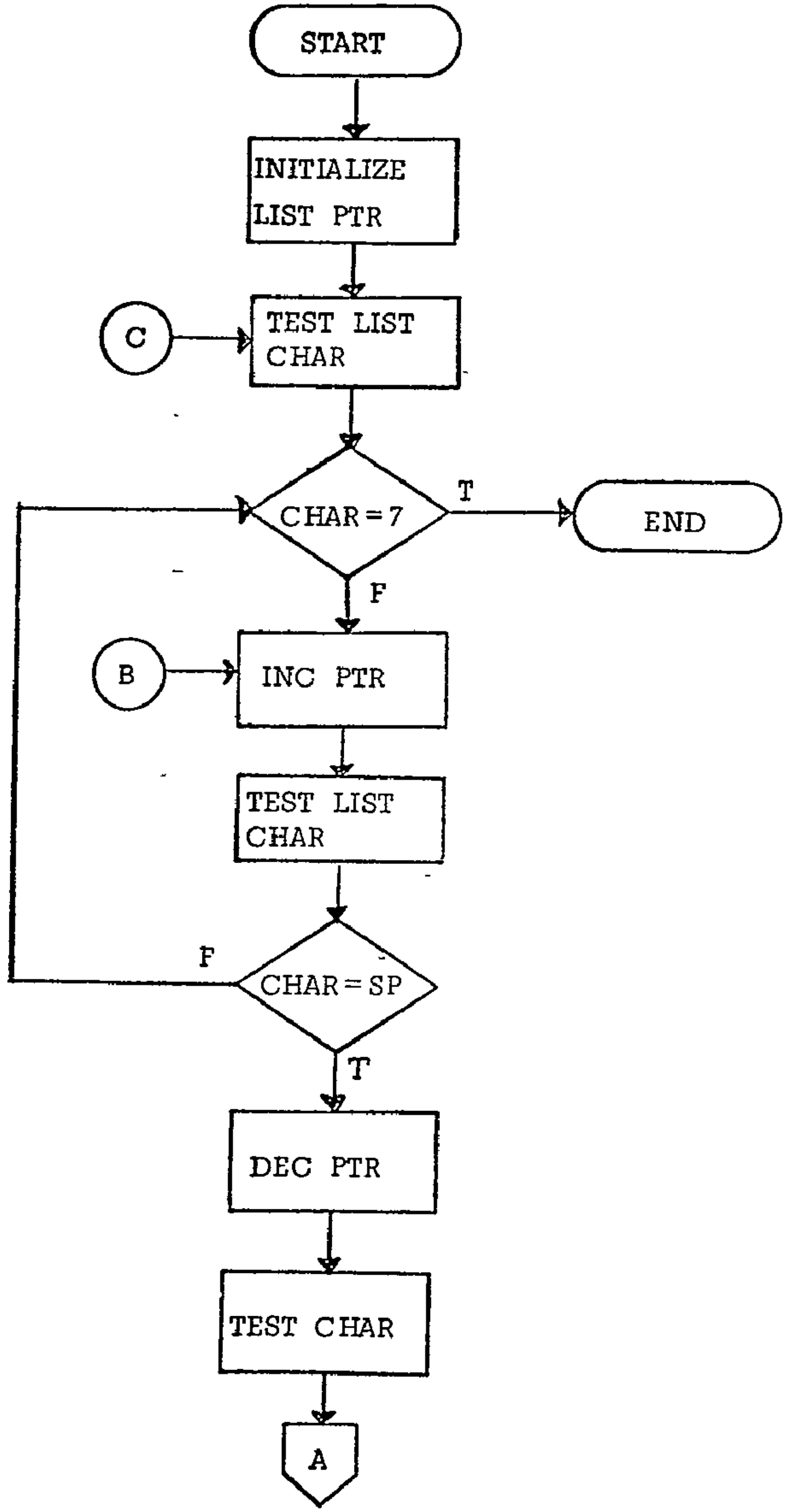
This subroutine outputs a character string from a list until it encounters a CR, then it waits on the operator to input character until he enters a CR. This continues until an EOT (ASCII 004) is encountered in the list. If the operator enters any character other than a CR, the character string after the last colon is deleted and the incoming character string is inserted into the list.

COMMENTS:

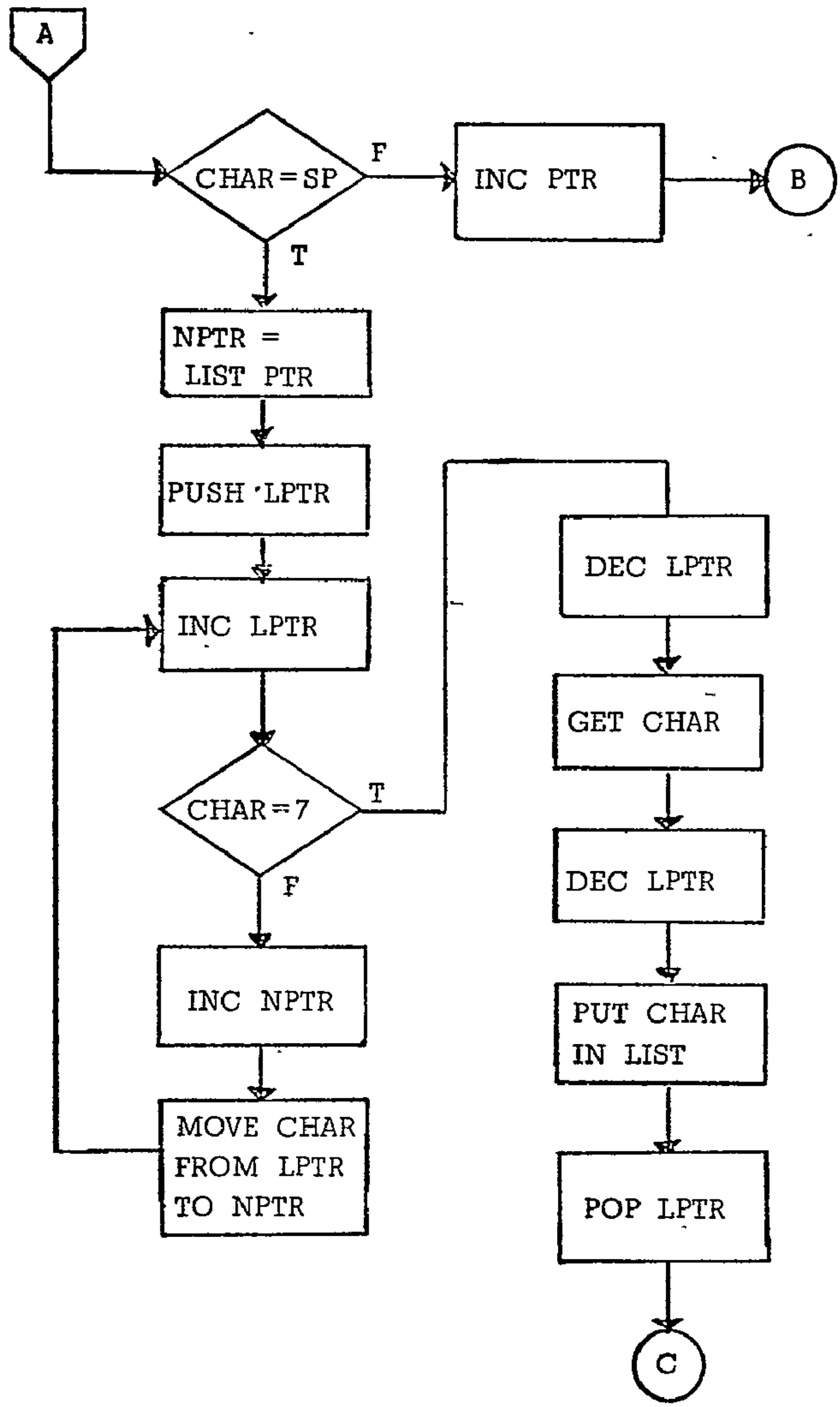
i) Assumes R2 contains pointer to head of list.

ii) When completed, R2 points to first character after EOT, i.e., to the head of the next list.

iii) Valid character includes the numbers 0 through 9, ".", "/", "-", and "+".



SUBROUTINE 16 (p. 1)



SUBROUTINE 16 (Continued)

SUBROUTINE 16

DELETE SPACES

MNEMONIC	ADDRESS	MACHINE CODE	
MOV #5002,R2	1510	012702	5002
CMPB (R2),#7(BEL)		121227	7
BNE .+2		1001	
RTS,PC		207	
CMPB (R2)+,#40		122227	40
BNE .-4		1371	
CMPB (R2),-(R2)		121242	
BNE .+3		1002	
BR .+4		403	
BR .-8		765	
INC R2		5202	
BR .-10		763	
MOV R2,-(R6)		010246	
MOV R3,-(R6)		010346	
MOV R2,R3		010203	
CMPB (R2)+,#7		122227	7
BEQ .+3		1402	
MOVB (R2),(R3)+		111223	
BR .-3		773	
MOV (R6)+,R3		012603	
MOVB -(R2),-(R2)		114242	
MOV (R6)+,R2		012602	
BR		761	

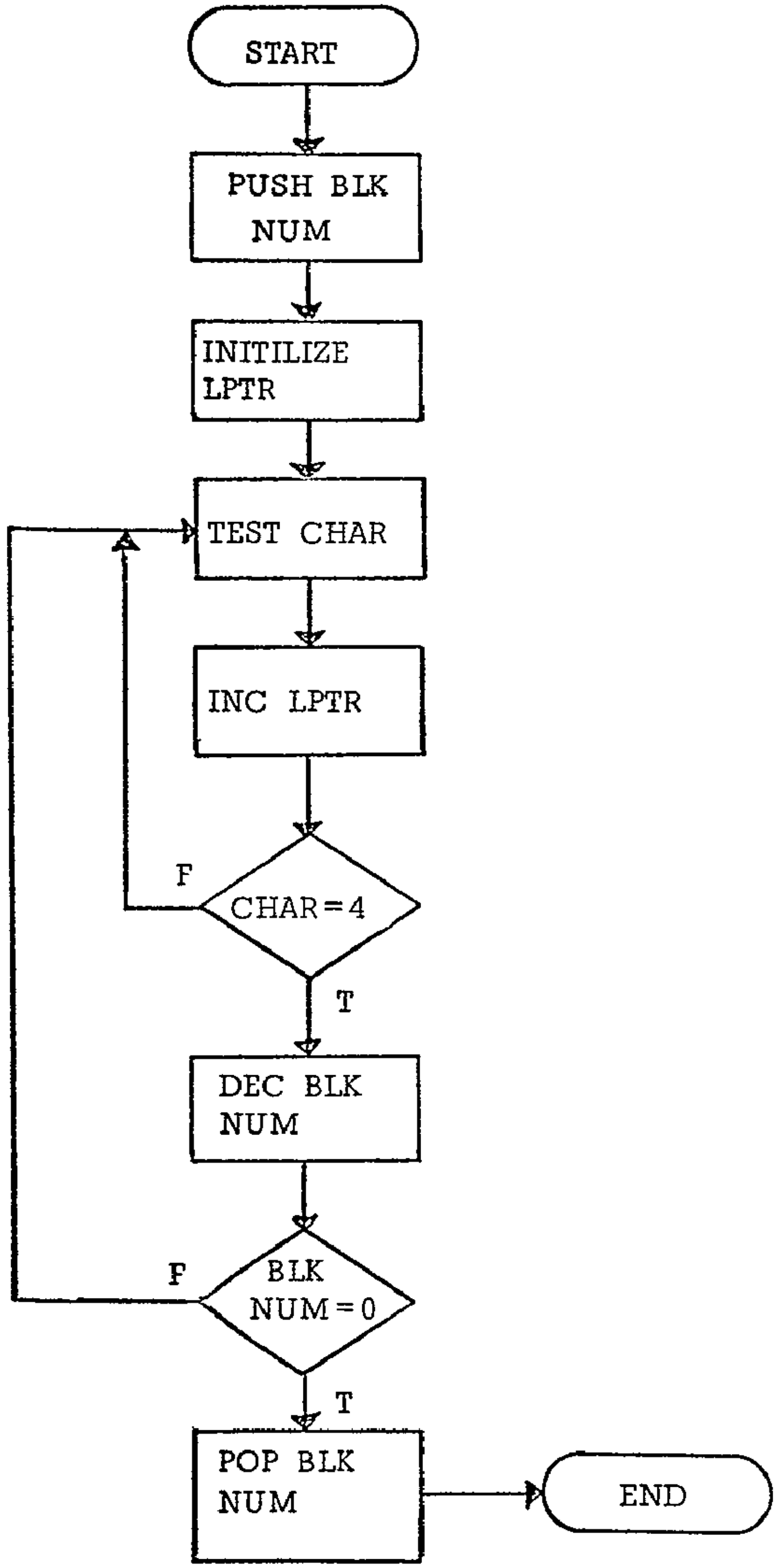
PURPOSE:

This subroutine deletes excess spaces in character list.

COMMENTS:

i) Contents of R2 are destroyed.

ii) Assumes list starts at location 5002 and ends with the character CTRL G (ASCII 007).



SUBROUTINE 17

SUBROUTINE 17

FIND BLOCK START

MNEMONIC	ADDRESS	MACHINE CODE	
MOV R5,-(R6)	1600	10546	
MOV #5002,R2		12702	5002
CMPB (R2)+,#4		122227	4
BNE .-1		1375	
SOB R5, .-2		77504	
MOV (R6)+,R5		12605	
RTS,PC		207	

PURPOSE:

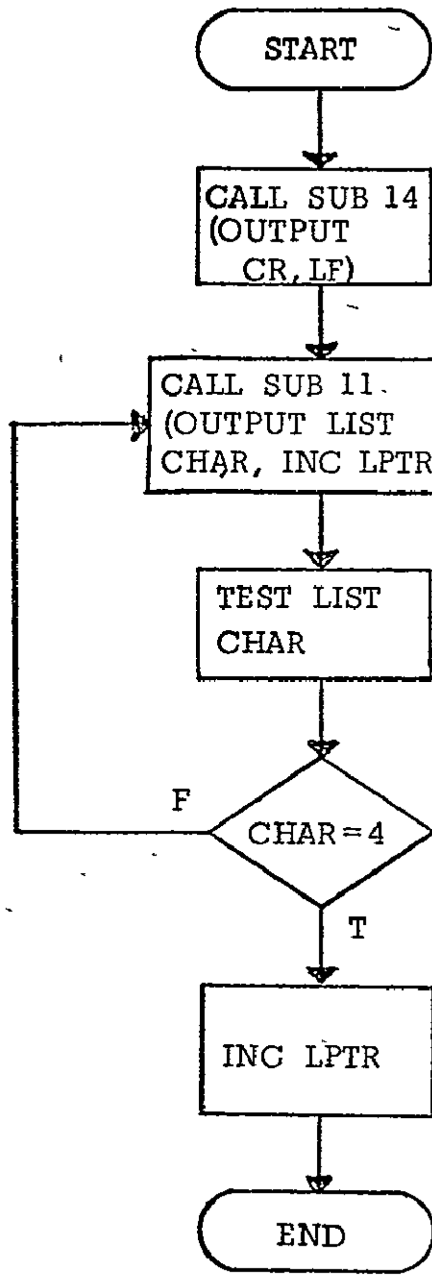
This subroutine finds the beginning of i^{th} character string from the list.

COMMENTS:

i) Assumes blocks of characters are separated by EOT (ASCII 004).

ii) R5 contains the number of the block.

iii) R2 returns the starting address of the i^{th} block.



SUBROUTINE 20

SUBROUTINE 20

OUTPUT CHARACTER STRING

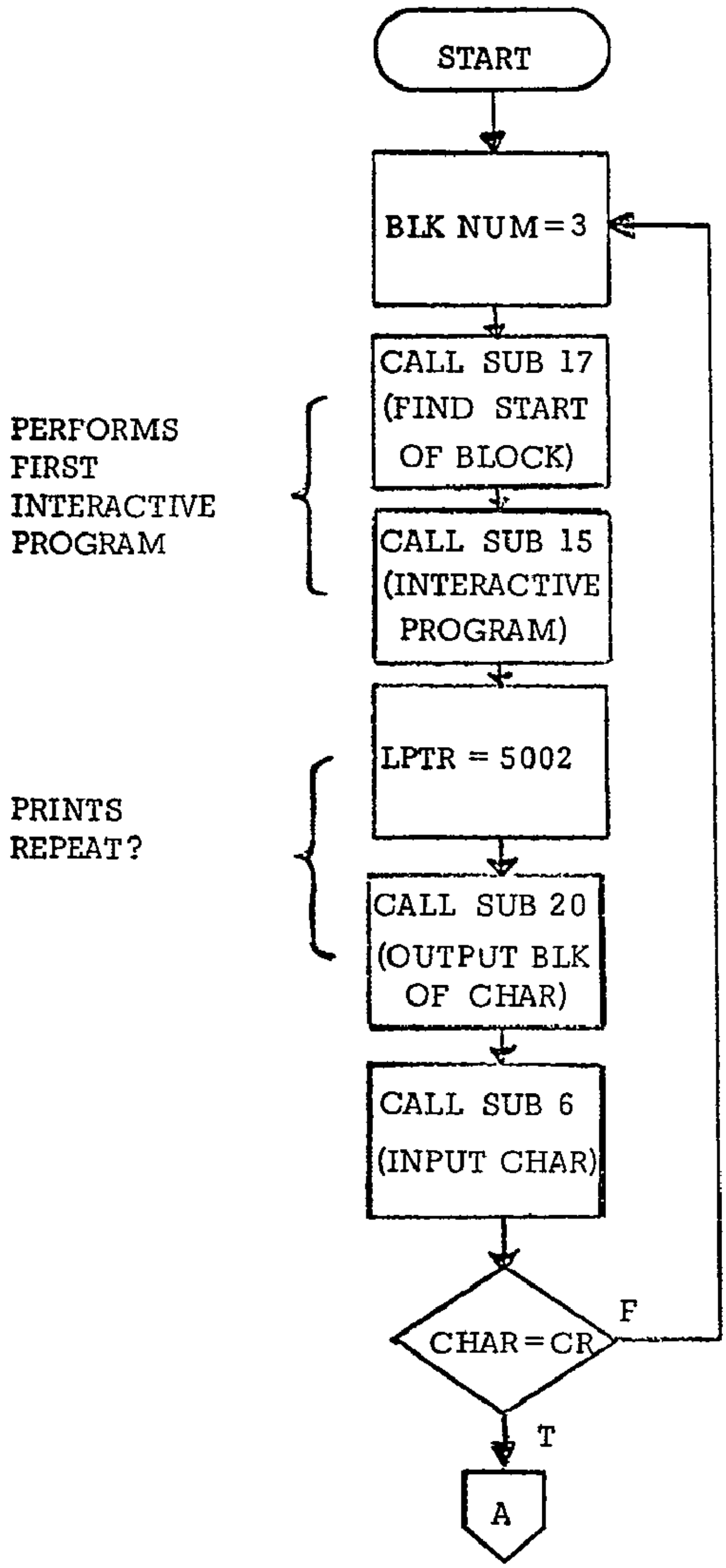
MNEMONIC	ADDRESS	MACHINE CODE	
TRAP 14	1630	104414	
TRAP 11		104411	
CMPB (R2),#4		121227	4
BNE .-2		1374	
INC R2		5202	
RTS,PC		207	

PURPOSE:

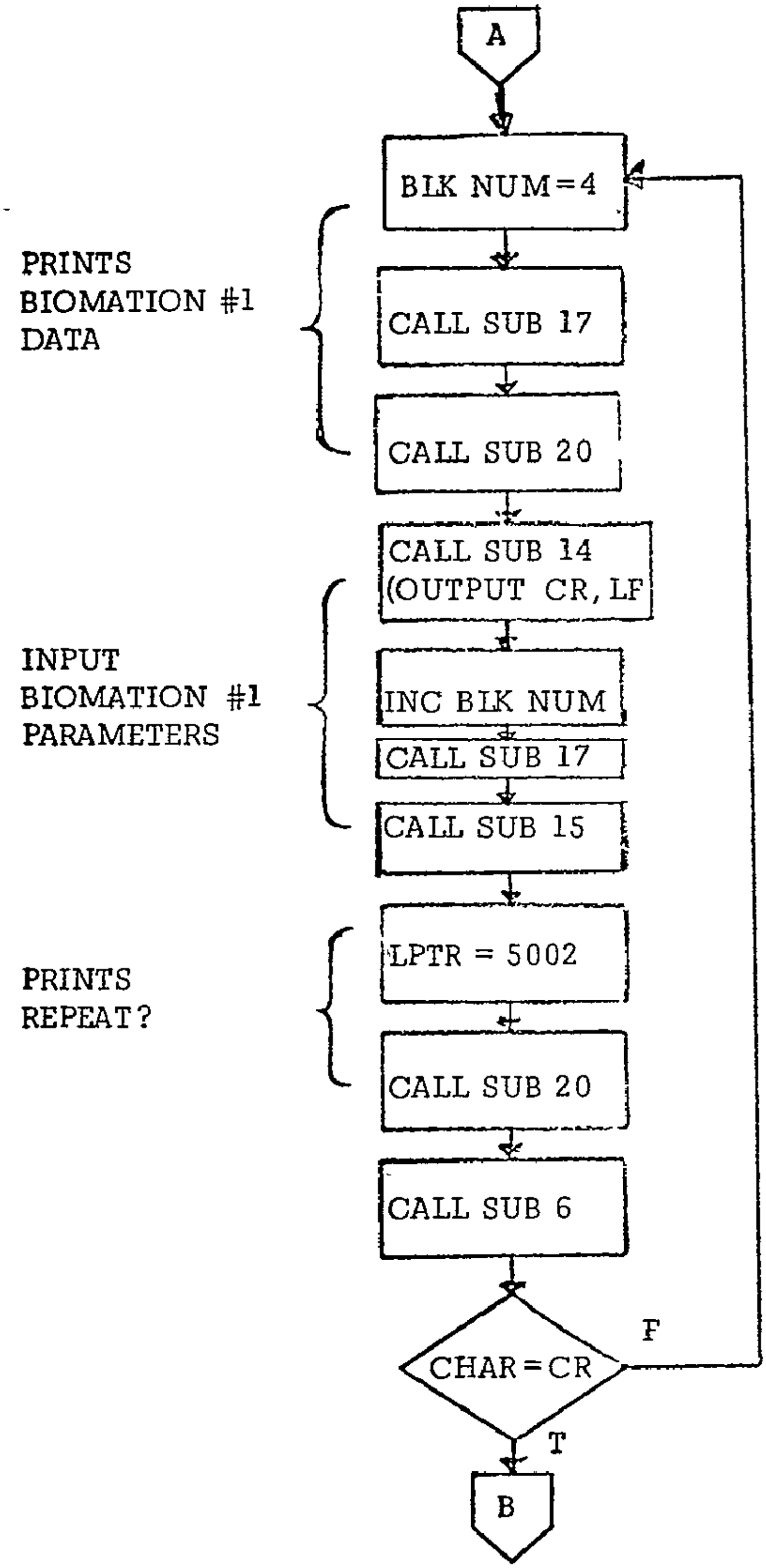
This subroutine outputs a character string whose beginning address is in R2.

COMMENTS:

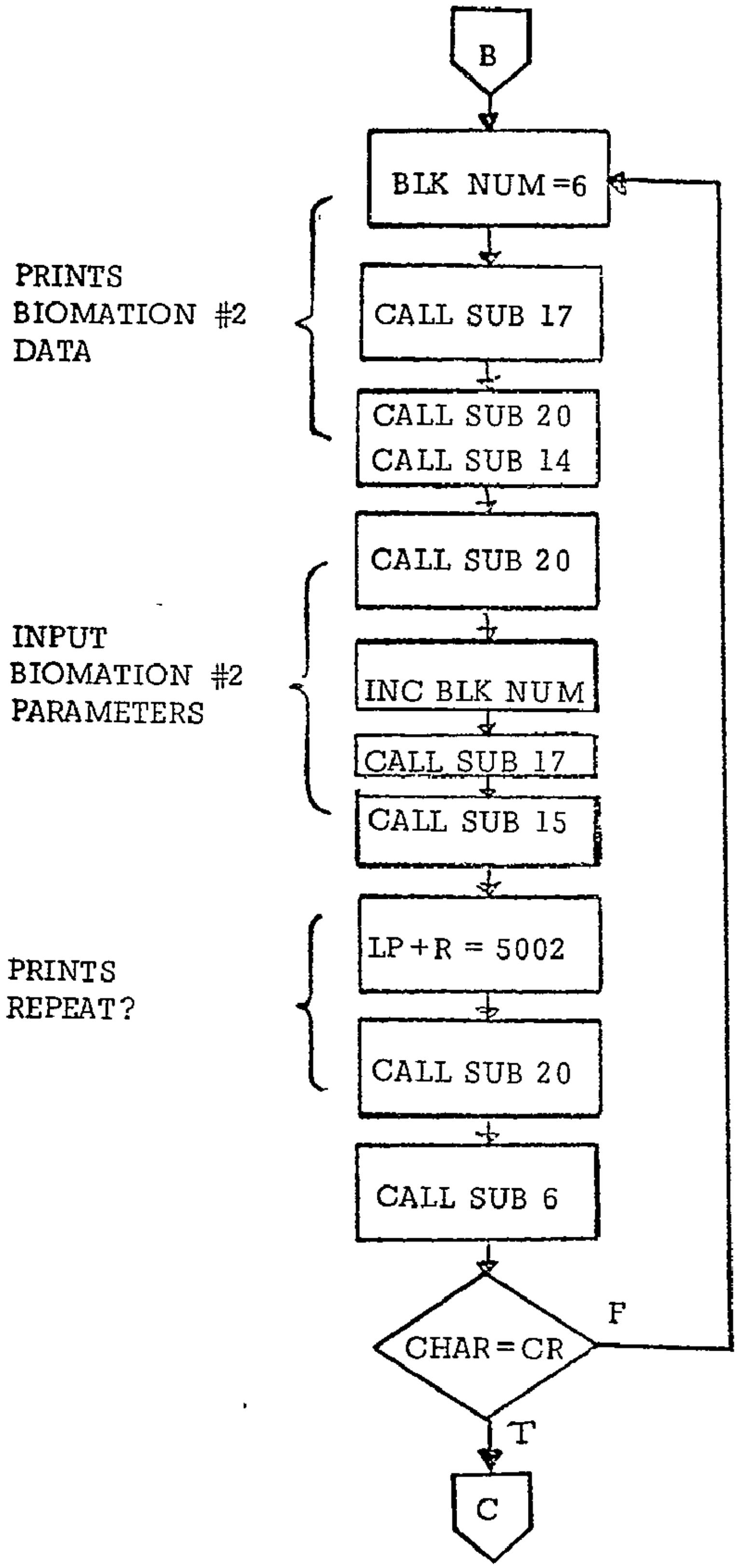
1) Assumes last character is EOT (ASCII 4).



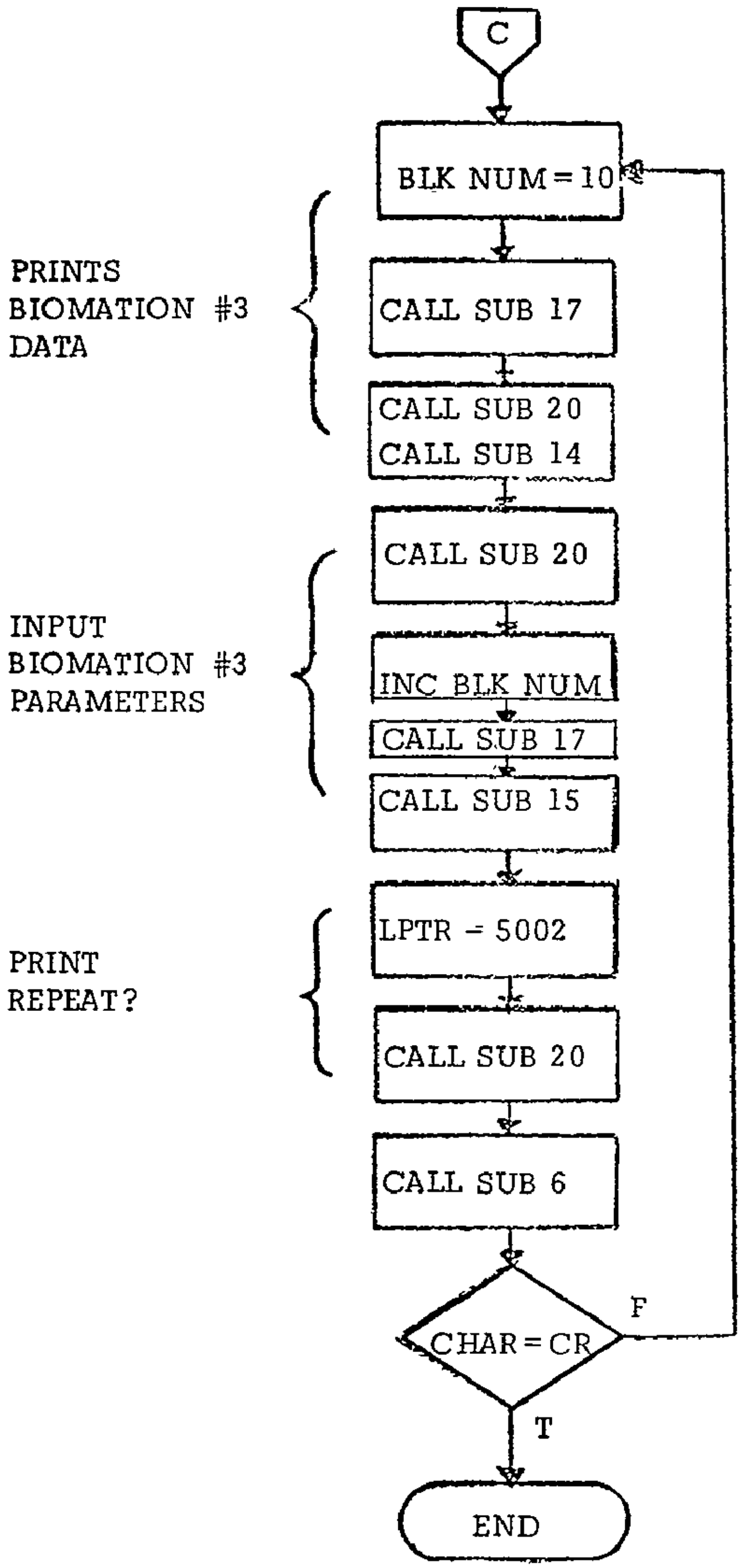
SUBROUTINE 21 p. 1



SUBROUTINE 21 p. 2



SUBROUTINE 21 p. 3



SUBROUTINE 21 p. 4

SUBROUTINE 21

INTERACTIVE PROGRAM II

MNEMONIC	ADDRESS	MACHINE CODE		
MOV #3, R5	1650	012705	3	
TRAP 17		104417		
TRAP 15		104415		
MOV #5002, R2		12702	5002	
TRAP 20		104420		
TRAP 6		104406		
CMPB@#177562, #15(CR)		123727	177562	15
BNE .-7		1364		
MOV #4, R5		012705	4	
TRAP 17		104417		
TRAP 20		104420		
TRAP 14		104414		
INC R5		5205		
TRAP 17		104417		
TRAP 15		104415		
MOV #5002, R2		12702	5002	
TRAP 20		104420		
TRAP 6		104406		
CMPB@#177562, #15(CR)		123727	177562	15
BNE .-11		1360		
MOV #6, R5		12705	6	
TRAP 17		104417		
TRAP 20		104420		
TRAP 14		104414		
INC R5		5205		
TRAP 17		104417		
TRAP 15		104415		
MOV #5002, R2		12702	5002	
TRAP 20		104420		
TRAP 6		104406		
CMPB@#177562, #15(CR)		123727	177562	1[illegible]
BNE .-11		1360		
MOV #10, R5		012705	10	
TRAP 17		104417		

SUBROUTINE 21 (Continued)

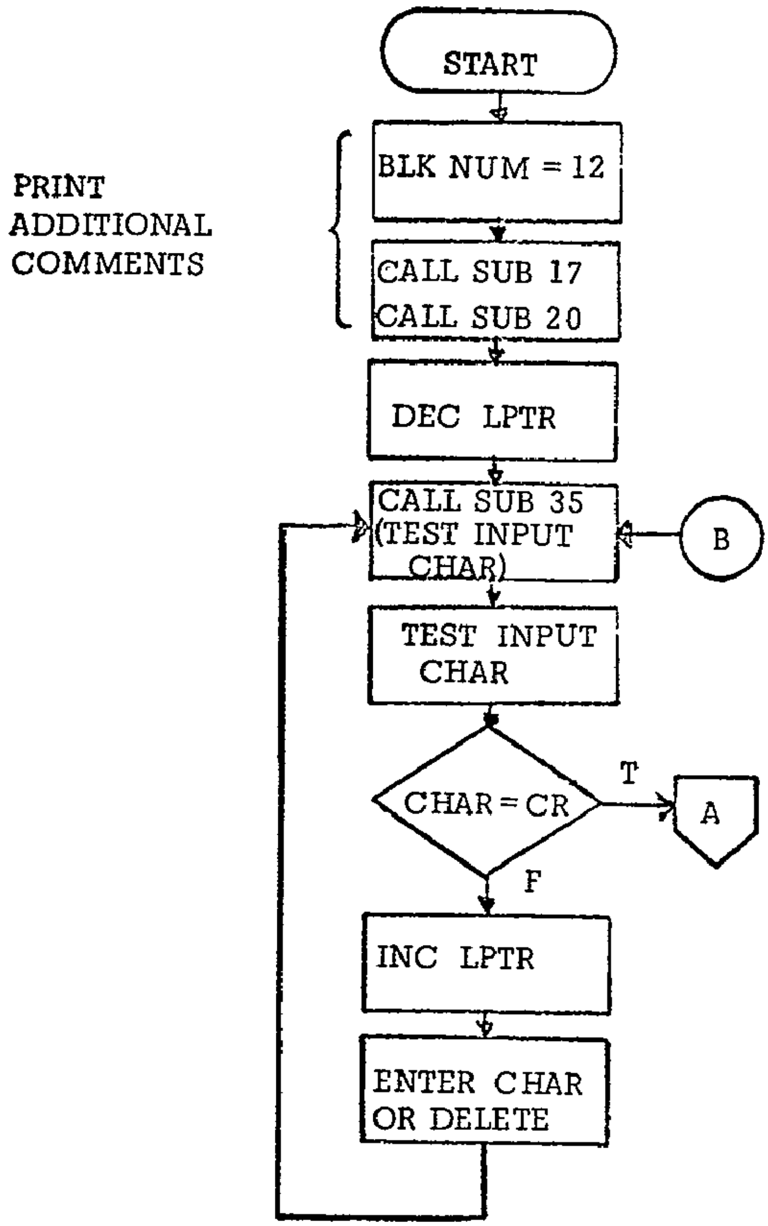
MNEMONIC	ADDRESS	MACHINE CODE		
TRAP 20		104420		
TRAP 14		104414		
INC R5		5205		
TRAP 17		104417		
TRAP 15		104415		
MOV #5002,R2		12702	5002	
TRAP 20		104420		
TRAP 6		104406		
CMP@#177562,#15		123727	177562	15
BNE .-11		1360		
RTS,PC		207		

PURPOSE:

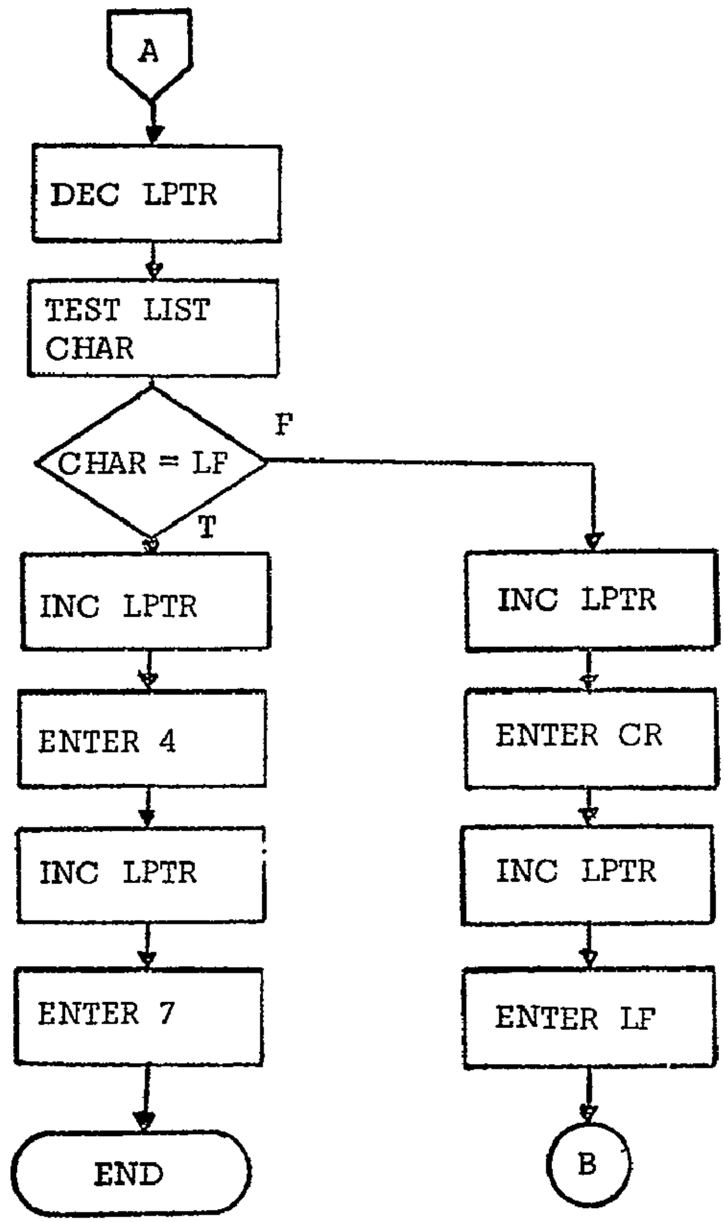
This subroutine does all the interactive list manipulation used to enter experimental data and data from all the Biomations.

COMMENTS:

1) Contents of R2 and R5 are destroyed.



SUBROUTINE 22 p. 1



SUBROUTINE 22 (Continued)

SUBROUTINE 22

ADDITIONAL COMMENTS ROUTINE

MNEMONIC	ADDRESS		MACHINE CODE
MOV #12, R5	2050	12705	12
TRAP 17		104417	
TRAP 20		104420	
DEC R2		5302	
TRAP 35		104435	
MOVB@#177562, R5		113705	177562
CMPB R5, #15		120527	15
BNE .+10		1015	
CMPB -(R2), #12		124227	12
BNE .+4		1004	
INC R2		5202	
MOVB #4, (R2)+		112722	4
BR .+12		417	
INC R2		5202	
MOVB #15, (R2)+		112722	15
MOVB #12, (R2)+		112722	12
BR .-12		755	
CMPB R5, #40		120527	40
BLT .-2		2774	
CMPB R5, #177		120527	177
BNE .+2		1001	
SOB R2, .-12_{10}		77232	
MOVB R5, (R2)+		110522	
BR.-7		766	
MOVB #7, (R2)		112712	7
TRAP 16		104416	
RTS, PC	2160	207	

PURPOSE:

This subroutine prints all the characters entered in the Additional Comments file then enters characters on the end of this list as the operator types them.

And using the RUBOUT Key any character can be erased with working backward from the end of a whole text.

SUBROUTINE 22 (Continued)

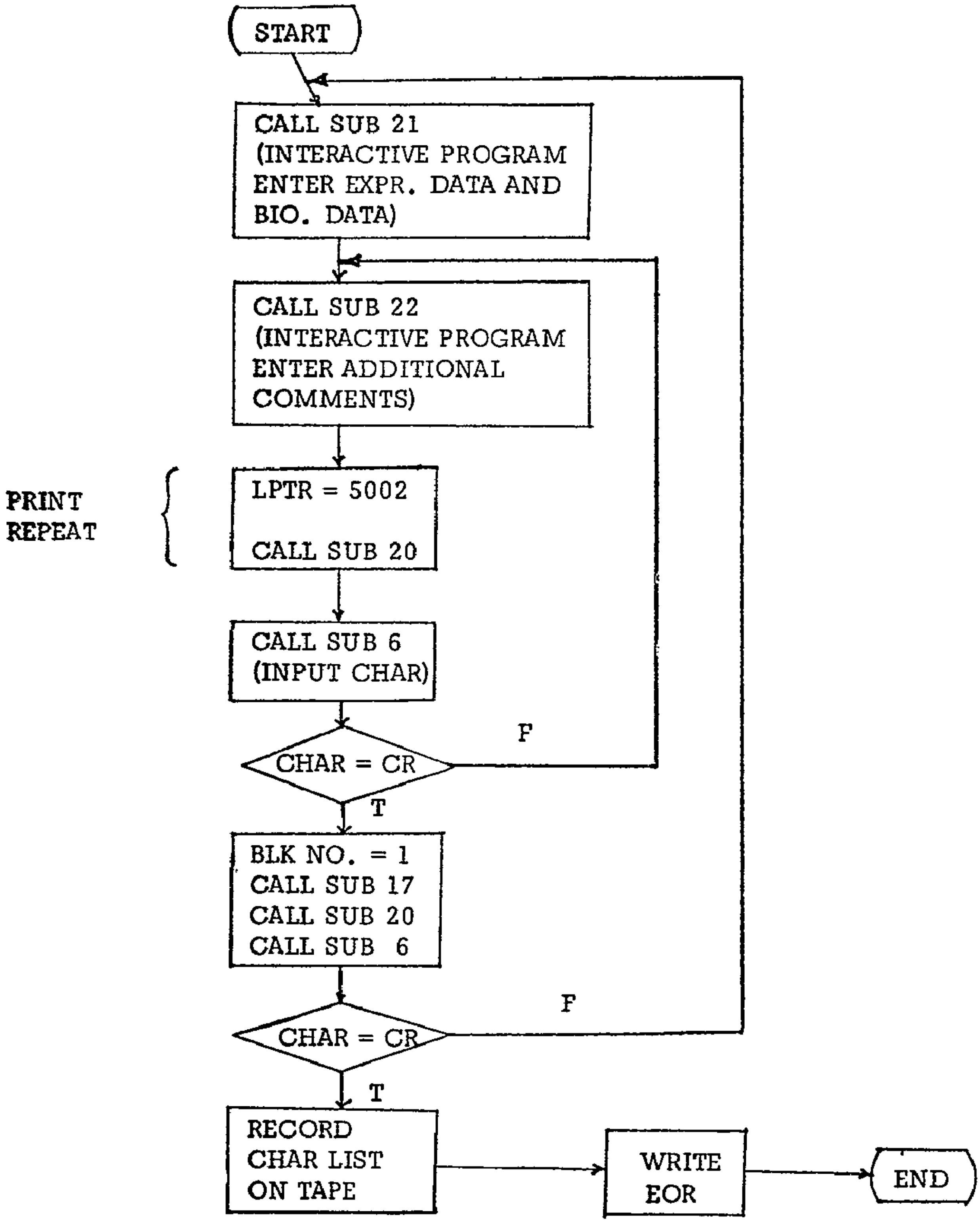
COMMENTS:

i) Exits with CR if no comments are added.

ii) Exits with two CRs if comments are added.

iii) Contents of R2 and R5 are destroyed.

Every Sentence is followedby two keys (CR and LF) which are never shown,on terminal, but which are treated as characters when erasing.



SUBROUTINE 23

SUBROUTINE 23

OUTPUT COMMENT RECORD

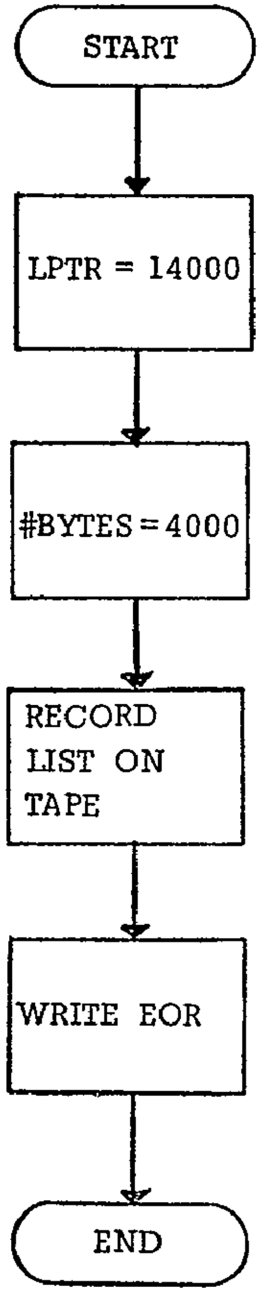
MNEMONIC	ADDRESS	MACHINE CODE		
TRAP 21	2170	104421		
TRAP 22		104422		
MOV R2, -(R6)		10246		
MOV #5002, R2		12702	5002	
TRAP 20		104420		
TRAP 6		104406		
MOV (R6)+, R2		12602		
CMPB @#177562, #15		123727	177562	15
BNE .-7		1365		
MOV R5, -(R6)		10546		
MOV #1, R5		12705	1	
MOV R2, -(R6)		10246		
TRAP 17		104417		
TRAP 20		104420		
TRAP 6		104406		
MOV (R6)+, R2		12602		
MOV (R6)+, R5		12605		
CMPB @#177562, #15		123727	177562	15
BNE .-18		1347		
MOV #5033, R1		12701	5033	
SUB R1, R2		160102		
MOV #1, @#167770		12737	1	167770
INC R2		5202		
TRAP 2		104402		
TRAP 4		104404		
RTS, PC	2274	207		

PURPOSE:

This subroutine executes all the interactive programs and then writes the characters on tape followed by an EOR mark.

COMMENTS:

i) Destroys contents of R1, R2, and R5.



SUBROUTINE 24

SUBROUTINE 24

WRITE BIOMATION DATA

MNEMONIC	ADDRESS	MACHINE CODE		
MOV #1,@#167770	2300	12737	1	167770
MOV #14000,R1 (ST ADD)		12701	14000	
MOV #4000,R2 (# BYTES)		12702	4000	
TRAP 2		104402		
TRAP 4		104404		
RTS,PC		207		

PURPOSE:

This subroutine writes the Biomation data onto tape followed by an EOR.

COMMENTS:

i) Destroys contents of R1 and R2.

ii) Assumes data in locations 14000 through 17776.

SUBROUTINE 25

BCD TO ASCII CONVERTER

MNEMONIC	ADDRESS	MACHINE CODE	
ADD #60,R4	2330	062704	60
MOVB R4,(R5)+		110425	
CLR R4		5004	
RTS,PC		207	

PURPOSE:

This subroutine converts a binary coded decimal (BCD) number into its ASCII code.

COMMENTS:

i) Assumes BCD number in R4.

ii) Puts ASCII character in the list whose pointer is in R5 and then increments R5.

iii) Clears R4.

SUBROUTINE 26

BINARY TO ASCII CONVERTOR

MNEMONIC	ADDRESS	MACHINE CODE	
MOV R5,-(R6)	2350	010546	
MOV R4,-(R6)		010446	
MOV #4772,R5		012705	4772
MOVB #40,(R5)+		112725	40
MOVB #40,(R5)+		112725	40
TST R3		5703	
BGE .+4		2004	
MOVB #55,-(R5)		112745	55
INC R5		5205	
NEG R3		5403	
CLR R4		5004	
SUB #1747,R3		162703	1750
BLT .+3		2402	
INC R4		5204	
BR .-3		773	
ADD #1747,R3		62703	1750
TRAP 25		104425	
SUB #144,R3		162703	144
BL .+3		2402	
INC R4		5204	
BR .-3		773	
ADD #144,R3		62703	144
TRAP 25		104425	
SUB #12,R3		162703	12
BL .+3		2402	
INC R4		5204	
BR .-3		773	
ADD #72,R3		62703	72
TRAP 25		104425	
MOVB R3,(R5)		110315	
MOV (R6)+,R4		12604	
MOV (R6)+,R5		12605	
MOV #4772,R2		12702	4772
TRAP 20		104420	
RTS,PC		207	

SUBROUTINE 26 (Continued)

PURPOSE:

This subroutine converts a 10-bit binary number into its decimal equivalent then stores the ASCII code for the 4-digit decimal number in a list and prints the number.

COMMENTS:

i) Assumes binary number in R3.

ii) Places BCD number in R4.

iii) Places 4-digit signed ASCII-encoded decimal number in locations 4772 through 5000.

iv) Prints number.

SUBROUTINE 27

SEARCH DATA

MNEMONIC	ADDRESS	MACHINE CODE	
MOV R5,-(R6)	2510	010546	
MOV #14000,R5		012705	14000
CLR@#470		5037	470
CLR@#472		5037	472
CLR@#474		5037	474
CLR@#476		5037	476
CMPB (R5),@#476		121537	476
BEQ .+12		1422	
BGT .+9		3014	
CMPB (R5)+,@#472		122537	472
BEQ .+5		1406	
BGT .+11		3007	
CLR@#470		5037	470
MOVB -(R5),@#472		114537	472
INC R5		5205	
INC@#470		5237	470
BR .+6		410	
MOVB (R5),@#476		111537	476
CLR@#474		5037	474
NOP		240	
INC@#474		5237	474
INC R5		5205	
CMP R5,#20000		020527	20000
BLT .-17		2745	
MOV (R6)+,R5		12605	
RTS,PC		207	

PURPOSE:

This subroutine finds both the maximum and minimum bytes in memory location 14000 through 17777 and records the number of times these values were encountered.

SUBROUTINE 27 (Continued)

COMMENTS:

i) Puts minimum byte in location 472.

ii) Puts number of occurences in location 470.

iii) Puts maximum byte in location 476.

iv) Puts number of occurences in location 474.

SUBROUTINE 30

PRINT MAXIMUM AND MINIMUM VALUES

MNEMONIC	ADDRESS	MACHINE CODE	
MOV R2,-(R6)	2630	10246	
MOV R3,-(R6)		10346	
MOV #4730,R2		12702	4730
TRAP 20		104420	
MOVB@#476,R3		113703	476
TRAP 26		104426	
MOV #4756,R2		12702	4756
TRAP 20		104420	
MOV@#474,R3		13703	474
TRAP 26		104426	
MOV #4743,R2		12702	4743
TRAP 20		104420	
MOVB@#472,R3		113703	472
TRAP 26		104426	
MOV #4756,R2		12702	4756
TRAP 20		104420	
MOV@#470,R3		13703	470
TRAP 26		104426	
MOV (R6)+,R3		12603	
MOV (R6)+,R2		12602	
RTS,PC		207	

PURPOSE:

This subroutine prints the maximum and minimum values stored in each Biomation with suitable titles.

SUBROUTINE 31

READ BIOMATION DATA

MNEMONIC	ADDRESS	MACHINE CODE	
MOVB #7, (R5)	2730	112715	7
TSTB, 2(R5)		105765	2
MOV #14000, R2		12702	14000
TST (R4)		5714	
BPL .-1		100376	
TRAP 36		104436	
MOVB 2 (R5), (R2)+		116522	2
CMP R2, #20000		020227	20000
BLT .-5		2770	
CLR (R5)		5015	
RTS, PC	2766	207	

PURPOSE:

This subroutine reads the data stored in a Biomation.

COMMENTS:

i) Assumes Biomation uses lower byte of a parallel interface.

ii) Assumes interface's address is in R4.

iii) Assumes interface's XBUF address is in R5.

iv) Uses R2 as list pointer.

v) Contents of R2 are destroyed.

SUBROUTINE 32

ONE'S COMPLEMENT

MNEMONIC	ADDRESS	MACHINE CODE	
MOV #14000, R2	2770	12702	14000
TSTB (R2)+		105722	
BPL .+7		100010	
CMPB #200, -(R2)		122742	200
BEQ .+3		1402	
DECB (R2)		105312	
BR .+2		402	
MOVB #377, (R2)		112712	377
INC R2		5202	
CMP R2, #20000		20227	20000
BLT .-9		2763	
TRAP 24		104424	
RTS, PC	3030	207	

PURPOSE:

This subroutine changes the Biomation's data to one's complement form from two's complement.

COMMENTS:

1) Contents of R2 are destroyed.

2) -128 is represented 377_8 but in one's complement, this number (377_8) represents (-0). Thus, I use this number to represent (-128).

SUBROUTINE 33

READ BIOMATION DATA II

MNEMONIC	ADDRESS	MACHINE CODE	
MOV R3, -(R6)	3040	010346	
MOV#3400, (R5)+		12725	3400
TST (R5)		5715	
MOV #14000, R2		12702	14000
TST (R4)		5714	
BPL .-1		100376	
TRAP 36		104436	
MOV (R5), R3		11503	
SWAB R3		303	
MOVB R3, (R2)+		110322	
CMP R2, #20000		20227	20000
BLT .-6		2767	
CLR -(R5)		5045	
MOV (R6)+, R3		12603	
RTS, PC		207	

PURPOSE:

This subroutine reads the data from those Biomations which use the most significant bits of the parallel interface.

COMMENTS:

i) Assumes CSR address is in R4.

ii) Contents of R2 are destroyed.

SUBROUTINE 34

TEST INPUT CHARACTER

MNEMONIC	ADDRESS	MACHINE CODE		
MOV R5,-(R6)	3110	10546		
TRAP 6		104406		
MOVB@#177562,R5		113705	177562	
CMPB R5,#15		120527	15	
BNE .+3		1002		
MOV (R6)+,R5		12605		
RTS,PC		207		
CMPB R5,#60		120527	55	
BLT .+6		2413		
CMPB R5,#71		120527	71	
BLE .-5(END)		3770		
TRAP 10		104410		
MOVB#77,@#177566		112737	77	177566
BR .-12		755		
CMPB R5,#55		120527	55	
BEQ .-10(END)		1760		
CMPB R5,#56		120527	40	
BEQ .-12(END)		1755		
BR .-7		764		

PURPOSE:

This subroutine tests the keyboard ASCII character generated by the operator to ensure numerical characters.

COMMENTS:

i) Valid characters include 0 thru 9, ".", "1", "-", "+".

ii) Invalid characters are followed by a "?" on the TTY.

SUBROUTINE 35

TEST INPUT CHARACTER II

MNEMONIC	ADDRESS	MACHINE CODE		
TRAP 6	3200	104406		
CMPB@#177562,#15		123727	177562	15
BNE .+4		1005		
TRAP 10		104410		
MOVB #12,@#177566		112737	12	177566
RTS,PC		207		
CMPB@#177562,#40		123727	177562	40
BGE .-2		2373		
BR .-8		761		

PURPOSE:

This subroutine tests the input character string for the Additional Comments section.

COMMENTS:

i) Valid characters are all alpha-numeric characters and CR.

ii) Outputs LF when CR entered.

SUBROUTINE 36

DELAY LOOP

MNEMONIC	ADDRESS		MACHINE CODE
MOV R3, -(R6)	3240	10346	
MOV #40, R3		12703	40
SOB R3, .		77301	
MOV (R6)+, R3		12603	
RTS, PG	3252	207	

PURPOSE:

This subroutine determines the time interval of requesting data from Biomation unit.

SUBROUTINE 42

AUTOMATIC FILE NUMBER

MNEMONIC	ADDRESS	MACHINE CODE
MOV 10 (R6), R3	4320/	16603
		10
MOV #2, R5		12705
		2
TRAP 17		104417
TRAP 11		104411
CMPB #72, (R2)		122712
		72
BNE .-2		1374
CMPB #71. R3		122703
		71
BEQ .+3		1402
INCB R3		105203
BR .+3		404
BICB #11, R3		142703
		11
ADD #400, R3		62703
		400
MOV R3, 10(R6)		10366
		10
MOVB R3, 2(R2)		110362
		2
SWAB R3		303
MOVB R3, 1(R2)		110362
		1
TRAP 11		104411
CMPB #4, (R2)		122712
		4
BNE .-2		1374
RTS, PC		207

PURPOSE:

This subroutine generates an automatic file number, which means the number increases by one at each run.

COMMENT:

At any time, the file number can be reset by running RESETTING FILE NUMBER (at 4420).

APPENDIX C

This Appendix is concerned with certain utility routines that we have found useful in debugging our programs and overall system.

PROGRAM DUMP

MNEMONIC	ADDRESS	MACHINE CODE		
MOV#10,000,R6	3700	12706	10000	
TRAP 5		104405		
MOV#1,@#167770		12737	1	167770
MOV#ST ADD,R1		12701	ST ADD	
MOV #OF BYTES, R2		12702	#OF BYTES	
TRAP 2		104402		
TRAP 5		104405		
RESET		5		
HALT		0		

PURPOSE:

This subroutine writes a block of memory onto tape.

COMMENTS:

1) Starting address is 0000; end address is 6550.

PROGRAM MOVE BLOCK

MNEMONIC	ADDRESS	MACHINE CODE	
MOV #BYTES, R3	3550	12703	BYTES
MOV OLD ST ADR, R1		12701	OLD ST ADR
MOV NEW ST ADR, R2		12702	NEW ST ADR
MOVB (R1)+, (R2)+		112122	
SOB R3, .-1		77302	
RESET		5	
HALT	3572	0	

PURPOSE:

This program moves blocks of memory from one position to another.

COMMENTS:

i) Contents of R1, R2, and R3 are destroyed.

ii) R1 contains the old starting address.

iii) R2 contains the new starting address.

iv) R3 contains the number of bytes.

PROGRAM INPUT CHARACTERS

MNEMONIC	ADDRESS	MACHINE CODE		
MOV #ST ADD, R0	3740	012700	(ST ADD)	
TSTB@#177560		105737	177560	
BPL .-1		100375		
MOVB@#177562,@#177566		113737	177562	177566
MOVB@#177562,(R0)		113710	177562	
CMPB@#177562,#07(BEL)		123727	177562	7
BNE .+3		001002		
RESET		5		
HALT		0		
CMPB(R0)+,#177(RUBOUT)		122027	177	
BNE .+3		1002		
DEC R0		005300		
DEC R0		5300		
BR .-12		754		

PURPOSE:

This program builds a list of characters entered from the keyboard.

COMMENTS:

i) R0 points to head of list and increments with each character.

ii) RUBOUT (ASCII 177) deletes last character.

iii) CTRL G (ASCII 7) ends the program.

iv) All other characters are valid.

RESETTING FILE NUMBER

MNEMONIC	ADDRESS	MACHINE CODE
MOVB #60, @#5047	4420	112737
		60
		5047
MOVB #60, @#5050		112737
		60
		5050

PURPOSE: This program reset the file number at any time.

PRINT ALPHANUMERIC DATA

MNEMONIC	ADDRESS		MACHINE CODE
MOV STAD, R0	4100	12700	(4730)
MOV #20, R1		12701	20
TSTB @#177564		105737	177564
BPL .-1		100375	
MOVB (R0) +, @ #177566		112037	177566
SOB R1, .-3		77106	
TSTB @#177560		105737	177560
BPL .-1		100375	
CMPB @#177562, #15		123727	177562
BNE .-3		1371	15
BR .-9	4142	760	

COMMENT:

This program prints out the content of ST AD by alphanumeric characters by 20 characters step.

SUBROUTINE 37

GENERATE SAWTOOTH WAVE

MNEMONIC	ADDRESS		MACHINE CODE
MOV #14000, R0	3260	12700	14000
MOVB R0, (R0)+		110020	
CMP R0, #20000		20027	20000
BNE .-2		1374	
HALT		0	

PURPOSE:

This program generates triangular wave form at the beginning address of 14000_8 .

SUBROUTINE 40

READ BIOMATION DATA

(TEST ROUTINE)

MNEMONIC	ADDRESS		MACHINE CODE
MOVB #7, (R5)	4200	112715	7
TSTB, 2(R5)		105765	2
MOV #14000, R2		12702	14000
TST (R4)		5714	
BPL .-1		100376	
TRAP 36		104436	
MOVB 2 (R5), (R2)+		116522	2
CMP R2, #17777		20227	17777
BLT .-5		2770	
CLR (R5)		5015	
RTS, PC		207	

PURPOSE:

This subroutine reads data stored in Biomation No. 1 (without switching to the OFF mode.*)

COMMENTS:

i) Assumes Biomation uses lower byte of a parallel interface.

ii) Assumes interface's address is in R4.

iii) Assumes interface's XBUF address is in R5.

iv) Uses R2 as list pointer.

v) Contents of R2 are destroyed.

* Refer to Biomation Manual (p. 50)

SUBROUTINE 41

READ BIOMATION II

(TEST ROUTINE)

MNEMONIC	ADDRESS		MACHINE CODE
MOV R3, -(R6)	4250	010346	
MOV #3400, (R5)+		12725	3400
TST (R5)		5715	
MOV #14000, R2		12702	14000
TST (R4)		5714	
BPL .-1		100376	
TRAP 36		104436	
MOV (R5), R3		11503	
SWAB R3		303	
MOVB R3, (R2)+		110322	
CMP R2, #17777		20227	17777
BLT .-6		2767	
CLR -(R5)		5045	
MOV (R6)+, R3		12603	
RTS, PC		207	

PURPOSE:

This subroutine reads the data from those Biomations which use the most significant bits of the parallel interface (without switching to the OFF mode*).

COMMENTS:

i) Assumes CSR address is in R4.

ii) Contents of R2 are destroyed.

* Refer to Biomation Manual (p.50.)

APPENDIX D

NOTES ON THE LSI-11

Since the LSI-11 instruction set and architecture is discussed fully by Digital Equipment Corporation (DEC) in the PDP 11/03 Programming Handbook, the PDP 11/03 Programming Manual, and the PDP 11/03 Maintenance Manual, this appendix mainly describes the I/O programming required to control the tape unit; however, a few general notes are included.

The LSI-11, which emulates DEC's PDP 11/40, is a 16-bit machine capable of directly addressing 64K bytes. Its two address architecture makes its instruction set extremely powerful. Among its seven addressing modes are an auto-increment and an auto-decrement feature which facilitate list manipulation, an important feature as the software employ this data structure extensively.

Another feature of great usefulness is the DRV-11 parallel interface. This interface has three internal 16-bit registers as described in the maintenance manual on page 6-27. The CPU programs these registers and the interface unit communicates via a handshaking mode with the outside world. The CSR has two read/write bits called the CSR0 and CSR1 which control the tape deck function. Other bits include the ready flags RQST A H and RQST B H and the interrupt enable bits. Since the system software does not employ the interrupt feature, this discussion centers on the use of the ready flags and control bits.

When the CPU wants to write data to the X-MIT BUFFER, it first tests RQST A H which indicates that the X-MIT BUFFER is empty and that the peripheral device has received the last byte. Next the CPU writes into the X-MIT BUFFER and the DRV-11 resets the RQST A H and generates a NEW DATA READY pulse which indicates a write operation to the peripheral device. The peripheral device then accepts the data and so informs the CPU by setting RQST A H.

When the CPU reads from the RECEIVE BUFFER, it first tests the RQST B H which indicates true when the peripheral device writes to the DRV-11. After RQST B H becomes true and the RECEIVE BUFFER contains data, the CPU reads the data and the DRV-11 resets RQST B H and generates a DATA X-MITED pulse which indicates to the peripheral device that the data has been read. The peripheral device then puts the next data byte into the RECEIVE BUFFER and sets RQST B H.

The control bits, CSR0 and CSR1, in the DRV-11's CSR may be read or modified under software control. The tape interface utilizes this feature to steer ready flags and handshaking pulses to perform the tape functions, read, write, write EOF, write EOR, reverse, and stop as described in detail in Appendix A, Section 1. Therefore, the system uses but one parallel interface to perform the multiple functions of the tape unit.

The addresses used by the various peripheral devices are shown below:

ADDRESS	FUNCTION	
177560	RCSR	
177562	RBUF	CRT TERMINAL
177564	XCSR	
177566	XBUF	
167770	CSR	
167772	XBUF	TAPE DECK
167774	RBUF	
167760	CSR	
167762	XBUF	BIOMATION #1
167764	RBUF	
167760	CSR	
167763	XBUF	BIOMATION #2
167765	RBUF	
167750	CSR	
167753	XBUF	BIOMATION #3
167755	RBUF	

APPENDIX E

OPERATING INSTRUCTIONS

Operating instructions for the system are enumerated below:

STEP 1: Turn on system and load the Interactive Program tape.

STEP 2: Manually enter the Bootstrap Loader.

STEP 3: Run the BOOTSTRAP LOADER by entering
13000 (RUN) G

The tape drive will stop when the unit reads the program and the LSI-11 will print its prompt character, "@."

STEP 4: Read the contents of register five (R5) by entering
R5/

R5 should contain 6550

STEP 5: Remove the Interactive Program tape and load a blank data tape.

STEP 6: Manually put the tape unit in the write mode and press FILE GAP. This writes an EOF at the beginning of the tape.

STEP 7: Run the Interactive Program by entering
3400 (RUN) G

STEP 8: Enter the experimental and bookkeeping data as the terminal indicates.

Once the Interactive Program has been started, the system requires no additional action from the operator to record the data on tape. Although the program may be halted by pressing the BREAK key, never stop the system unless the program is prompting the operator. When the day's experiment is finished, wait until the system restarts the Interactive Program, then power down This ensures an accurate tape format.

The programming required to interace the Biomations is relatively straightforward. First, an octal seven is written into the XBUF in the appropriate DRV-11 interace. Then the DATA X-MITED pulse generated from reading the RBUF sequential accesses the Biomations memory. When the data is valid, the FLAG signal from the Biomation goes high. Since this FLAG signal connects directly to the RQST B H input, the program merely tests the RQST B H signal in the CSR until the data is valid then inputs the data. The program then stores the data in memory locations 14000-17777.

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TABLE I. - INTERACTIVE PROGRAM PROMPTER

FILE NUMBER:

DATE:

RUN NUMBER:

ANODE VOLTAGE (KV):

ANODE CURRENT (AMP):

MAX. MAGNETIC FIELD (TESLA):

PRESSURE (MICRO-TORR):

AVERAGE PLASMA NUMBER DENSITY (ELECTRONS/ (M**3)):

RADIAL POSITION OF PROBES FROM THE CENTRE OF PLASMA (CM):

POTENTIAL PROBE ANGULAR DISPLACEMENT (DEGREE):

REPEAT?
BIOMATION NO. 1 DATA.

INPUT RANGE SETTING (VOLT):

SAMPLE INTERVAL (MICRO-SEC):

ANTI-ALIAS FILTER (MHZ):

PRE-AMP GAIN (VOLT IN BIO./VOLT IN PLASMA):

REPEAT?
BIOMATION NO. 2 DATA.

INPUT RANGE SETTING (VOLT):

SAMPLE INTERVAL (MICRO-SEC):

ANTI-ALIAS FILTER (MHZ):

PRE-AMP GAIN (VOLT IN BIO./VOLT IN PLASMA):

REPEAT?
BIOMATION NO. 3 DATA.

INPUT RANGE SETTING (VOLT):

SAMPLE INTERVAL (MICRO-SEC):

ANTI-ALIAS FILTER (MHZ):

PRE-AMP GAIN (VOLT IN BIO./VOLT IN PRE-AMP.):

D.C. VOLTAGE AT PRE-AMP INPUT (VOLT):

REPEAT?
ADDITIONAL COMMENT?

REPEAT?
REPEAT ENTIRELY?

TABLE II. - COMMAND SIGNAL FUNCTIONS FROM DRV-11

			Function Performed By	
			Read from RBUF	Write to XBUF
Mode	CSR1	CSR0	DATA X-MITED	NEW DATA READY
0	0	0	No effect	No effect
1	0	1	Puts Tape Unit in Read Mode	Writes one 6-bit Character on Tape
2	1	0	Stops Tape Unit	Writes EOR Mark
3	1	1	Puts Tape Unit in Reverse Mode	Writes EOF Mark

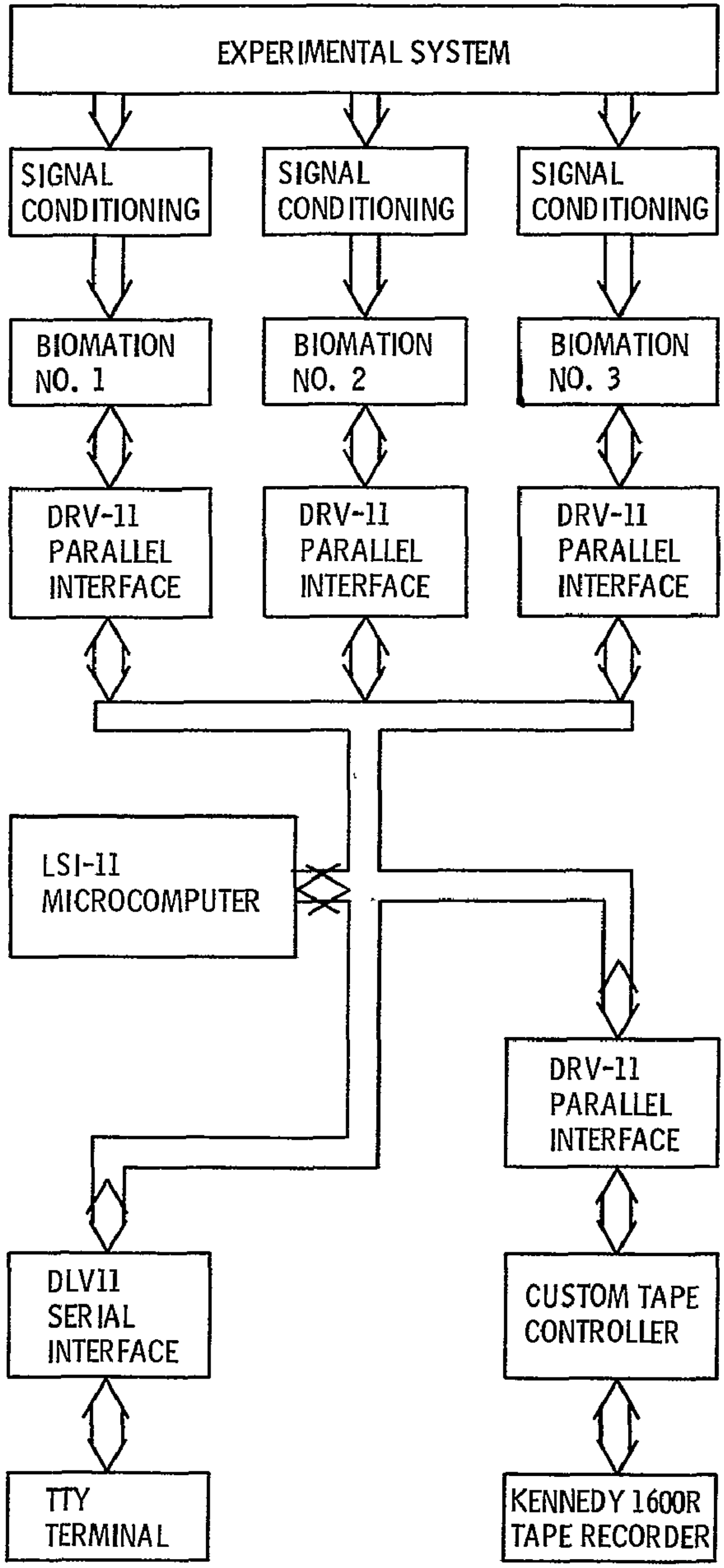


Figure 1. - Block diagram of system hardware.

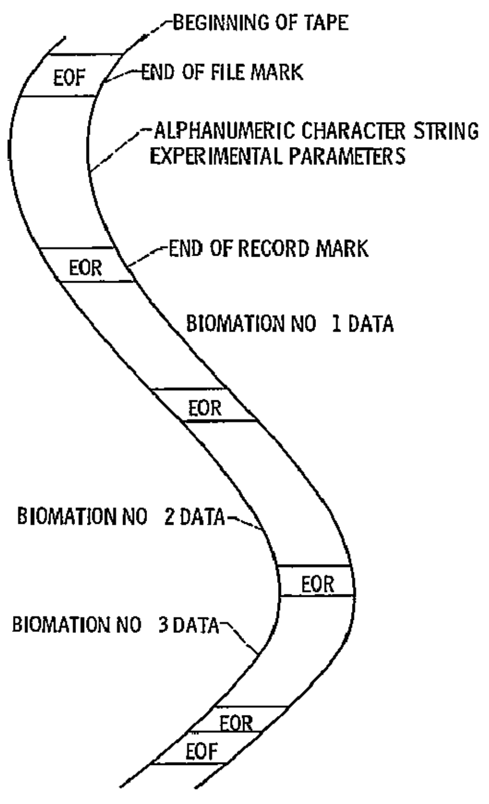


Figure 2. - CDC 6600 tape format for a nonstandard tape

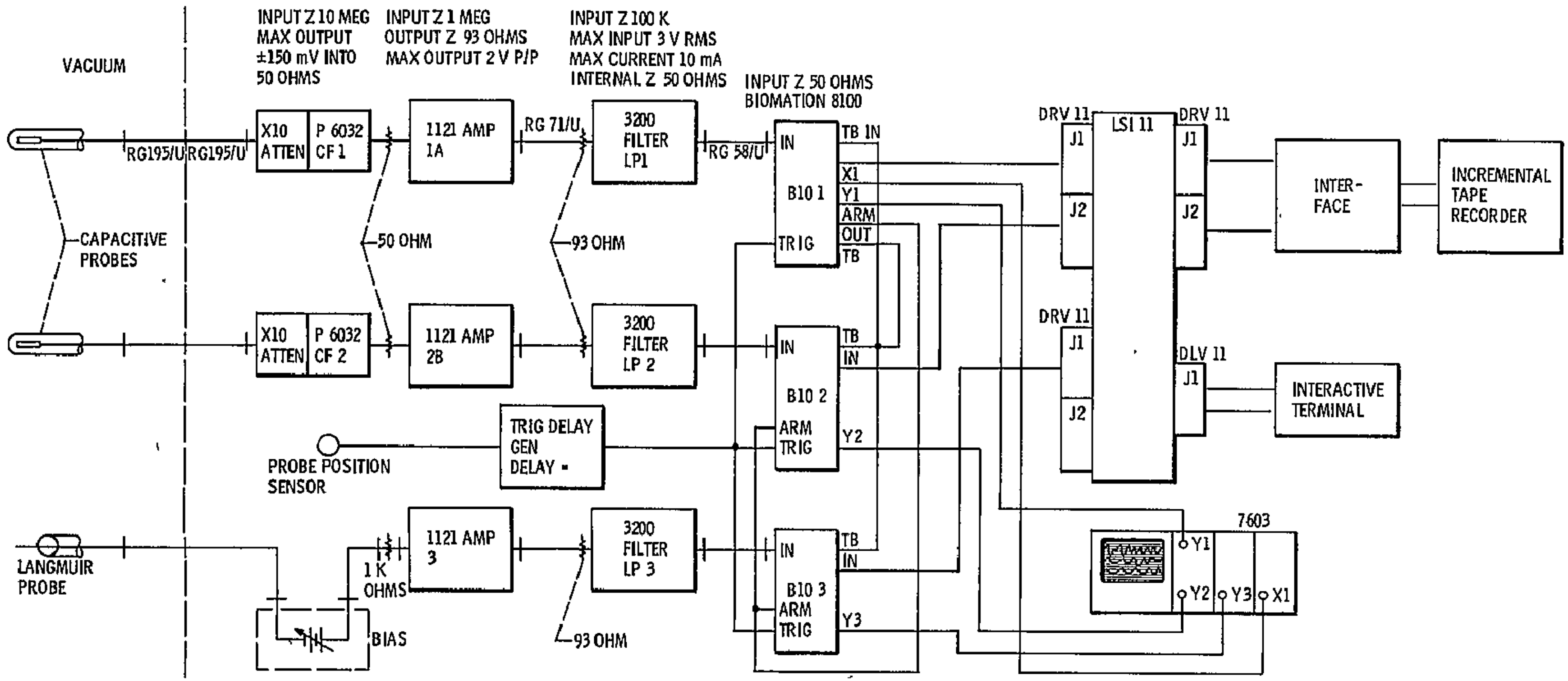


Figure 3 - Block diagram of data system

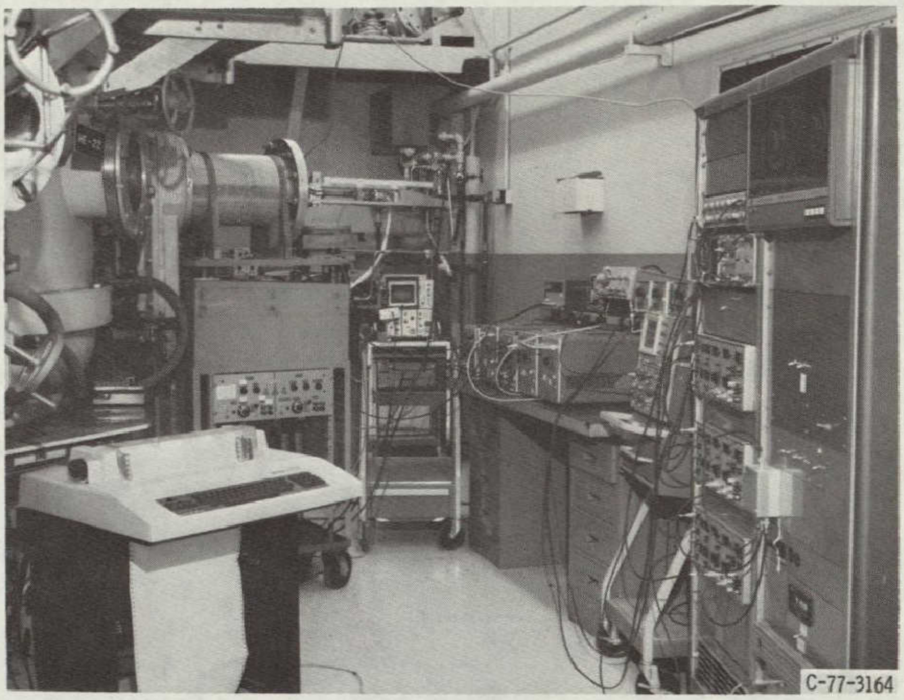


Figure 4.

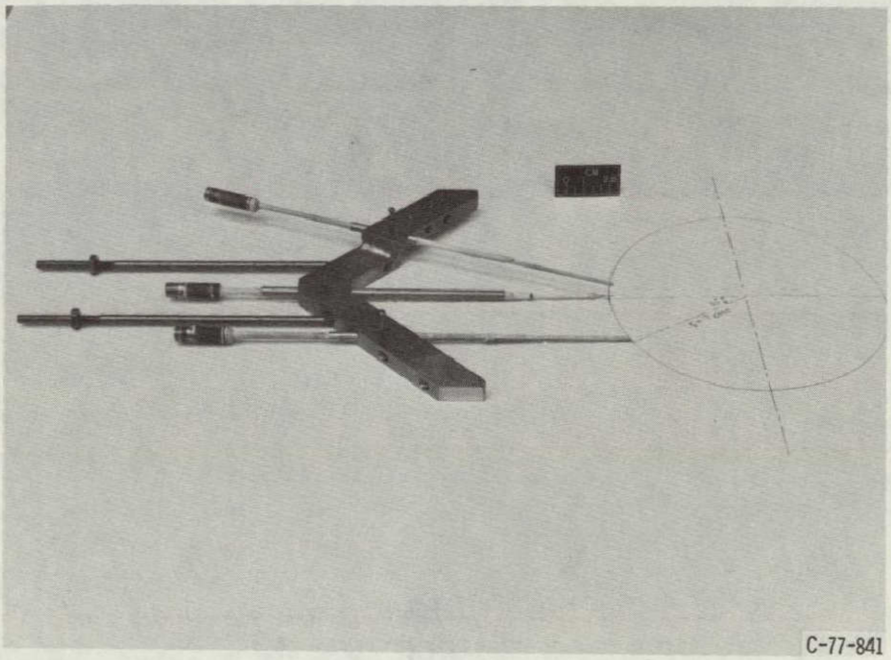
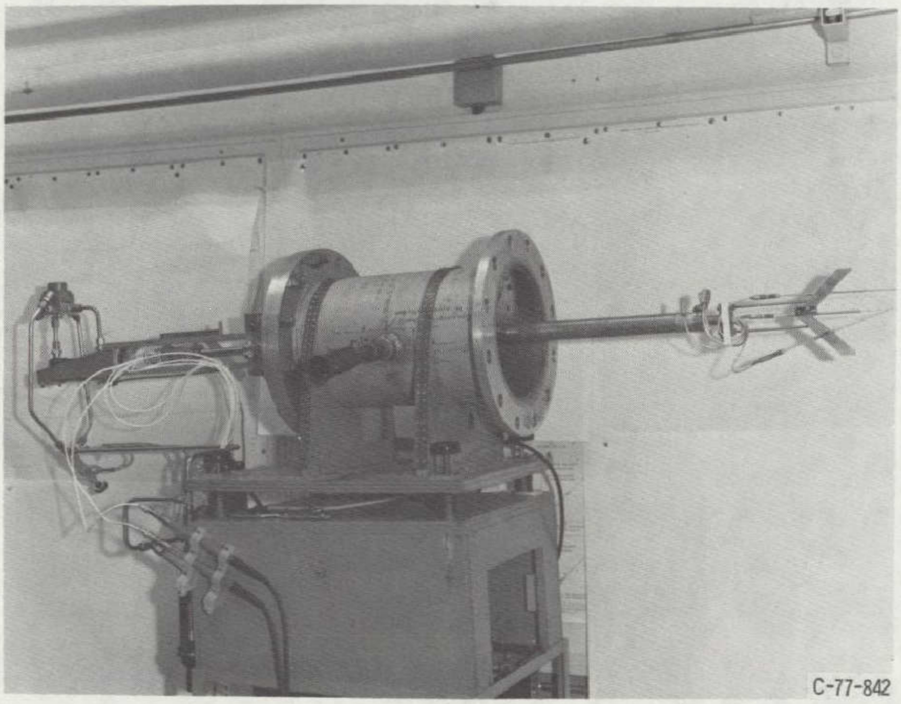


Figure 5.



C-77-842

Figure 6.

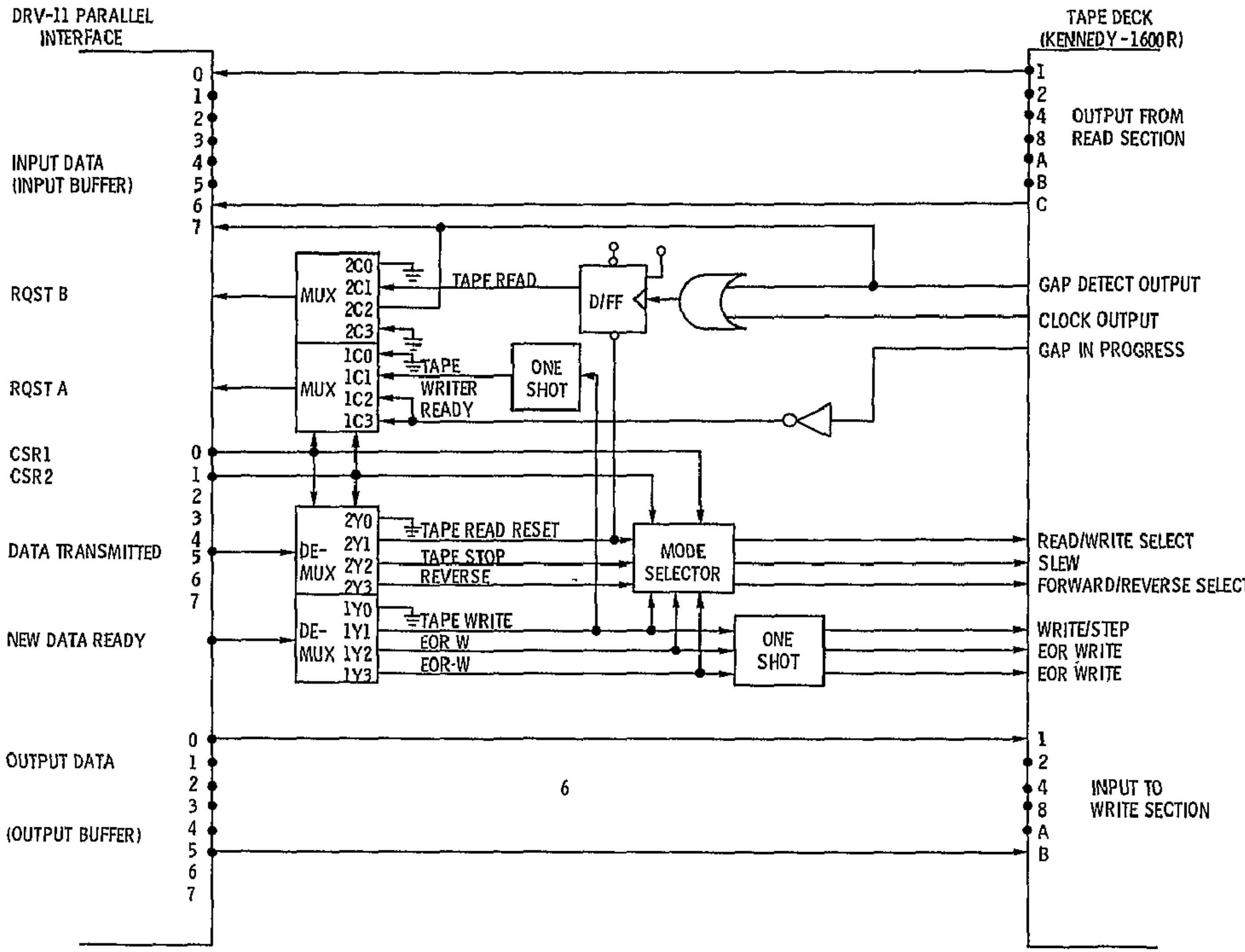


Figure 7. - Block diagram of custom tape controller.

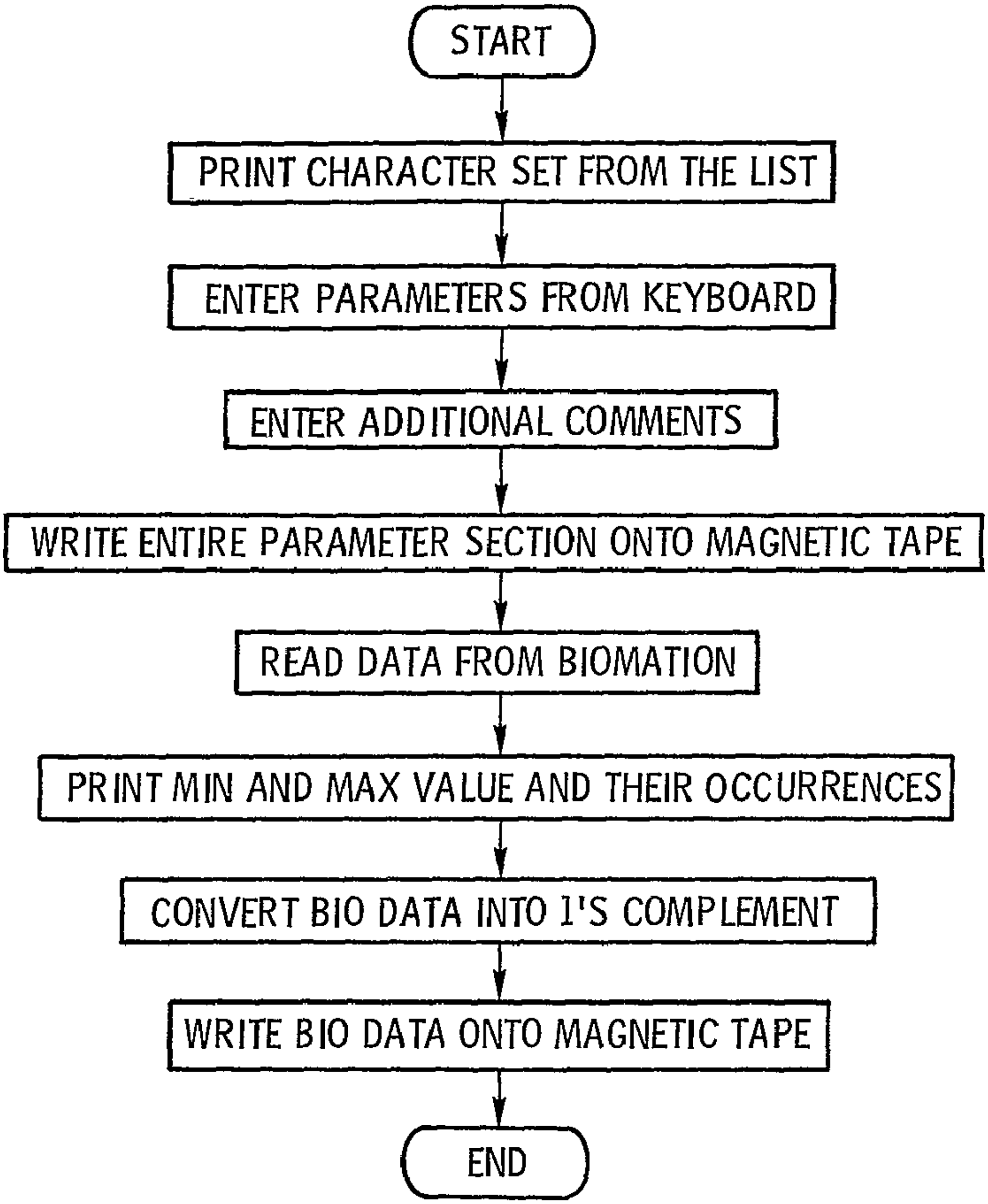
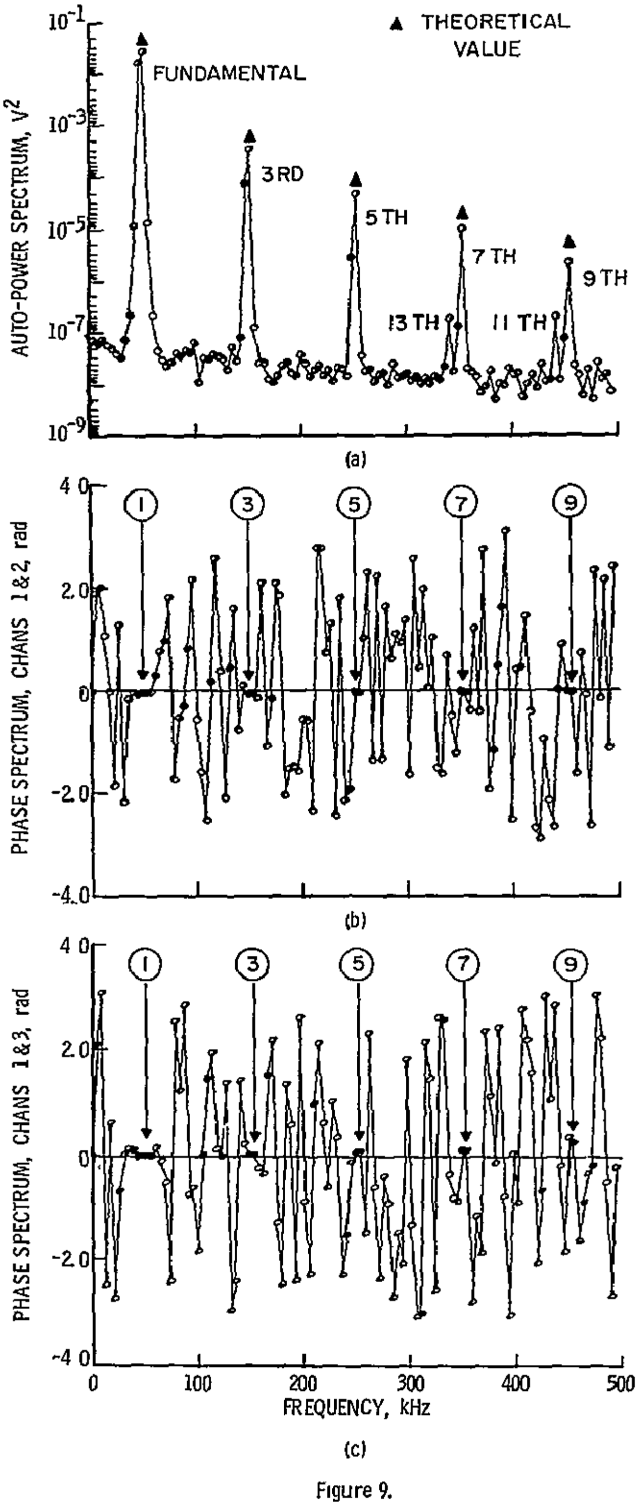


Figure 8. - Simplified flowchart for interactive program.



THEORETICAL VALUE
FUNDAMENTAL
3RD
5TH
7TH
9TH
13TH
11 TH
AUTO-POWER SPECTRUM, V2
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
(a)
PHASE SPECTRUM, CHANS 1&2, rad
4.0
2.0
0
-2.0
-4.0
(b)
PHASE SPECTRUM, CHANS 1&3, rad
4.0
2.0
0
-2.0
-4.0
0
100
200
300
400
500
FREQUENCY, kHz
(c)

Figure 9.

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