AN ON-LINE MASS SPECTROMETER

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ABSTRACT

A mass spectrometer has been interfaced to a computer for rapid data acquisition and analysis. The spectrometer, a Nier-type instrument, with a sixty degree sector magnetic field and six inch radius of curvature, is set up for gas analysis. The computer is a PDP-9 manufactured by Digital Equipment of Canada, Limited. The system avoids the expense of conventional on-line mass spectrometers by replacing the digital-to-analog-to-digital signal processing system with one utilizing direct digital data acquisition. The system has been used to measure the ratio of mass 46 carbon dioxide to mass 44 carbon dioxide, the ratio of ^{202}Hg to ^{200}Hg and the ratio of ^{82}Kr to ^{86}Kr.

LIST OF FIGURES

LIST OF APPENDICES

LIST OF PHOTOGRAPHS

TABLE OF CONTENTS

INTRODUCTION

The events with which experimental physics is concerned are quantal events. This fact is no less true in mass spectroscopy than in nuclear physics, but the types of detection apparatus used in the two fields have for some time been different in kind.

The mass spectroscopist has taken advantage of statistics in his detection apparatus. Aware that he can construct his spectrometers so as to deal with orders of magnitude larger numbers of events than can the nuclear physicist, he has constructed detection equipment which, in general, acts as a digital to analog converter, producing voltage levels or currents which are proportional to the rate at which detectable events are occurring in his apparatus, or proportional to the total number of such events which have occurred. While such apparatus may not detect one event, it will be able to detect some lowest number of such events, if they occur close enough to each other in time that the integrating effect of the detection device will add them together to produce a detectable change from the null condition.

This approach vastly simplified data analysis, for now it was possible to measure mass differences or isotopic ratios simply by measuring peak positions or relative peak heights, either on a strip chart, or in a more recent development, with an Enhancetron, an electronic device which digitizes the analog signal and stores it, very much in the manner of a multi-channel analyzer in the scale mode.

The advent of the electronic computer has induced mass spectroscopists, as it has most other physicists, to attempt to utilize the speed and accuracy of computers in the analysis of the output data of a mass spectrometer. By somehow feeding the analog output signal of the spectrometer to the computer, it was expected that properly written programs should be able to detect peak centres, separations, and relative peak heights, more reliably and with less bias than could a human operator, and thus could produce, in a very short time, a complete analysis of the data, including statistical computations which would require many hours of human labour to duplicate. The advantages in terms of saving man-hours were obvious, and many mass spectroscopists were quick to take advantage of them.

The most common detection devices which are utilized in mass spectroscopy are the vibrating reed electrometer, and the combination of electron multiplier and electrometer. Both of these devices produce output voltage levels which are analogs of the rate of detection of ions. For chart recording these levels are fed directly to the recorder. In the most common method of making this information useful to a computer, these levels are fed into a digital voltmeter, the output of which is coded and punched onto tape which can then be fed either directly or indirectly into the computer. Alternatively, it is possible to code the digital voltmeter output for direct access to the computer. These two processes are known as off-line and on-line applications respectively.

But, as has been pointed out in the opening paragraph, the basic output of the mass spectrometer is inherently digital. It is not necessary, therefore, to utilize a three-step process in which digital information is converted to analog which is then reconverted to digital and fed into the computer. Instead, it should be possible, indeed, it may even be preferable, to utilize directly the digital output of the spectrometer, bypassing the two conversion steps, because of the inevitable approximations involved in digital to analog conversion, e.g. the statistical fluctuation in electron multiplier output for single-mass, monoenergetic ions, and the further approximations involved in the analog to digital conversion. If these approximations could be avoided, the quality of information should be substantially improved.

The purchase of the PDP-9 computer from Digital Equipment of Canada, Limited, by the University of Manitoba, Department of Physics, has made it possible to attempt to put a mass spectrometer on-line, and to utilize digital techniques in data-acquisition. At the suggestion of Dr. B. G. Hogg, I have constructed the necessary electronics hardware to interface the spectrometer to the computer, and have written a program for the acquisition, analysis and subsequent output of the data. This will describe the system, and some of the results achieved with it.

II GENERAL THEORY

A charged particle, moving in a magnetic field, is subject to a force which is dependent on the sign and magnitude of its electric charge, its velocity and on the strength of the magnetic field. Mathematically, it is expressed as

$$\underline{F} = q\ \underline{v} \times \underline{B} \qquad 1)$$

where $\underline{F}$ is the force vector, q the charge, $\underline{v}$ the vector velocity, and $\underline{B}$ the magnetic field strength. The vector product of the velocity and the field strength is denoted by X.

If we impose constraints upon the motion of the particle, and upon the shape of the field, we can specify a particular direction for the action of the force. We therefore specify that the particle enter the magnetic field at right angles to both the field direction, and to its boundaries, which we assume to be discontinuous. We further impose the condition that the field be uniform. Under these contitions, the vector product has the magnitude of the algebraic product and a direction perpendicular to both the velocity and the field direction. Since the force acts at right angles to the instantaneous velocity, it does not affect that velocity, but provides a component of momentum at right angles to it. This force is therefore a central force, the magnitude of which is given by elementary mechanics as mv^2/r, where m is the particle mass, and r is the radius of curvature of its circular path. Thus,

$$qvB = mv^2/r \tag{2}$$

or,
$$r = mv/qB \tag{3}$$

and we have established a condition in which the path followed by a singly charged ion in a uniform magnetic field depends only on its momentum. The result of passing a beam of such ions of no particular mass or energy through a magnetic field in this manner would be a momentum spectrum. A doubly charged ion would act like one of half the momentum, a triply charged ion like one with a third of the momentum, and so on.

If we now specify that these ions are to be produced in a source and accelerated by falling through a potential drop, they will all have the same energy,

$$\tfrac{1}{2}mv^2 = qV \tag{4}$$

where V is the potential drop. Solving for v in equation 3) and substituting, we have:

$$\tfrac{1}{2}m(qBr/m)^2 = qV \tag{5(a)}$$

or,
$$\tfrac{1}{2}qB^2r^2/m = V \tag{5(b)}$$

or,
$$m/q = B^2r^2/2V \tag{5(c)}$$

or,
$$r = (2Vm/q)^{\frac{1}{2}}/B \tag{5(d)}$$

Now, for singly charged ions of identical energy, moving in a uniform magnetic field, the radius of curvature of the circular motion they follow will depend only on the ionic mass, and the momentum spectrum will have become a mass spectrum, when the constraint of mono-energetic ions is applied. This, then is the basic theory of a mass spectrometer.

As well as the dispersion effect discussed above, magnetic fields possess focussing properties which enable them to provide momentum and mass spectra of divergent beams of ions whereas the discussion above is restricted to single ions or beams with strictly identical paths for all ions. The refocussing property of magnetic fields was first used for mass analysis by Dempster in 1918. It was not until 1934, however, that a general analysis of this property was published by Herzog. He was able to show that the semicircular magnetic field of Dempster was a special case of the general sector magnetic field, the refocussing properties of which had recently been demonstrated by Barber and Stephens.

He considered the problem of a divergent beam of mono-energetic ions impinging on a homogeneous magnetic field with sharply defined boundaries. The beam is produced at point P_1. Herzog found the condition for first-order refocussing of this beam at a point P_2 to be:

$$r \sin\phi + L_1 \frac{\cos(\phi-\varepsilon_1)}{\cos\varepsilon_1} + L_2\left[\frac{\cos(\phi-\varepsilon_2)}{\cos\varepsilon_2} - L_1\frac{\sin(\phi-\varepsilon_1-\varepsilon_2)}{r\cos\varepsilon_1\cos\varepsilon_2}\right] = 0 \qquad 6)$$

where r is the radius of curvature of the beam in the magnetic field, L_1 the distance from P_1 to the point where the central ion ray strikes the boundary of the magnetic field, L_2 the distance from the exit point of the central ion ray on the boundary of the magnetic field to the focussing point P_2, ϕ the angle of deviation of the central ion ray in the magnetic field, ε_1 the angle which the central ion ray makes with the field boundary at the point of incidence, and ε_2 the angle which the central ion ray makes with the field boundary at the point of emergence.

If we restrict ourselves to the case where the beam strikes the boundary at right angles, $(\varepsilon_1 = \varepsilon_2 = 0)$, and in which the distances L_1 and L_2 are equal, i.e. the case of the symmetric spectrometer, the condition for refocussing at P_2 to first order may be reduced to

$$L = r(\cot\phi + \operatorname{cosec}\phi) \qquad 7)$$

where $L = L_1 = L_2$. This is the mathematical statement of Barber's Rule, which specifies that the object point, image point, and centre of curvature of the ion orbit, lie on a straight line. This rule applies to asymmetric as well as symmetric spectrometers.

This refocussing is, however, not perfect. From simple geometric considerations, one can see that a diverging beam entering a uniform magnetic field will suffer a spherical aberration of $2r(1 - \cos\alpha)$ resulting from the non-uniqueness of the centre of curvature for different ions in the beam, where α is the half-angle of divergence. Where α is small, the focussing error may be expressed as $r\alpha^2$ to first order in α. This is the formula for a symmetric instrument, which is derived from a more general formula deduced by Stephens for the total spread S, measured normal to the central ray at the position of best refocussing, which is given by

$$S = (r\alpha^2/2)(((l_2^2 + r^2)/(l_1^2 + r^2))^{\frac{1}{2}} + (l_1^2 + r^2)/(l_2^2 + r^2)) \quad 8)$$

Examination of the reduced first-order focussing condition reveals that it demands that the source point, the apex of the magnetic field, and the image point must lie on a straight line. Deviations from this condition result in further aberrations. Aberrations are also produced by the non-discontinuity of the field boundaries, field inhomogeneities, space charge effects (negligible in this instrument because of the low currents at which it is used), and deviation from the condition of monoenergetic ions.

The resolution of a mass spectrometer will naturally depend on the extent to which such aberrations can be avoided or corrected for. An expression for the resolution of the instrument may be derived as follows. Two beams of ions, one having ions of mass M, and the other having ions of mass M + dM, will be completely distinguished only when the dispersion is equal to or greater than the sum of the collector slit width plus the total image spread. If the source slit width is given by S_1, let the collector slit width be given by S_2. Since most of the aberrations are functions of the radius r, we will denote the image widening by A(r), and the total image width will then be given by $S_1 + A(r)$. The resolution is then found from

$$r(dM)/M = S_1 + A(r) + S_2$$

The theoretical limit to the resolving power in the case of no aberrations is then:

$$M/dM = r/(S_1 + S_2)$$

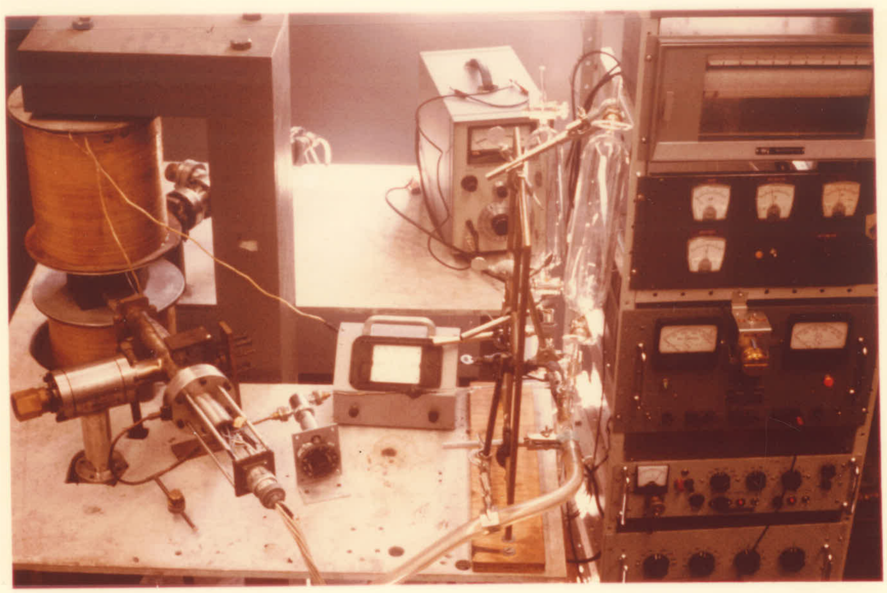
This limit has a value of approximately 1000 for a 6" radius instrument. The resolving power is usually measured by measuring the separation, at the base line, of the two peaks. It is often convenient, however, to make this measurement at the half-maximum of the peak, where the actual location of the base line is in doubt. This second method has been the one used for this instrument, and naturally gives a somewhat larger figure for the resolving power than does the other.

The limiting value of resolution stated above corresponds to 0.003" slits which is the practical limit of adjustment for the source slits in this instrument. For a 6" radius of curvature, and an α of 0.02 radians corresponding to such slits, $r\alpha^2$ is 0.003", representing a broadening of the beam by an amount equal to its width. In the face of such large first order effects, higher order aberrations are unimportant, and all together probably do not contribute more than an additional 0.001" of broadening. These are minimum values, for optimum slit widths, and the first order aberrations will increase slightly faster than linearly with the slit width.

III THE SPECTROMETER

The spectrometer is a Nier-type unit, which was constructed partly in Winnipeg and partly in Dr. Nier's laboratory in Minneapolis. It has a six inch radius of curvature and a sixty degree sector magnetic field. The source is of the type developed by Nier for gas analysis. The sample is admitted to the source as a gas and passes through the ionization region where it is bombarded by electrons boiled off a filament carrying a current of 4.5 A. This current is adjustable and is supplied by a 6 V. lead-acid battery. These electrons have an energy in the neighbourhood of 135 V. in the ionization region. This is obtained by the use of three 45 V. dry cells placed in series, with the positive terminal of the combination connected to the shield which provides the positive high tension for ion acceleration. The negative terminal is connected to the positive terminal of the 6 V. battery. Thus the filament battery and filament are held at -135 V. with respect to the shield. The electron trap, a small metal box placed across the ionization region from the filament, and isolated from the shield, is held 45 V. positive with respect to the shield by means of another battery and collects electrons which make their way across the source region. The ions are repelled by the shield, usually held at 2100 V. above ground potential. The shield is connected to ground by a series combination of ten 270 K. ohm resistors and a 11 Megohm resistor, which form a voltage divider. The ion beam passes through a series of collimating slits, into the beam pipe and towards the magnetic field. One such slit consists of two semi-circular plates which tap into the voltage divider network which supports the shield voltage. They can be adjusted with respect to ground by means of a double stepping switch whose two contacts always span two 270 K. ohm resistors. This means that the voltage across the two contacts is 85 V. The lower contact can move from 1675 V. to 2015 V., and the upper contact is always 85 V. higher, when the shield is at 2100 V. The two plates are further isolated from each other (see Fig. 3, contacts J_1 and J_2.) by means of a pair of 1 Megohm potentiometers which are cross connected and then attached to the terminals of the double stepping switch. This arrangement permits the mean voltage of the plates to be varied in 85 V. steps from approximately 1720 V. to nearly 2070 V. Further, the relative voltage between the two halves of the slit can be adjusted from -85 V. to 85 V. This provides a means for centering of the ion beam.

To provide the maximum possible resolution, it is necessary that the ions be formed in as small a volume as possible, necessitating some focussing of the bombarding electrons. To this end, a pair of small permanent magnets is placed outside the beam pipe on a small U-shaped iron stand. The air gap between the pole faces of the two magnets is filled by the beam tube when the magnets are in position. The direction of the magnetic field produced by this pair of magnets is directed parallel to the filament-electron trap line. Thus, any electrons which have a component of momentum which does not lie on this line



Photograph 1: Spectrometer and Control Panel

will experience a force tending to bend them back towards the line. The off-axis motion will then be converted into a circular motion, and the electrons will move in a helix through the sample gas. Thus, an electron which has a component of momentum corresponding to one-third of its kinetic energy perpendicular to the axis will move in a helix of radius approximately 0.4 cm., centered on the axis. Without the magnet it would strike the far side of the shield box about 1 cm. from the axis. Clearly this magnet can provide a great improvement in the focusing of the electron beam. If the ions are produced as nearly as possible in the same region, the effects of field gradients in the source can be minimized, with consequent improvements in the energy distribution of the ion beam. In practice it has been found that, the best resolution attainable when no particular attention was paid to source magnet position was on the order of 250. When the spectrometer was focussed on the ^{40}A peak, and the source magnet adjusted to provide for maximum beam it was found that it was possible to increase the beam intensity by nearly two orders of magnitude, and the resolution by a factor of four. It is not, however, necessary for the trap current to be a maximum for these optimal conditions.

The magnet was constructed in Winnipeg by the Dominion Bridge Co., Ltd., Winnipeg. The pole faces are made of mild steel, as the flux densities are relatively low, on the order of 3 kG. for focussing of mass 45. The dimensions of the pole faces and yoke are shown in Fig. 2.

The beam pipe was constructed in Minneapolis and is made from 2" O.D. stainless steel pipe. The portion which passes between the pole faces has been pressed to form a pipe of mearly rectangular cross-section. The source is mounted on a flange which has a short length of this pipe on its upstream end. This pipe is sealed with a glass plug and the electrical feedthroughs to the source are made through this glass. The gas inlet to the source is through a hole drilled radially into the flange itself. Inside the flange a glass tube takes the gas from a small pipe protruding from this hole, to the ionization region. There are four other distinct components in the beam pipe. First, the curved flattened portion which passes between the pole faces of the magnet. Secondly, a 2 and 3/16 inch long spacer which has been included in the design so that the spectrometer may be adapted for double focussing operation by the addition of an electrostatic analyzer, and by the removal of this spacer. Thirdly, the detector slit and detector housing assenbly, and fourthly, the detector itself. The detector slit is adjustable by means of a spring-loaded push rod, driven by a second push rod, which itself moves in response to a motion of the threaded knob in which it is seated. The two push rods are separated by an aluminum diaphragm for vacuum sealing. The detector is mounted on a blank flange, and all connections to the detector are made through insulated feedthroughs on the blank face of the flange. The detector is a ten-stage DuMont SPM. It is customarily operated at -3400 V. at the target dynode. A suppressor grid prevents secondary emission electrons released at the target from proceeding back up the beam tube towards the source. It normally provides a gain of the order of 10^5.

The magnet mount is provided with wheels and can be rolled along a horizontal line at right angles to the source slit-detector slit line. The entire beam tube is thus exposed. An asbestos box has been constructed which encloses the entire beam tube with the exception of the detector, and which has a length of heating element suspended from its inner surface, which permits baking of the vacuum system at temperatures of the order of 200 degrees C. Unfortunately, the present arrangement does not permit proper baking of the inlet system.

Vacuum is maintained by three pumps. Two of these are mechanical Duo-Seal Vacuum Pumps, capable of pumping at 33.4 litres/min. @ 300 r.p.m. The third is a VacIon pump by Varian Associates, which is rated at 8 litres/sec. One mechanical pump operates on the inlet system, and is in continuous operation. The other mechanical pump acts as a roughing pump, pumping on the beam tube to bring its pressure down to the point where the VacIon pump, which can be sealed off by a valve, is capable of pumping efficiently. The mechanical pump is cut off from the system by a valve when the VacIon valve is opened, so as to prevent pumping through the mechanical pump into the spectrometer. All flanges in the beam pipe are sealed with copper gaskets.

Other associated apparatus consists of:

1) Power supplies:

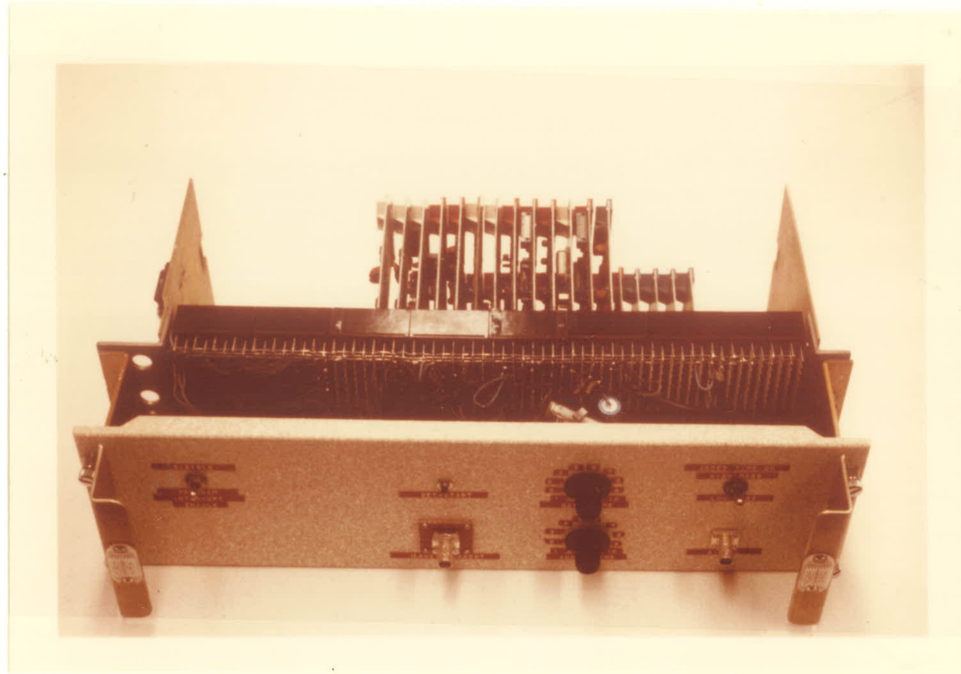
   a) John Fluke Manufacturing, Co., Inc., Model 408A DC Power Supply (0-6010 V.), which provides the -3400 V. for the electron multiplier.

   b) Fluke Model 413 A/Ag DC Power Supply (0-3600 V.), which provides the 2100 V. acceleration bias.

   c) A Regatron DC Power Supply, of the Electronic Measurement Company (0-1000 V.), which provides the magnet current. This supply has been provided with a small electric motor, which rotates the current control potentiometer, enabling the operator to scan slowly through the spectrum.

2) An S11U/A/DV.5M Strip Chart Recorder, Westronix, Inc.

3) Keithly 610 A Electrometer.



Photograph 2: Complete Interface

IV THE COMPUTER

The Programmed Data Processor-9 or PDP-9 is an electronic computer manufactured by Digital Equipment of Canada, Ltd. of Carleton Place, Ontario. It is constructed entirely from solid state hybrid circuits distributed in blocks or modules. Each module is usually restricted to one or several examples, depending on circuit complexity, of a particular circuit. For example, a single module may contain one bistable multivibrator (flip-flop), two one-shot delays, three diode gates or four inverter circuits.

The PDP-9 system is a single address, 18 bit word, parallel binary computer. It comes with various combinations of peripheral devices. The computer purchased by the Cyclotron Group of the Physics Department of the University of Manitoba includes the elements of the basic PDP-9 configuration:

1) central processor and integrated control console,
2) core memory stack of 8192_{10} (17777_8) 18 bit words,
3) a paper tape reader (300 cps),
4) a paper tape punch (50 cps),
5) an input/output teleprinter, Teletype Model KSR 33,
6) a real-time 60 cps clock,
7) input/output facilities:
    a) I/O bidirectional bus (or I/O Bus)
    b) four data channels (DCH)
    c) a direct memory access channel (DMA)
    d) a program interrupt control (PI)

e) I/O status word provision

f) conditional skip on external device status

Furthermore, the system has been expanded to include:

1) an oscilloscope and light pen

2) an ADC interface to the Nuclear Data N.D. 160 F analyzer

3) a Calcomp plotter

4) two Dectape units. This is dual track, fixed-address magnetic tape. It is not compatible with IBM mag tape.

5) Extended Arithmetic Element (EAE)

6) Automatic Priority Interrupt (API)

In future, it is hoped that it will also be possible to interface the PDP-9 directly to the IBM System 360-65 computer owned by the University of Manitoba, and to take advantage of the on-line capabilities of the PDP-9, and the high-speed, large memory computational facilities of the 360-65.

The speed of the PDP-9 is defined as the time required to load a word from memory into the memory buffer, and since this is destructive of that word in the memory, it includes the time necessary to rewrite the word into its former location. The information, after one such cycle, exists in its former location and in the memory buffer (MB). This is defined as the cycle time. For the basic PDP-9 with an 18 bit word, this cycle time is 1 microsecond. It is possible to extend the PDP-9 word to 19 bits, in which case the cycle time is increased to 1.2 microseconds.

The MB, or memory buffer is an 18 bit register which is intermediate or "buffers" between the memory proper and the central processor. Normally, the memory is addressed through the central processor unit (CPU). That is, any peripheral device, e.g. an on-line experiment, the tele-printer, or the tape reader, reads data from the memory, or writes it into memory via the I/O Bus and the CPU. It is possible, however, to bypass the CPU, allowing direct access to the memory. This is offered by the DMA facility. The functions of the CPU must necessarily be halted while DMA is being used, but this system allows very rapid data transfer, each such transfer requiring only one machine cycle. DMA transfers have priority over all other system actions, and are especially useful for high data-rate devices. Up to three devices may be serviced in this way, by multiplexing this input. Use of this method of addressing the memory clearly involves special interfacing problems, since the peri-pheral device must provide a series of core-driving currents, rather than voltage levels, which are used in the rest of the computer.

A slightly slower method of accessing the memory is known as data channel (DCH). The processor is suspended for three or four cycles (for read-into-memory or write-from-memory applications, respectively) while the peripheral device addresses the memory directly through the MB, rather than the CPU proper, the other major registers of which are not disturbed. Four peripheral devices may be serviced in this manner.

If the input data requires processing before storage, it clearly must be handled directly by the CPU. This can be done in several ways. If the device to be serviced is the only one on-line, then clearly no special arrangements need be made for the use of the CPU, and and the data word can be fed directly into the CPU through the I/O Bus, where its arrival will trigger the processing subroutine, and from which it will be stored via the MB.

If, however, other devices are also on-line, it is then possible that both devices will require servicing simultaneously. Clearly, some method of assigning priorities is necessary. This is achieved through the use of the automatic priority interrupt or API. Each peripheral device is given a priority level, and the CPU, if it is working for one of the devices, will grant an interrupt, that is, stop working on the original program and jump to a subroutine to service the requesting device, after storing the program count and accumulator contents in memory, only if the interrupting device has a higher priority than the interrupted device. If this is not the case, the CPU completes the present job before it grants the interrupt requested.

The final method of servicing several peripheral devices simultaneously involves the program interrupt (PI) system. With the PI, each device has the same priority level and any device can interrupt any other device. This method is particularily useful where there is a mixture of high and low data-rate devices on-line. While most of the computer time is allocated to the high data-rate device, the low-rate device is still assured of service, which it would not be under the API system, unless it were of higher priority.

Mixing of the different modes of executing I/O transfers is possible. That is, DMA, DCH, API, and PI may all be operating simultaneously. If this is the case, some priority must be established among these modes so that, for example, PI does not interrupt DCH. The following priority structure has been established for operation of the PDP-9:

1) DMA
2) DCH
3) Real-time clock counting
4) API
5) PI
6) Main program in progress.

If high data-rate usage is not a problem with the computer, it is then possible to have the computer periodically interrogate each of the peripheral devices in turn, to see which of them, if any, is ready to be serviced.

The computer waits in the interrogation loop until one of the devices signals that it is ready to be serviced, whereupon the computer jumps to that service subroutine, after which it returns to the interrogation loop.

All transfers which are made under program control, i.e. everything except DMA, require programmed instructions to carry out the transfer. Even DMA, of course, operates under program control, in the sense that some instructions must be delivered to suspend operation of the CPU and to restart it again. A pair of instructions is the minimum possible for such a transfer. Upon receipt of a program interrupt request, whether by PI, API, or DCH, the computer issues a pulse which checks to see that the device really has signalled that it is ready to be serviced. This is referred to as the IOT 1 pulse (input/output transfer-IOT). The number 1 refers to the fact that the pulse is generated if the instruction word has a 1 in its lowest order bit, e.g.

$$111000101000000001_2$$

The awkwardness of binary notation for everyone but the computer has led to the shorthand octal notation. The 18 bit word is split up into groups of three bits, and the word is then written as an octal number. Unless otherwise noted, all numbers found in this thesis are decimal numbers. A subscript 8 after a number indicates that it is an octal number. Thus the above binary number can be shortened to:

$$705001_8$$

which is the machine language instruction for:

70- issue an IOT pulse

50- direct the pulse to device 50

01- this is to be an IOT 1 pulse).

If the results of issuing an IOT 1 pulse are positive, in a manner to be discussed further in the chapter on the interface, the computer is instructed to deliver an IOT 2 pulse by the command:

$$705002_8$$

The reason it is called an IOT 2 pulse should by now be obvious. This pulse reads the data word into a segment of the CPU. In order to prevent the previous contents of this register from affecting the incoming data word, it is cleared before the word is read. This is accomplished by a slight modification of the above instruction. It is changed to:

$$705012_8$$

The data word is now in the CPU, and operations may be performed on it.

A third pulse, the IOT 4, is available from the computer to provide a second read command, or to clear and reset a device's data register or flag, the flip-flop which issues the program interrupt when it is set. It may not however, be used to test the flag. The IOT 2 pulse, like the IOT 4 may not test device flags, but may be used as a clear or reset command. The IOT 4 pulse is called by:

$$705004_8$$

The second pair of digits represent the device number, and 50_8 has been used here only as an example. Clearly there are 100_8 possible device numbers, some of which are used by such standard devices as the teleprinter, tape reader and punch, or the Dectape system.

The I/O facilities of the PDP-9 have all been discussed, albeit in something less than complete detail, with the exception of the I/O Bus itself, and the manner in which the devices are linked to the computer. All peripheral devices are chain-linked, that is, hooked up in series, and only the first one is in direct connection with the CPU. I/O information passes through each of the devices in turn. It is for this reason that all the devices are numbered, and explains the searching routine which the computer must follow when it is operating in the PI mode. Each IOT pulse is thus coded so that it will be recognized by only one of the peripheral devices. Physically, the connection is a 144 conductor cable of which approximately one-half are grounds for the co-axial cables used to carry pulses to and from the CPU.

The CPU, into which the data word has been loaded consists of seven major registers and three control elements. Transfers between registers are accomplished through a transfer bus. Data is jam-transferred between registers at DC levels to minimize timing problems. No logical delays are used at this level, to keep the circuits simple. The jam-transfer system is such that data can be shifted from one register to another at the same time as new data is read into the first. In a sense, the new "jams" the previous contents of the register into the next register.

The seven major registers are:

1) Adder (ADR)- a 19 bit register which performs as a fast adder for arithmetic operations and is also the path for all inter-register transfer and shift operations.

2) Accumulator (AC)- an 18 bit register, which retains the result of arithmetic or logical operations between instructions. Arithmetic and logical operations may also be performed on the AC.

3) Link (L)- a one bit register extends the arithmetic capability of the AC. It is included with the AC in arithmetic and logical instructions and operations, but may be referenced and sensed independent of the AC:

4) Arithmetic Register (AR)- functions with the AC in arithmetic operations. It is not accessible to the programmer.

5) Multiplier-Quotient Register (MQ)- part of the optional EAE package, it is used as a part of the AC in multiplication, division and normalization.

6) Program Counter (PC)- a 13 bit register, which may be increased to 15 bits with memory enlargement, which contains the address in memory of the next instruction to be executed.

7) Memory Buffer (MB)- an 18 bit register through which

all data transferred into or out of memory (with the exception of DMA transfers) must pass.

Clearly, some elements must be present to organize the activities of these registers, and to execute the operations ordered by the words. This function is fulfilled by the three control elements:

1) Instruction Register (IR)- a five bit register which examines the first five bits of an instruction word to determine the entry point into the control memory microinstruction sequence necessary to effect the desired response. The first four bits indicate the nature of the instruction and the fifth specifies direct or indirect addressing. The latter will be considered more fully when the addressing system is discussed. In the IOT instructions discussed above, the first five bits are: 11100_2. The 1110_2 indicates an I/O instruction. The 0 in the fifth bit indicates direct addressing. Indirect addressing would be indicated by a 1 in this position.

2) Control Memory (CM)- a very fast, read-only, magnetic core storage unit, prewired with the microinstruction sequences required to fetch and execute program instructions, to effect operation of the data channels, and to respond to commands initiated at the control console.

3) Control Register (CR)- delivers gating signals to transfer busses and readdresses the CM depending on the sensed conditions.

The memory of the PDP-9 is a random-access, magnetic core storage unit. The basic unit contains 17777_8 words, but it may be extended in increments of 17777_8 to a maximum of 77777_8 words. Each memory module is self-sufficient in terms of sense amplifiers, core drivers, and a memory address register and has two ports for data entry and retrieval. One is connected to the MB and the other to the DMA bus.

All addresses in the core memory are referred to in octal notation. The instruction word format for memory reference instructions in the PDP-9 consists of a division of the basic 18 bit word into three groups or fields. The first of these consists of the 13 bits from bit 5 to bit 17. This field specifies the address to which the instruction refers. Clearly, only 2^{13} or 8192 or 17777_8 different possible locations can be addressed with a binary field of this size, indicating the rationale behind the choice of this number as the basic memory size for the PDP-9. For an extended memory it is necessary to include up to 2 additional bits to this field. This is accomplished by the option known as the Memory Extension Control, which also extends the PC, and permits addressing across memory module boundaries.

The second field is only one bit long. Bit 4 specifies whether the address specified by the first mentioned field is the address of the data word to be processed, or whether it is the address of the address of the data word. The first possibility is denoted by a 0 in bit 4, and is referred to as direct addressing; the second is denoted by a 1 in this position, and is referred to as indirect addressing.

The third field is the remaining four bits, 0-3, which indicate the instruction to be executed.

Eight locations in memory (10-17), are autoindex registers, which, when addressed indirectly, are incremented by one and the resulting contents of the register are considered as the effective address for the instruction. Autoindexing occurs only on indirect reference to an autoindex register.

The set of instructions which can be issued to the PDP-9 is subdivided into two sets: those which refer to the memory, and those which do not. A "memory reference instruction" references, either directly or indirectly, a location in memory in order that the contents of that register may be read out, or changed. The other type of instruction is referred to as the "augmented instructions" in that the full 18 bits can be utilized for specifying an operation. This group is further subdivided into three classes, operate instructions, IOT instructions, and EAE instructions.

The format for memory reference instructions has already been discussed. It is to be noted that with a field 4 bits long, only 2^4 or 16 memory reference instructions are possible. However, only 13 of these are utilized. The other three must be retained to specify which of the three augmented instruction subclasses is being called. The octal code 64 represents EAE instructions, and particular instructions are specified by the remaining 14 bit field. 70_8 represents IOT instructions as in the example used previously. The 14 bits remaining are used as follows in IOT instructions:

bits 15-17: indicate which IOT pulse or combination of pulses is to be delivered.

bit 14: indicates the clearance (1) of the AC prior to issuance of the read-in command pulse IOT 2 or IOT 4.

bits 6-11: gives the device code (2^6 or 100_8 devices).

bits 12-13: permits selection of a sub-section of a device (which permits a maximum of 256 on-line devices).

bits 4-5: unused.

The octal code 74 represents operate instructions, which are used to sense or alter the contents of the link and AC, and the remaining 14 bits specify which operation is to be executed.

The list of all instructions is shown in the Appendices. This list also includes instructions which are not applicable to our PDP-9, because we do not have the options to which they refer. They are included in the expectation that some or all of these options will be part of the PDP-9 package at the University of Manitoba at some future date. Also included is the list of octal codes for the various letters, numbers, and other characters to be used in addressing the teletype.

All arithmetic operations in the PDP-9 with the possible exceptions of addition and subtraction are conducted in 2's complement arithmetic. It is possible to perform addition and subtraction in either 1's or 2's complement arithmetic. Signed numbers can also be recognized by the computer. The highest order bit, bit 0, indicates sign by its state. A positive number is represented by a 0 in this bit, while a negative number is represented by a 1.

Taking sign into consideration, the largest number which can be stored in a single word is $2^{17}-1$, and the lowest is $-2^{17}-1$. If no sign is considered, the 0^{th} bit can be used simply as another factor of 2, giving a maximum of $2^{18}-1$ and a minimum of zero. It is possible to extend the range of numbers storeable in the computer, by utilizing what is known as double precision arithmetic. In this case two words are used for number representation, giving, with sign, a range from $-2^{35}-1$, to $2^{35}-1$, or an unsigned range from 0 to $2^{36}-1$.

All arithmetic operations on the PDP-9 are accomplished in fixed point arithmetic, that is, the octal or binary equivalent of the decimal point in 10's notation, called the octal or binary point respectively, must be kept track of by the programmer. It is possible, however, to write a subroutine which will automatically monitor the position of the octal point. This subroutine is available as the Floating Point Package. It also includes several mathematical subroutines which can be done in floating point simply by calling up the appropriate section of the package.

It is to be noted that all the instructions used by the PDP-9 are in numeric codes. It would be virtually impossible for a programmer to remember all the instruction codes in binary format, hence the use of octal representation of binary numbers. This is somewhat easier, but the use of mnemonics greatly facilitates program writing for most programmers. The PDP-9 Basic Software Package (a package of basic programs) therefore includes a program which permits the programmer to write his program into the computer in symbolic language, i.e. that one using mnemonics, which stores the program in this form, types out any portion of the program on the teletype, permits the programmer to change or augment his program, and which can punch it out, in symbolic form onto a paper tape, or read it onto Dectape, in one of two code forms. This program is called the Symbolic Tape Editor. Use of another program, the Symbolic Tape Assembler, then converts the symbolic tape into a binary form acceptable to the computer. The language used contains no mnemonics, and is referred to as machine language. The computer cannot execute a tape given to it in symbolic language.

The basic software also includes a Fortran II Compiler, which enables the programmer to mix the convenience of Fortran instructions with machine language instructions. This compiler occupies 4000 locations in memory. A tape is also present which permits program modification and checking in machine language via the teletype keyboard and paper tape punch. The Dynamic Debugging Technique program occupies 2000 locations. Several kinds of loaders are necessary to provide a set of basic instructions for loading of further programs. A Teletype Output Package permits the programmer to call the teletype for data output. The basic software also includes several maintenance programs.

V THE INTERFACE

In previous chapters the mass spectrometer and the PDP-9 computer have been described. Clearly for the computer to be useful to the mass spectroscopist some means must be available to link the two devices and to translate signals from one into something meaningful to the other. This role is filled by the interface.

A mass spectrometer such as the one described in Chapter III finds its basic function in the study of isotopic abundance ratios and in chemical identification work. For isotopic abundance ratio studies, it is desired to know the relative numbers of ions of each isotope formed from a particular sample. In accordance with the ideas expressed in the Introduction, the best way to find out this information would be to count the ions of each type as they are detected by the electron multiplier. Since the spectrometer is of the single-slit type, it is impossible to detect both isotopes simultaneously, so it will be necessary to arrange to count first the ions of one isotope, and then the ions of the other. Since the relative abundances of isotopes can be very high, it may be necessary to have a counting time which can be adjusted so as to provide a long counting time at the low abundance isotope and a relatively short one at the high abundance isotope.

Two means of switching the spectrometer from one mass to another, are magnetic and voltage switching. The principle of magnetic switching is to change the magnetic field so as to focus a different mass number on the slit. Voltage switching involves changing the accelerating voltage in the source so as to change ion energy and velocity. This would change the amount of bending suffered in the magnetic field, with the result that a different mass would be focussed on the detector slit. Both methods have disadvantages. Magnetic switching demands that the hysteresis loop of the magnet be as narrow as possible, so that the change in the magnetic field with a change in the current driving the magnet will be as reproducible as possible. Voltage switching has the disadvantage that the change in the complex field distribution of the source may be such as to affect the extraction efficiency of the source. Magnetic switching affects the rate of ion production only in so far as the fringing field of the main magnet perturbs the field of the source magnet. With a sector type instrument, it is possible to have rather large separations of source and focussing magnetic field, making magnetic switching the more practicable of the two. Furthermore, with sufficiently good beam shape and resolution, some small fluctuations in the magnetic field can be tolerated. That is, if the beam can be sufficiently well focussed, there will be a small range of magnetic fields over which the whole beam is being collected by the electron multiplier cathode. By opening up the detector slit this range of fields can be widened. If the electron multiplier output were fed into an electrometer and strip chart, this arrangement would produce trapezoidal peaks. Anywhere on the top of this peak, all the beam is being collected, and thus, anywhere in this region the peak height will give an exact measure of beam intensity, if we disregard the statistical distribution in electron multiplier output for single-mass, mono-energetic ion inputs. This statistical effect can be avoided if we restrict ourselves to pulse counting.

The way in which magnetic switching is to be achieved, is to insert a resistor in series with the magnet coils. A second resistor is connected in parallel with this first resistor through a relay. The second resistor is fully adjustable from 1000 ohms to 1.211 Megohm. The magnets provide a fixed resistance of 2000 ohms. The series resistor is 750 ohms, if large magnet currents are required. Since 200 mA. is ample to focus ^{200}Hg, a 1000 V. supply driving 2750 ohms should have no trouble bringing ^{200}Hg into the detector. From the relation developed in Chapter II, we have:

$$M = \frac{B^2R^2}{CV}$$

The dependence of M on B is found by differentiation;

$$\frac{dM}{dB} = \frac{2\ BR^2}{CV}$$

Approximating to finite changes in B;

$$\frac{\Delta M}{M} = \frac{2\Delta B}{B}$$

If we assume that, over a short range of currents, B varies linearly with I, then we have;

$$\Delta M/M = 2\Delta I/I$$

But

$$I = E/r,$$

where E is the voltage, and r is the resistance.

For constant E, $\Delta I = -E\Delta r/r^2$

and,

$$\Delta I/I = -\Delta r/r,$$

where the negative sign indicates that the current and resistance change in opposite directions. Therefore,

$$|\Delta M/M| = 2\Delta r/r$$

When the 1.211 Megohm resistor parallels the 750 ohm resistor, Δr = 0.2 ohms. Thus,

$$|\Delta M/M| = \frac{2 \times 0.2}{2.75 \times 10^3} = 1.5 \times 10^{-4}$$

and we can switch between mass differences as small as 1.5 parts in 10000.

When the 1000 ohm resistor parallels the 750 ohm resistor, Δr = 322 ohms, thus,

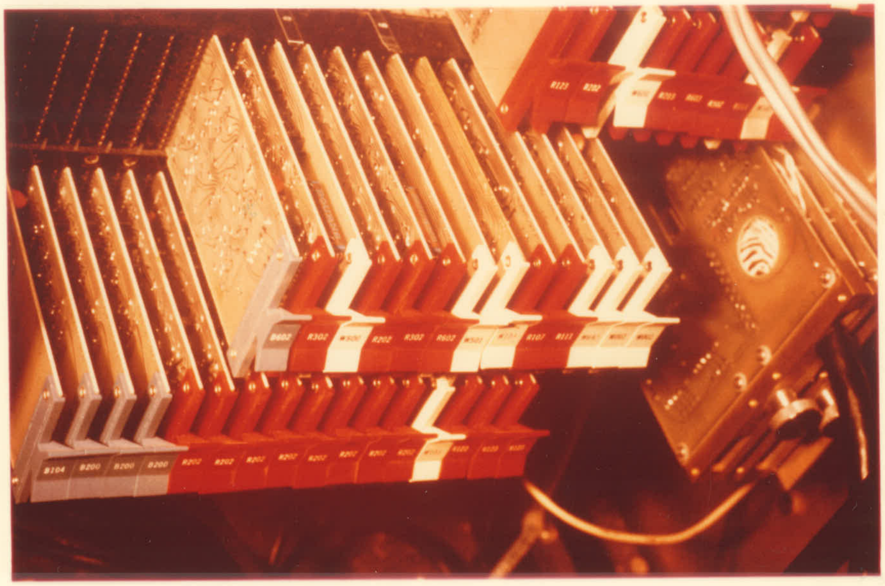
$$|\Delta M/M| = \frac{2 \times 322}{2750} = 0.23$$

and we can switch over a range of 23 parts per 100. This is more than adequate for any pair of isotopes with which the instrument is likely to be asked to work.

For low current work, a series resistor of 4700 ohms may replace the 750 ohm resistor and a 7000 ohm resistor replace the 1000 ohm resistor as the minimum in the paralleling chain. Very similar ranges will be possible in this mode (from 5.7 parts in 1000 to 56 parts per 100).

Controlling and switching the current is only one part of the problem. Once the isotope is being collected, pulses must be obtained from the electron multiplier and counted. With a gain in the E.M. of approximately 10^5, each ion incident on the first dynode liberates an average of 100,000 electrons which are collected, at the anode. This has been found to produce very small voltage pulses, necessitating several amplifications stages. An TMC FET pre-amp was connected directly to the E.M. output, and a series of pulses, varying in height between 10 and 50 mV. was observed, after amplification of approximately 1000. An instability in the FET was discovered, necessitating the replacement of that component. This instability had led to noise pulses approaching 10 mV. in height, making it difficult to separate the smallest signals from the largest noise pulses. These signals were then fed to an Ortec amplifier and single channel analyzer. The output pulses were taken from the single channel analyzer. These 4 V. positive pulses were about 0.5 microseconds long. A pulse transformer was used to invert the pulses so that they could drive the scaler.

The preamps and current control circuits are located with the mass spectrometer. The final pulse output is fed down from the spectrometer in Rm. 409, by means of co-axial cable to the cyclotron control room, at which point the PDP-9 is located. The magnet current is fed down through co-axial cable to the relay, which is located



Photograph 3: Rear of Interface-Mounted in Computer
-Note I/O Bus-

in the module rack of the interface, mounted in a rack near the computer. When the relay is closed, an additional DC resistance must be included in the calculations above regarding the range of adjustment due to DC line resistance, but measurements have placed this resistance at approximately 8 ohms, which can be neglected in calculation, and which can easily be corrected for in the initial set-up, if any correction is necessary. It would be most obvious for low values of parallel resistance, and these values are very seldom used.

The balance of the interface is located with the PDP-9 in the cyclotron control room and connected to the computer by a 5 foot I/O Bus. The interface is constructed entirely from circuit modules purchased from Digital Equipment of Canada, Ltd., which are immediately compatible with the PDP-9. After making these purchases, it was discovered, in conversation with users of PDP computers at Canadian Nuclear Research Laboratories of AECL, at Chalk River, Ontario, that integrated circuit equivalents of the DEC modules are much more compact, and more to the point, much cheaper. However, we were committed by this time to the use of DEC modules. I would recommend that anyone, wishing to proceed further with interfacing to the PDP-9, investigate the possibilities of fabricating the modules from purchased integrated circuits.

The balance of the interface consists of an 18 bit binary scaler and its controls, a device selector, pulse amplifiers, diode gate circuits to gate the scaler to the I/O Bus, current switching relay and driving circuits, flag, and logic circuits to recognize and reply to IOT pulses.

The scaler is constructed very simply, by connecting 18 flip-flops in series. The first three of these are capable of operation at 10 MHz., (module number B200) and the remaining 15 are capable of 2 MHz. operation (R202). The scaler as a whole is thus capable of running at 10 MHz. The slow flip-flops are enabled by grounding the level input pin of the DCD gate through which they are pulsed. These flip-flops are continuously enabled. They are fed by the output of the three fast flip-flops, which are enabled by grounding the emitters of their input transistors. Thus the entire scaler can be enabled or disabled by the emitter levels of the input transistors in the three fast flip-flops. The scaler counts so long as they are at ground and stops, holding the count, when they fall to -3 V.

The emitter level is controlled by a one-shot delay (R302) whose normal output is ground, but which drops to -3 V. for the duration of the delay, when triggered. It then returns to ground. This output is fed to an inverter (B104), whose output is fed to the emitters. Thus, by controlling the delay time, it is possible to control the time for which the scaler counts. The R302 is governed by the value of the RC constant of the circuit, where R = the resistance of a potentiometer, plus 1000 ohms of internal resistance, and C = 220 pf. of internal capacitance plus any external capacitance paralleling it.

External capacitance has been added in this case, and through a 10-position switch, several values of external capacitance are available, 0.02, 0.22, 2.2, 22, 47, 600 microfarad, giving a range of counting times from 400 nsec. to approximately 10 sec. Earlier, the possibility of different counting times on different mass values was discussed. That has been provided by an identical second bank of external capacitors, which can be made to parallel the first bank, thus adding to the counting time. The second stack is switched in and out of the circuit by a W800 relay. It is then possible to have counting times which alternate between A, and A plus B where A is the delay produced by the main capacitor bank, and where B is the delay which could be produced by the secondary capacitor bank alone. The W800 relay, driven by the output of an R202 flip-flop.

Another W800 relay, driven by another R202, provides the current switching. These relays are initially synchronized by setting the two flip-flops to the "1" position. Each flip-flop has two output terminals, which are referred to as the 0 and 1 outputs respectively. The 0 output is at -3 V. when the flip-flop is in the "1" state, and the 1 output is at ground. Thus, either of the logic levels used in DEC modules are available, no matter which state the flip-flop is in. The current switching relay is connected to the 1 terminal. With the FF set to "1" the relay input is at ground. This input opens the relay. With a higher resistance in the magnet circuit, the lower mass is being focussed on the detector slit. If the timing control relay were also connected to the 0 terminal of the FF, the counting time on the high mass would be A plus B. If, however, the higher mass were more abundant, it would require the shorter rather than the longer counting time. This could be achieved by connecting the relay input to the 1 terminal of the FF. Either option is available through the expedient of a two-position switch which can connect the relay input to either the 0 or the 1 terminal of the flip-flop.

When the counting time has elapsed, the delay output level returns to ground. The delay output is being fed to the input of an R202, which can be triggered by a positive pulse or a positive going level change. Unchanging levels of either sign, or negative-going level changes will not fire the flip-flop. Thus the end of the counting time is signalled by a change in the state of this flip-flop. The -3 V. level of the 0 terminal when the FF is in the "1" state is fed into the I/O Bus as the Program Interrupt pulse.

The generation of a program interrupt will cause the computer to search for the device doing the interrupting, and on learning which it is, will jump to that service subroutine. The search is carried out by issuing IOT 1 pulses to each peripheral device in turn. Each device contains a module which is set to accept only one particular combination of levels of the device selection lines of the I/O Bus, by means of the arrangement of diodes in its input circuits. If this code is not the one issued by the computer, the pulse is ignored by the device and goes on to the next device in the chain. This module is known as the device selector. When the IOT 1 pulse is issued to a device it is passed through the device selector (W103) and proceeds from there to a logical AND gate. The output of the flag is also fed to this gate (R111), as the second input. If both are present, indicating that the flag is indeed up, a ground level output is produced by the gate which is fed back to the computer along the I/O Skip line of the I/O Bus. A ground level on this line authorizes the computer to issue the IOT 2 pulse, while a negative level means a false alarm, and the computer returns to its previous job.

The IOT 2 pulse arrives through the W103, and passes along to a pulse amplifier (W640), the output of which is a 1 microsecond long negative pulse. This pulse is fed to 18 diode gates (R123) for the purpose of opening them. The 1 outputs of the FFs forming the scaler are fed into these gates and the FF levels are thus strobed onto the I/O Bus and into the AC. The IOT 2 pulse also is fed to a pulse amplifier and then to the R202's controlling the W800 relays, complementing them. The IOT 4 pulse arrives through the W103 and is amplified by an R602 pulse amplifier and fed in parallel to a B602 pulse amplifier which produces a pulse capable of clearing the 3 B series (10 MHz.) FFs in the scaler; to the 15 R series (2 MHz.) FFs in the scaler, clearing them; to the flag, clearing it; and to the R302 delay which controls counting times, thus initiating a new counting sequence.

Since current switching through a large electromagnet can be expected to be slow, due to inductive effects, some short time will pass before the other mass number is collected by the detector. The smaller the current change, of course, the shorter the time. A quick test indicated that a time on the order of ten seconds was sufficient to accomodate a current change of the order of a few mA. This wait is allowed for by having the computer wait for some preselected period of time, after issuing the IOT 2 pulse which complements the relays and the IOT 4 which restarts the data-taking cycle. The number of such data-taking cycles which occur is regulated by the program.

A Schmidt trigger circuit, fired by depressing a switch on the front panel of the interface, feeds an R302, set for a very short delay, the output of which sets the two relays in the same initial position.

The modified electron multiplier pulses arrive at the BNC connector on the face of the panel, and are fed to a B602 pulse amplifier which shapes them so as to be compatible with the B200 FF's, which they are to drive. Another terminal provides a connection for the co-axial lead carrying the current to the relay (both of which have been wired so as to supress contact bounce using circuits which are built into the relay module). Current comes down through the central wire and returns to the spectrometer and ground through the shield of the co-axial line. The current terminal on the interface panel has therefore been isolated from ground.

The system, as described, operates in the PI mode outlined in the chapter on the computer. In practice, however, it has turned out that the computer is available to one user at a time. The computer can therefore stay in a wait and test loop, generating IOT 1 pulses until the device flag goes up. The PI line can be disabled in this case, and this has been provided for by a switch on the front panel of the interface. A slight program modification and closing of this switch would suffice to convert back to the PI mode.

Physically, the interface consists of two standard 19" racks, mounted alongside the computer. One of these contains the 27 modules necessary to do the tasks described above, the other of which carries the power supply which provides the power for the interface electronics. The module rack has enough space to accomodate 64 modules. Each module is provided with 18 electrical connections, three of which are power connections. The modules are approximately 2½" wide by 5" long, and are about ½" thick. The I/O Bus requires space equivalent to that required for 8 modules, and this has to be allowed for, leaving space for 56 modules on the main rack. An additional 32 modules could be mounted on space available in the power supply rack, and the additional connectors necessary (H800F) can be purchased and mounted fairly simply, should a need for more than 56 modules arise in the future.

Emphasis has been placed on the isotope abundance ratio measurement in the design of this interface. It is quite capable of quick modification for the production of spectra. Removal of the current switching networks is easily achieved by switching one lead on the spectrometer. Removal of the W800 module will give constant counting times (still fully adjustable), and removing the inductance delay from the program will eliminate unnecessary lost time. This completes modification of the interface. A program will have to be written which merely stores the contents of the scaler, and prints them out after data collection is complete, if necessary. A more rapid, and possibly more esthetically pleasing method of outputting the data would be via the Calcomp plotter, or the oscilloscope screen. Probably one or the other of these, coupled with a numerical output, would be the most satisfactory system. Current control would now devolve on the electric motor which drives the magnet supply, scanning the spectrum. Once started, the device would behave like a scaler with automatic output, and variable dwell time.

The system described in this and the previous two chapters, therefore, provides a highly versatile digital output system for a mass spectrometer of this type, when properly programmed, a topic to be discussed in the next chapter. The possibility of the use of on-line computers for the other type of mass spectrometer, i.e. that type which has sufficiently high resolving power to measure nuclear separation energies to a thousand electron volts or less, such as the two large instruments at the University of Manitoba, has been discussed at some length with Dr. R. C. Barber, and although no action has as yet been taken in this direction, it is hoped that the interface described herein will be useful to that project.

VI PROGRAMMING

Programming the PDP-9 is a very straightforward and relatively simple job. Like all computers, however, the PDP-9 makes no allowance for programmer failure, and the task can sometimes become frustrating when a tired programmer becomes error-prone. The usual symptoms of program error customarily become apparent when the computer halts unexpectedly or stays in a loop that the programmer knows should have been broken. The Dynamic Debugging Technique (DDT) and console controls make program examination and correction relatively simple and rapid.

Programming consists entirely of assembling a set of machine language instructions which will have the effect of making the computer execute a job in the particular way that the programmer wants it executed. The complete list of such instructions and their mnemonics is to be found in Appendix I, along with a short summary of the results of each instruction. As a consequence, I shall not dwell on the reason for the choice of a particular instruction, as that should be clear from the context in which it appears. Furthermore, I have found from experience, that no two programmers would ever do any job in exactly the same way, and certainly with the PDP-9 instruction set many alternatives are possible. I shall therefore merely outline the job I wish to do and then present the program which I have written to do it, justifying it only by its efficacy, that is, it works!

The job of the program is to:

1) Continually test the device flag;
2) Upon receipt of a signal which indicates that the flag is up, to read the contents of the scaler in the interface into the AC, and then to store this octal number in memory.
3) Upon successful data storage, to issue an IOT 4 pulse to restart the data-taking cycle. It must not, however, continue to actuate the data-taking process indefinitely, but must halt the collection process when a preselected number of runs has been made.
4) For each pair of numbers in the memory, corresponding to the numbers of ions of each mass which were collected by the electron multiplier, it must calculate one ratio, and for reasons dictated by the nature of the available instructions, it must always be the ratio of the less abundant isotope to the more abundant isotope.
5) It must store these ratios in memory.
6) It must calculate an average of all the ratios thus stored, and store the average in memory.
7) It must calculate a standard deviation of the ratios from the mean ratio calculated in step 6 and store the standard deviation in memory.
8) It must then print out the data in decimal numbers, in a neat array, and print out the ratio associated

with each pair of numbers opposite that pair. Further, it must print out the calculated average and standard deviation.

9) It must also be able to allow for a certain amount of operator error, by being able to recognize when the data has been entered in the wrong order, that is, with the number of counts collected on the first higher mass measured greater than that collected on the measurement of the second mass, and correct for it. Further it must be able to recognize if some error in the program or the computer operation has resulted in an odd number of data-cycles being made. This is necessary to prevent division into zero, or some invalid data word, and the computer must be able to skip the step which would lead it to divide into this incorrect number. It should also be capable of printing out an error message when such errors have occurred.

The reason for leaving the typing to the last, rather than typing out data and ratios as they are collected, is that it has been discovered that the pulses which are used by the computer to address the typewriter are getting past the teletype along the I/O Bus and have the effect of triggering the counting time delay at irregular intervals. That is, it has the effect of short-circuiting the inductance delay.

The reason that one must specify that the larger number of counts be the first to be stored will become clear when the divide instruction and storage arrangement are examined.

The process of doing a run with this program is as follows:

1) Turn on the spectrometer.

2) Permit the sample gas to flow into the source. The sample must be contained in a reservoir large enough that continued pumping on it in the course of a run will not change the sample pressure, or the pumping speed, appreciably. A typical value for the inlet system pressure would be 250 microns of mercury. The pressure in the source can be monitored on the guage of the VacIon pump, which is pumping directly on the source region. Source pressure should not be allowed to rise above 10^{-6} mm. of Hg during a run. The opening of the sample inlet valve can be adjusted so that the source pressure can be maintained at less than this upper limit.

3) The spectrometer must then be focused on the two masses to be measured. This is most conveniently done using the electrometer and strip chart for locating the proper currents.

4) Connect the pulse electronics to the output of the electron multiplier. Make sure that the pulses are arriving at the interface.

5(a) Place the Read-In Mode Loader (Rim Loader) tape in the tape reader on the PDP-9 console. Set the address switches on the control panel to 17763, press the I/O reset key, then the Read key. The computer will now load in the loader, or

5(b) Place the FAST-9 Start Tape in the tape reader. Set the address switches to 17600, press I/O Reset and Read keys.

6(a) Place the Isotope Abundance Ratio Data Output and Analysis tape in the tape reader. Set the address switches to 17770, press the I/O Reset key, then press the Start key. The computer now loads the program into its memory, or

6(b) With the address switches at 17600, determine which block of Dectape is occupied by the program, put up <u>only</u> that AC switch, press start. If all is done correctly, the computer will halt with 777777_8 in the AC. Press Continue. The program will be read into memory from Dectape.

7) Set the address switches to 22, the starting location of the program. Make sure that the interface electronics are turned on. Press the set-start button, wait ten seconds, and press the set-start button again. At the same time, press Start.

8) Wait for the results to be typed out on the teletype The data-taking process can be monitored by watching the contents of the MB register. Depending on the length of the inductance delay they should change between the command to count the clock and the command which reads the contents of the scaler.

Once the data-taking cycle has stopped, the results should appear on the teletype in under five seconds, as the calculation time is very short.

9) Another run may be started by returning to position 7 in this guide, after making sure that the spectrometer is still operating as outlined above. A telephone connection has been established between the spectrometer and the computer for this purpose.

VII RESULTS

In order to verify the thesis that it is possible to measure isotopic abundance ratios using direct, on-line, digital data acquisition techniques, it is necessary, naturally to measure some such ratios. It was decided to demonstrate the capabilities of the system by measuring the ratio of $^{12}C^{16}O^{18}O$ to $^{12}C^{16}O_2$ in a specially prepared sample, doped with ^{18}O. This sample was prepared by sealing a quantity of normal CO_2 in a vessel containing water which was enriched in ^{18}O. The vessel was shaken for three days to speed the dissolving of the CO_2 in the water, with a consequent increase in the rate at which ^{18}O atoms replaced the ^{16}O atoms in the carbon dioxide. After three days the reaction was stopped, the carbon dioxide dried, and the gas placed in a flask which was then sealed. The calculation of the rate at which the reaction proceeds to equilibrium yielded a theoretical value of 30.624 for the 44/46 ratio.

This ratio was measured several times, in two cases with equal counting times on both mass numbers, to give a direct measure of the ratio, and once with a longer counting time on the high mass, low abundance isotope, in order to demonstrate the capabilities of the instrument. The ratio of the counting times in the cases of unequal times was measured using a 100KHz. crystal controlled oscillator, and with the settings used, was found to be

$$0.2864 \pm 0.0005$$

The results of these measurements were:

Run #1- 33.9

Run #2- 37.9

Run #3- 30.8

Run #3 was the run done with unequal counting times, and the improvements consequent with better statistics can easily be seen. Previous to these runs, a run, using equal counting times, was done on the 44/46 ratio of the residual gases in the spectrometer. The result of this measurement was a ratio of 0.00704, somewhat higher than the accepted value for air, which is in the neighbourhood of .004. This is undoubtedly due to the fact that several unsuccessful runs were done on this prepared sample before the system became fully operational.

It was not intended that the runs so far discussed and those which follow should establish new levels of accuracy of measurement. Rather, it was intended that they demonstrate that such a direct digital data collection system could, indeed, work. It is not possible, with the present system, to provide more accurate measurements of natural and other isotopic abundances, but it is clear that, at this stage, the limiting factor is not the inherent limitations of the method, but rather of the spectrometer, and the electronics necessary to make the output of the electron multiplier of sufficient amplitude to drive the interface scaler. These limitations will be be discussed further after the rest of the data collected is presented.

Analyses were also performed of samples of mercury, and of samples of krypton, in large measure to demonstrate that the system works over a large range of masses in its present form, and that the spectrometer has got enough resolving power to work at mass 200. The pair of isotopes studied at mercury were ^{202}Hg and ^{200}Hg. Because the accepted ratio of these isotopes is nearly unity, it was decided to utilize equal counting times. The accepted value of the 202/200 ratio is 1.288, and the ratio measured by the instrument was 1.294. No claim is made that this value is better than the presently accepted one, as only one run was made on this pair, and for that one the statistics were very poor; an average count period would yield only a few hundred counts. It is, however, further evidence that the system is a workable one.

Finally, a brief run was done on a krypton sample. The pair chosen in this sample, ^{82}Kr, and ^{86}Kr, were chosen because they demand a larger change in the magnet current, and indicate that the system has considerable range. Once again, the ratio is of order unity, and equal times were used in the counting system. The accepted value for the ratio of the mass 82 isotope to the mass 86 isotope is 0.665. The result of the measurement made on this instrument was 0.706. If the spectrometer output is fed to an electrometer and strip chart recorder in the standard fashion, the measured ratio in this sample was found to be 0.69. It is to be remembered that no calibrations were possible with any of these sources, and consequently, large correction factors may need to be applied for mass discriminatory effects in the sample inlet system and ion source. It is further reassuring to note that all these runs, except Run#1 on the CO_2 sample were done at the same setting of amplifiers and discriminators. As to possible corrections for the source, it is interesting to note that the proximity of our measured value to the currently accepted value seems to be inversely proportional to the mass of the ion being examined. The source corrections would vary in the same way.

Thus, it would seem that the system is a workable one, and that the limitations of the accuracy of the measurements at this stage are entirely due to the limitations of the spectrometer. Perhaps the most important limitation at present in the system is the electron multiplier. It is, in fact, the multiplier part of an old photomultiplier, the photocathode of which has been removed. It is noisy, provides only low gain, and as a result is limiting the current which it is possible to utilize in the spectrometer with any hope of success. The mechanism by which this comes about is as follows: the output pulse of the multiplier has an envelope of noise superimposed on it. Further, the pulses are long, and consequently can pile up rather more easily than could they if they were short. If, in an attempt to get good statistics on the low abundance isotope, the spectrometer is run at high counting rates on the high abundance isotope, pulse pile-up will occur to such an extent on the high abundance isotope that the threshold established in the single channel analyzer will be effectively lowered. This permits much more noise to come in on the high abundance measurement than on the low, with a completely erroneous measurement as the result. The maximum counting rate acceptable appears to be about 5000/second. Another problem associated with the poor electron multiplier is that of low output voltages. The pulses available from this multiplier are so small that noise from subsequent amplifiers becomes very important. The figure quoted earlier in this thesis for the gain that is obtained from the multiplier may well be overly optimistic by a factor of 5.

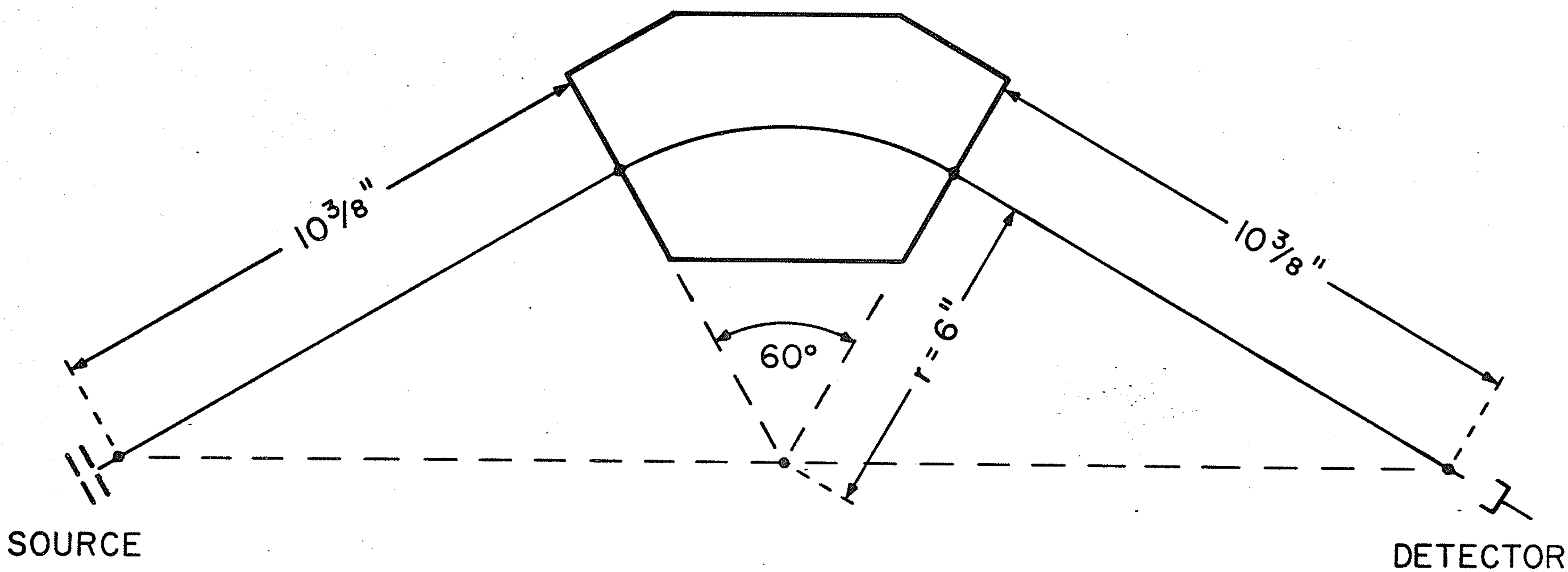
One other instrumental problem can play havoc with measurement. This is the problem of beam drift. Whether this is due to a slow drift in the magnet current supply, or to one in the accelerating voltage, has yet to be determined. If it is just a short term problem which can be cured by giving the supplies enough time to settle down, or if it indicates a definite failure of one on the supplies has not been determined. In any case, the beam will remain focussed for periods on the order of one hour without too much difficulty. Since a run can take anywhere from 15 minutes, to one hour, the spectrometer focussing needs to be checked before each run.

These instrumental problems are merely outlined to indicate that the limitations of the present system are present in the spectrometer, and not in the method. These limitations reduce the value of the measurements presented herein, as evidenced by the fact that the standard deviations on the results ranged from 5 - 15%. These large standard deviations can largely be attributed to the low gain and lack of sensitivity of the electron multiplier, which kept the total number of counts which could be recorded to a minimum. The lowest standard deviation found was that for the measurement of the enriched carbon dioxide sample, utilizing unequal counting times, thus recording the largest number of counts and the best statistics. (See Appendix 6) Clearly, an improved electron multiplier would go a long way to reducing the errors, or standard deviations quoted above.

VIII CONCLUSIONS

The design and construction of an on-line mass spectrometer have been discussed, with reference to the feasibility of utilizing direct digital data acquisition for the measurement of isotopic abundance ratios. A program has been presented which collects such data, and analyzes it, producing an average ratio, standard deviation and a list of the number of ions of each type collected with the ratio of each pair. Several test measurements of isotopic abundance ratios of CO_2 (44/46), $^{202}Hg/^{200}Hg$, and $^{82}Kr/^{86}Kr$ have been performed and the results of these measurements presented. The limitations of the present system have been discussed, and it can be concluded that the method of digital operation of a mass spectrometer has been fully verified.

Fig. 1 Spectrometer Geometry



10 3/8"
10 3/8"
60°
r = 6"
SOURCE
DETECTOR

Fig. 2 Magnet

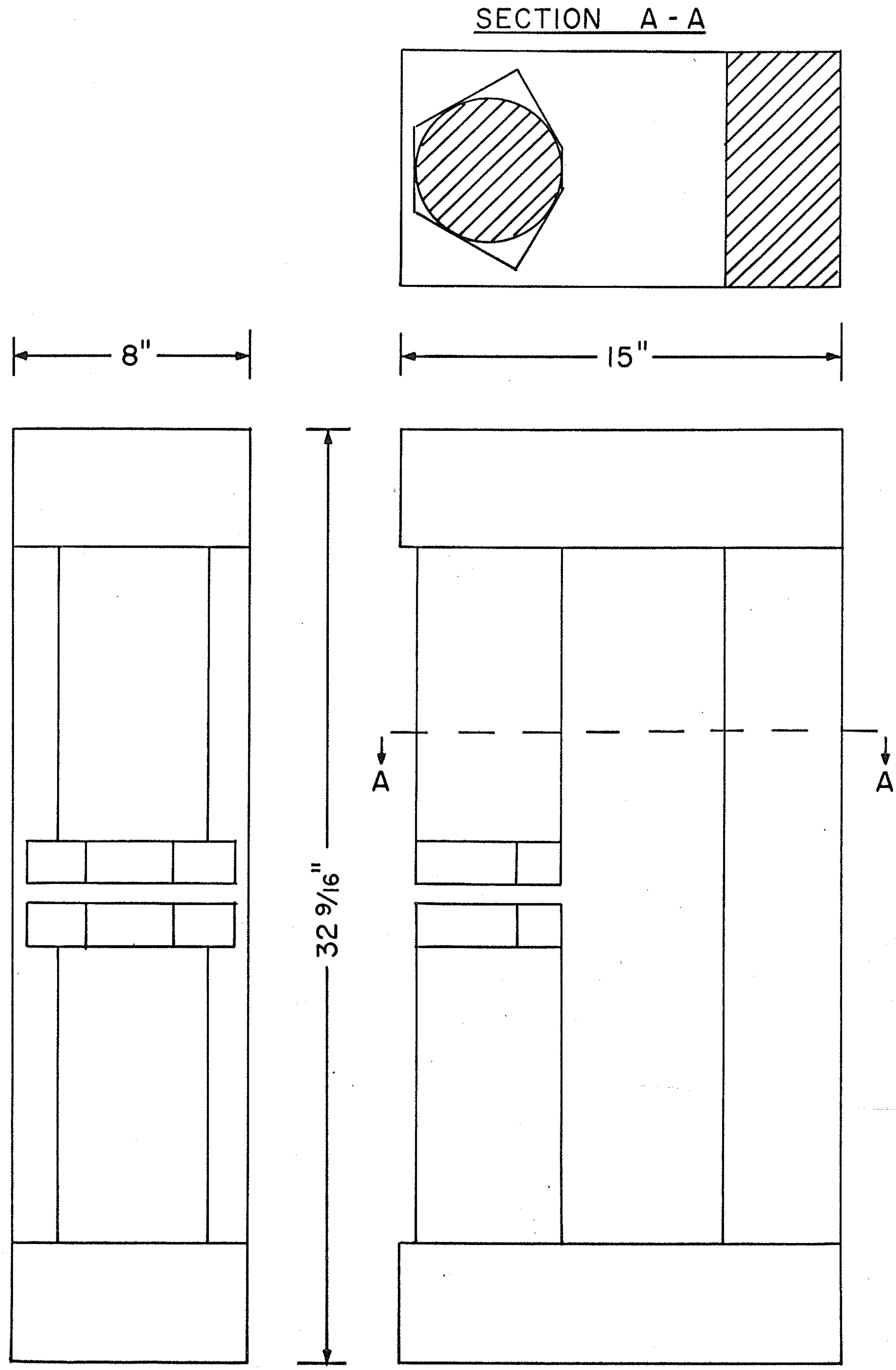

SECTION A - A
8"
15"
32 9/16"
A
A

Fig. 3   Ion Source Emission Current Regulator

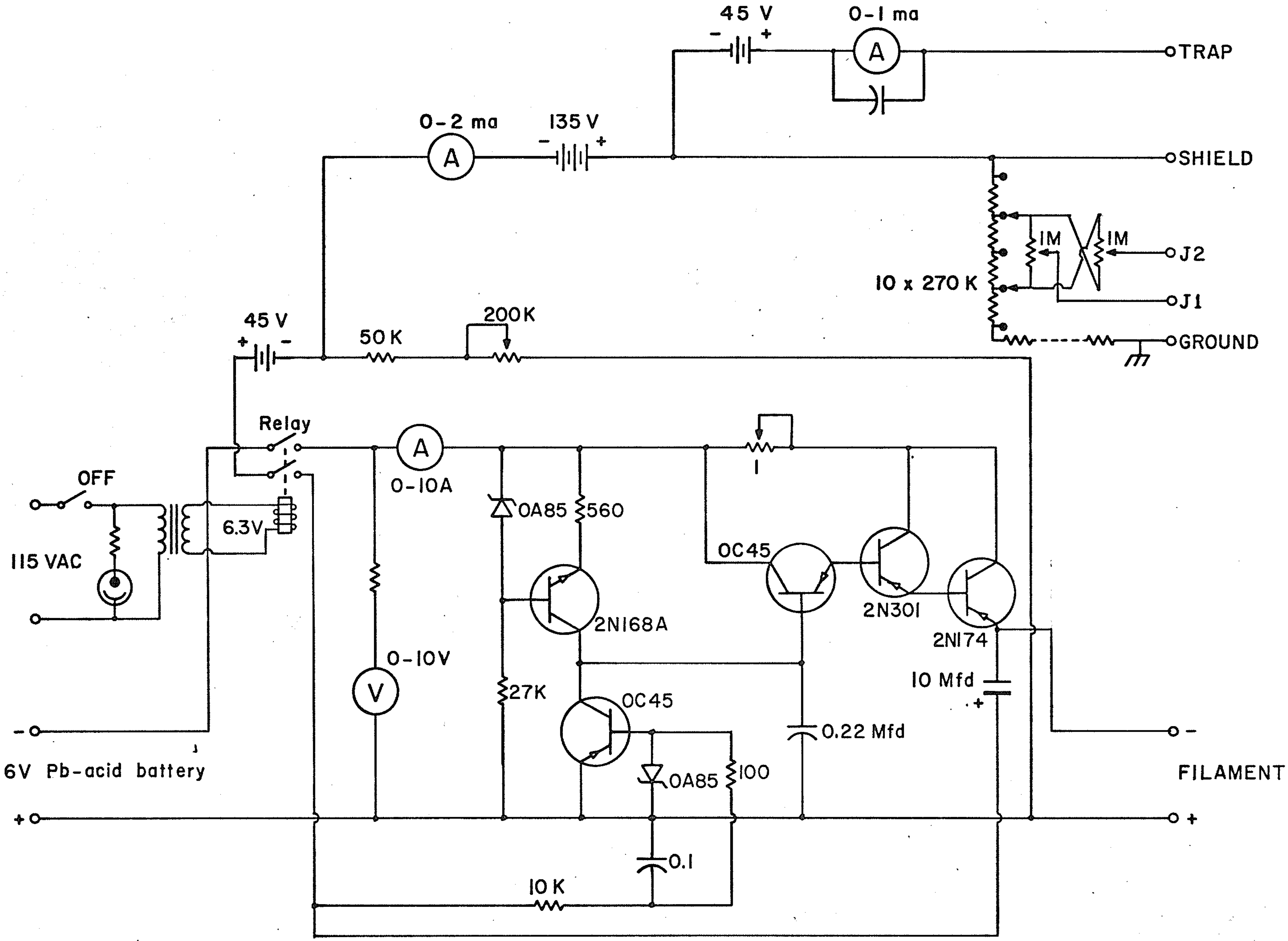

45 V
0-1 ma
TRAP
0-2 ma
135 V
SHIELD
IM
IM
J2
10 x 270 K
J1
45 V
50 K
200K
GROUND
Relay
OFF
115 VAC
6.3V
0-10A
OA85
560
1
OC45
2N301
2N168A
2N174
0-10V
10 Mfd
27K
OC45
0.22 Mfd
6V Pb-acid battery
OA85
100
FILAMENT
0.1
10 K

Fig. 4   Switching Current Control

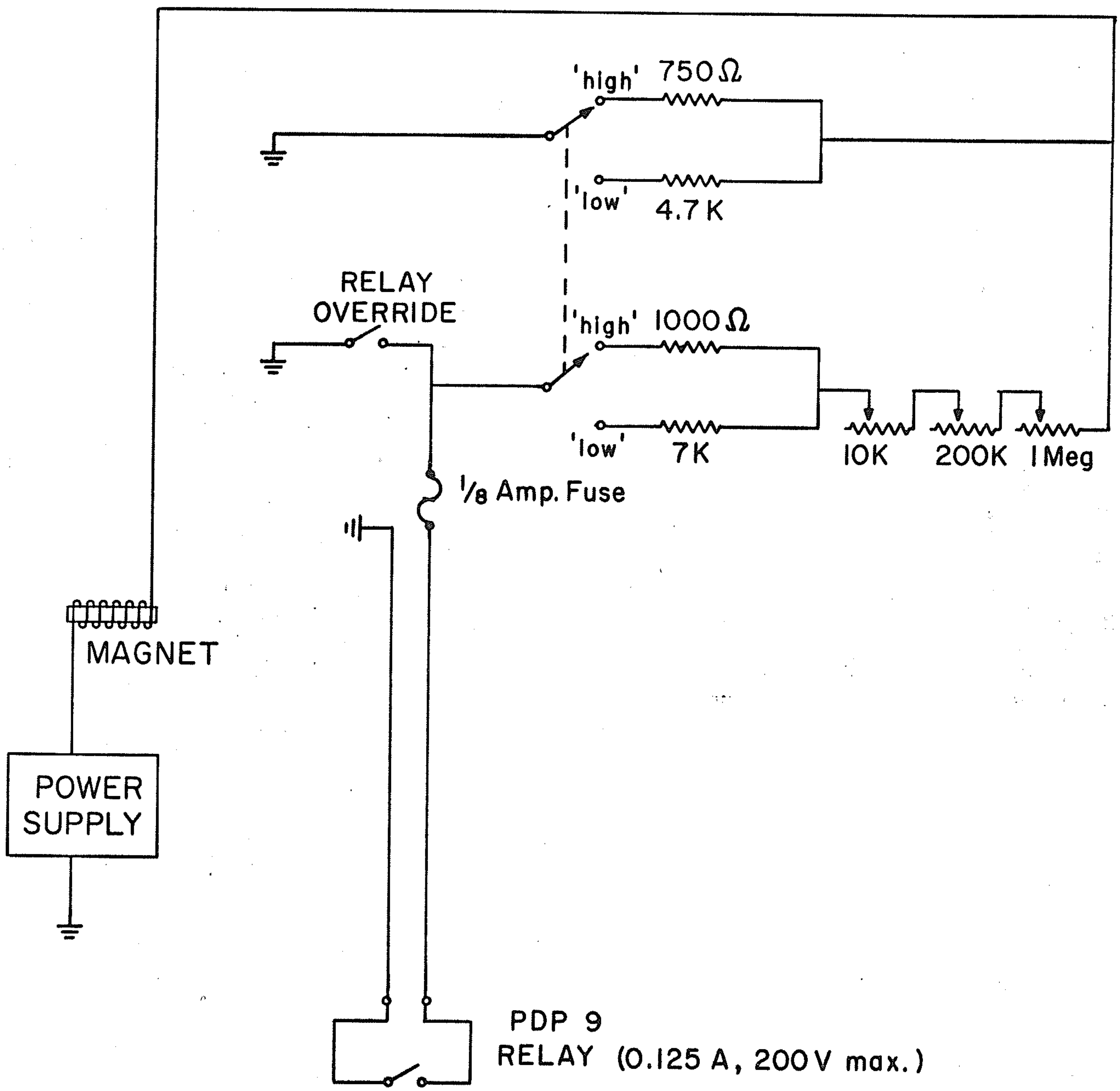
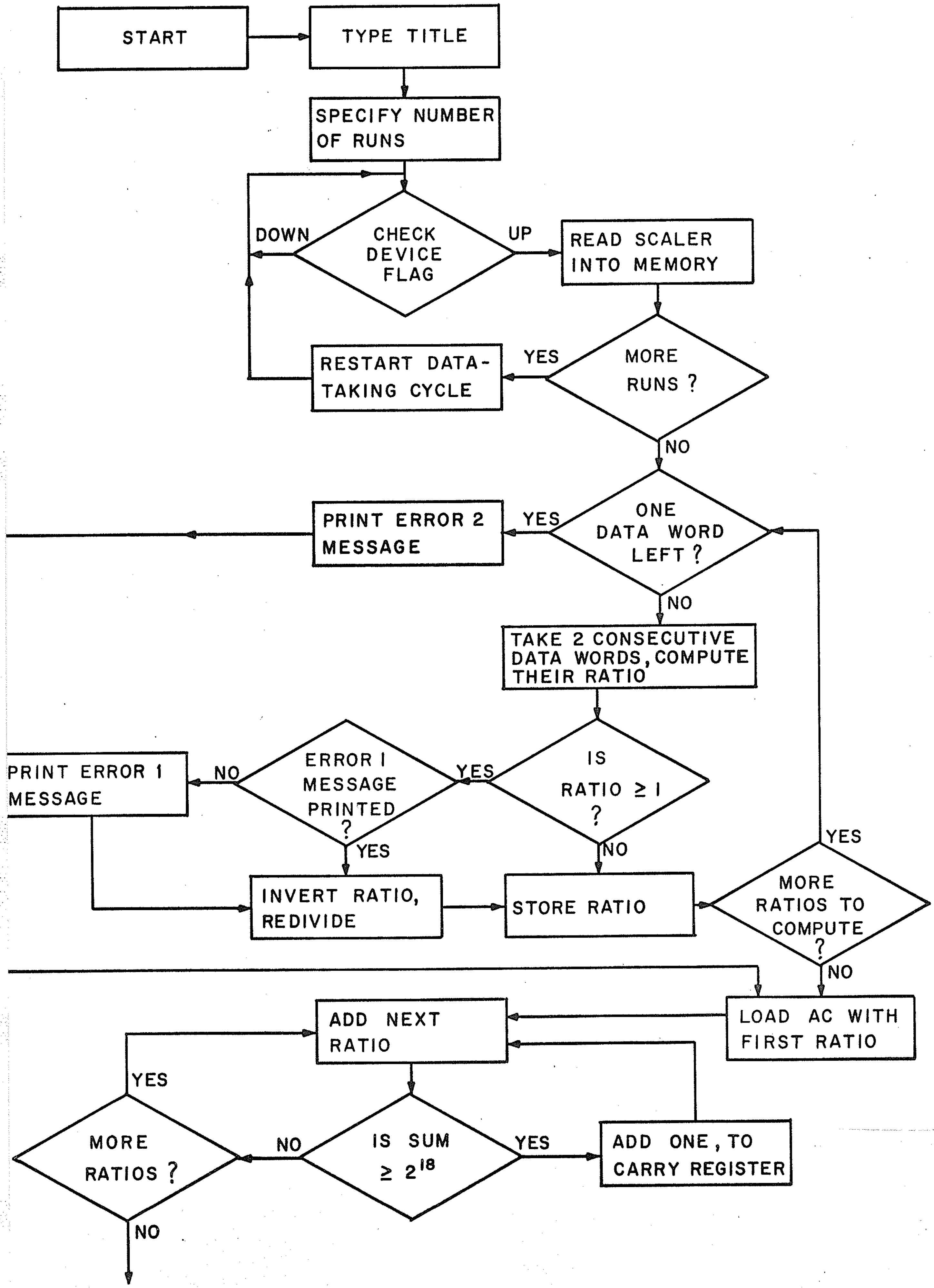
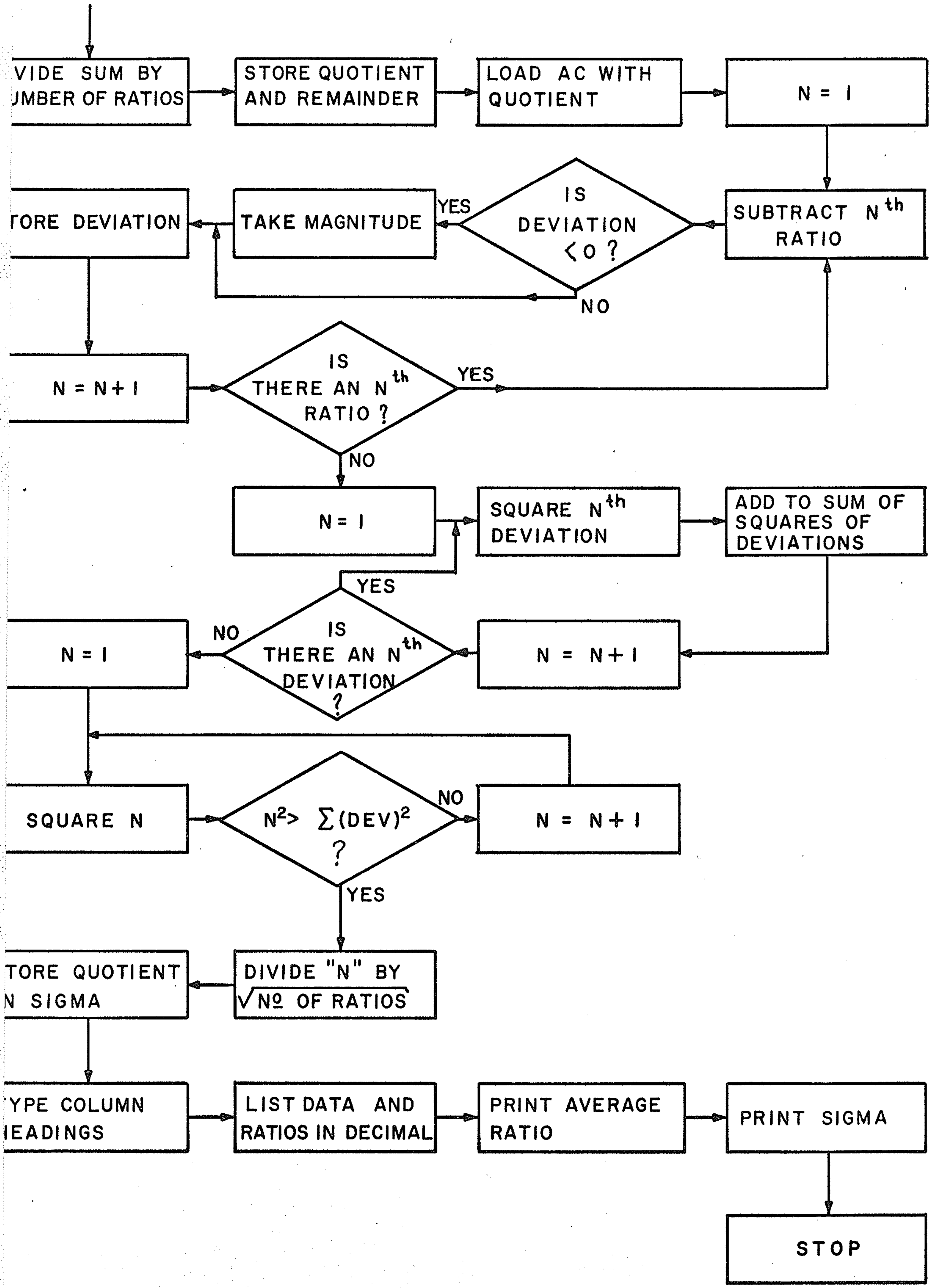

'high' 750Ω
'low' 4.7K
RELAY
OVERRIDE
'high' 1000Ω
'low' 7K
10K
200K
1Meg
1/8 Amp. Fuse
MAGNET
POWER
SUPPLY
PDP 9
RELAY (0.125 A, 200V max.)

Fig. 5 Isotope Abundance Ratio Data Output and Analysis Flow Chart



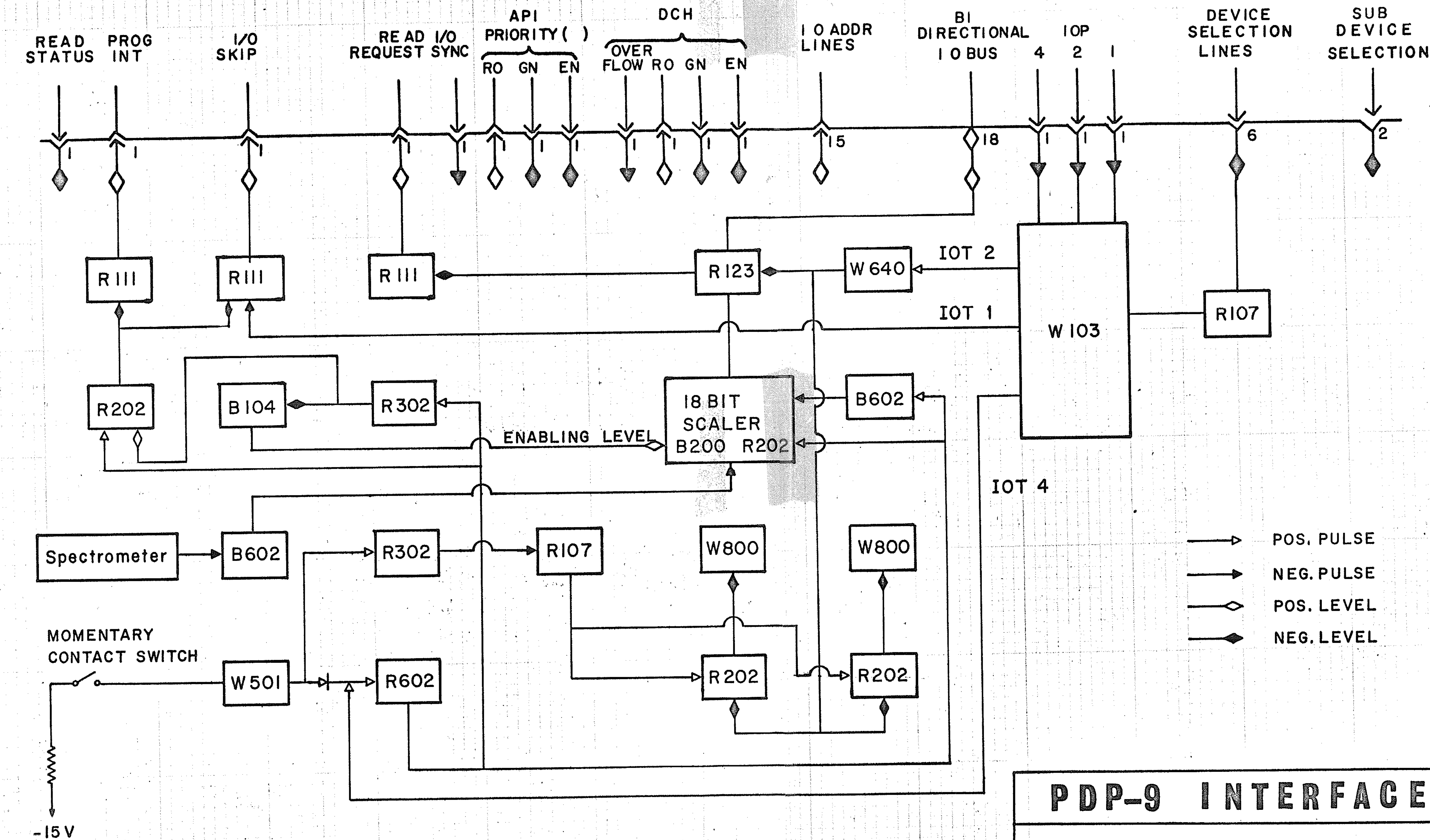
START
TYPE TITLE
SPECIFY NUMBER OF RUNS
CHECK DEVICE FLAG
DOWN
UP
READ SCALER INTO MEMORY
MORE RUNS ?
YES
NO
RESTART DATA-TAKING CYCLE
ONE DATA WORD LEFT ?
YES
NO
PRINT ERROR 2 MESSAGE
TAKE 2 CONSECUTIVE DATA WORDS, COMPUTE THEIR RATIO
IS RATIO ≥ 1 ?
YES
NO
ERROR 1 MESSAGE PRINTED ?
NO
YES
PRINT ERROR 1 MESSAGE
INVERT RATIO, REDIVIDE
STORE RATIO
MORE RATIOS TO COMPUTE ?
YES
NO
LOAD AC WITH FIRST RATIO
ADD NEXT RATIO
IS SUM ≥ 2^18
YES
NO
ADD ONE, TO CARRY REGISTER
MORE RATIOS ?
YES
NO



VIDE SUM BY
JMBER OF RATIOS
STORE QUOTIENT AND REMAINDER
LOAD AC WITH QUOTIENT
N = I
SUBTRACT N^{th} RATIO
IS DEVIATION <O ?
YES
NO
TAKE MAGNITUDE
TORE DEVIATION
N = N+I
IS THERE AN N^{th} RATIO ?
YES
NO
N = I
SQUARE N^{th} DEVIATION
ADD TO SUM OF SQUARES OF DEVIATIONS
N = N+I
IS THERE AN N^{th} DEVIATION ?
YES
NO
N = I
SQUARE N
$N^2 > \sum(DEV)^2$?
NO
N = N+I
YES
DIVIDE "N" BY $\sqrt{N^{\underline{o}} \text{ OF RATIOS}}$
TORE QUOTIENT
N SIGMA
TYPE COLUMN
IEADINGS
LIST DATA AND RATIOS IN DECIMAL
PRINT AVERAGE RATIO
PRINT SIGMA
STOP

Fig. 6 Interface Block Diagram

Fig. 7   Interface Wiring Diagram



PDP-9 INTERFACE TO	
MASS SPECTROMETER	
TITLE CONTROL AND DATA ACQUISITION SYSTEM	
FOR MS 2-6-60	
DRAWN BY	DATE
APPROVAL	REVISION

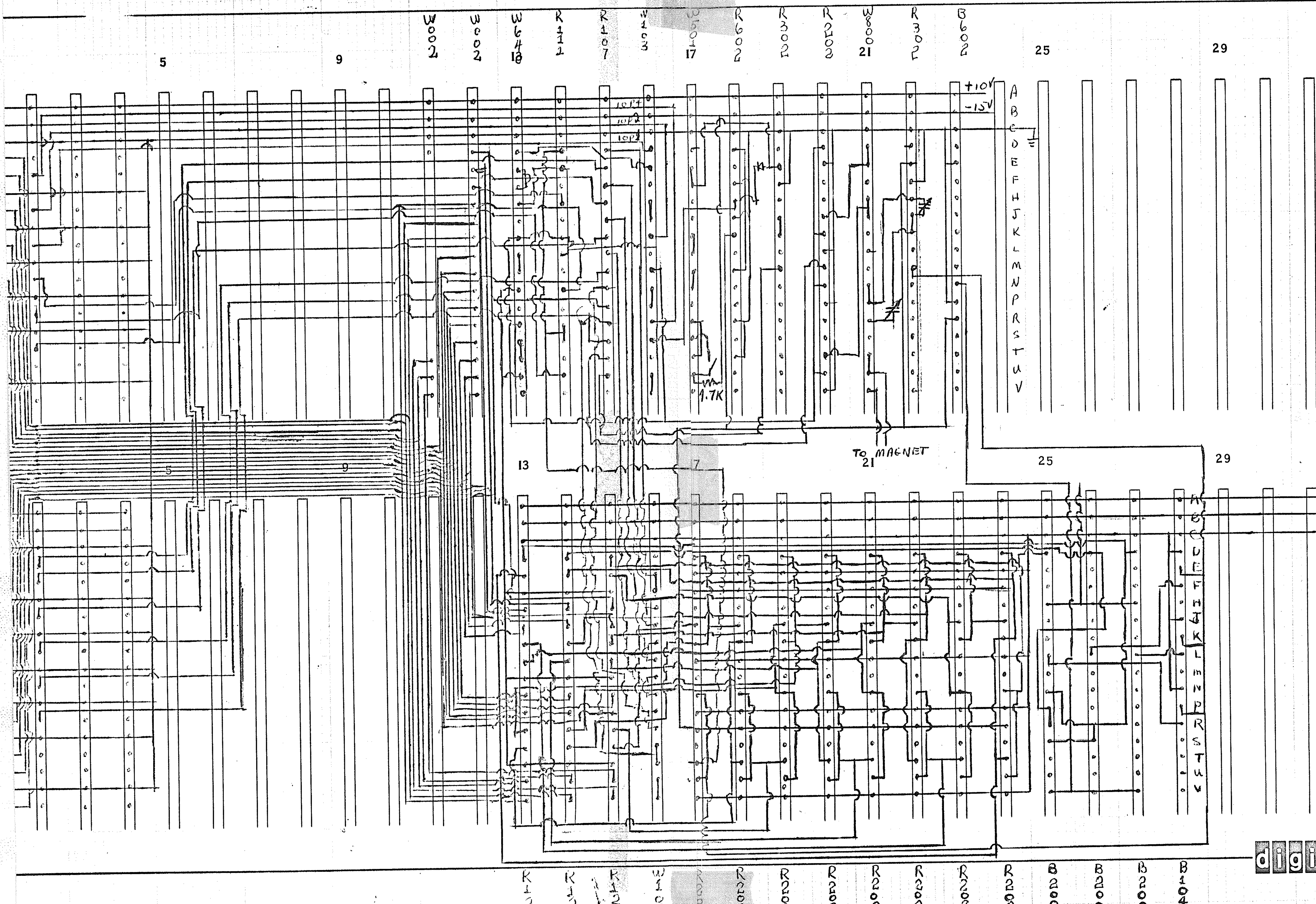
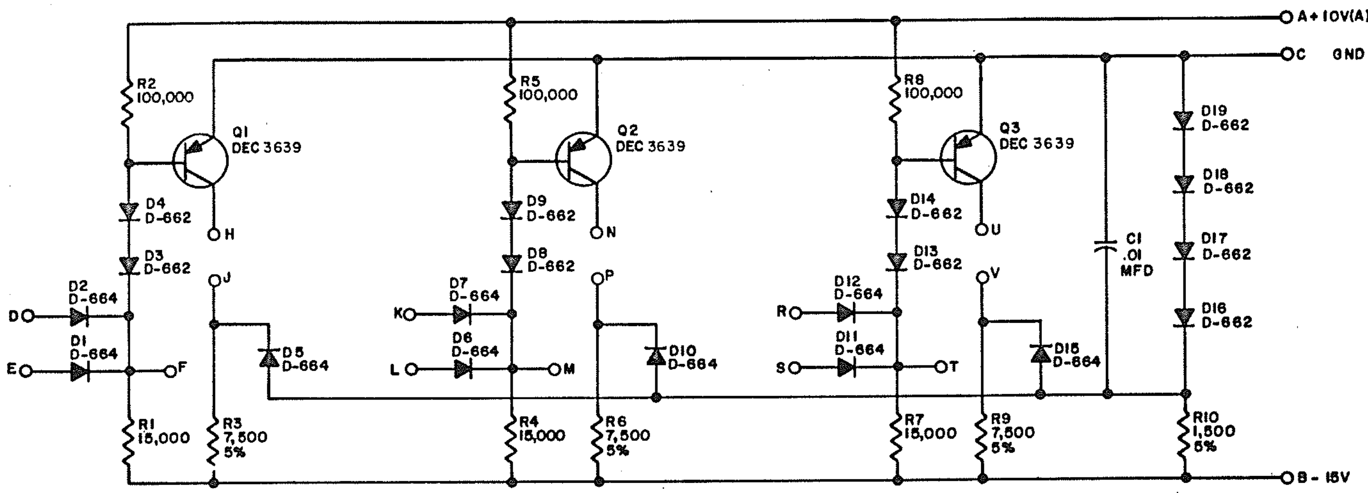

5
9
13
17
21
25
29
+10V
-15V
10pf
4.7K
TO MAGNET
A
B
C
D
E
F
H
J
K
L
M
N
P
R
S
T
U
V

Fig. 8(a) R111 Diode Gate

Fig. 8(b) R123 Diode Gate

-B-R111-2



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 10%

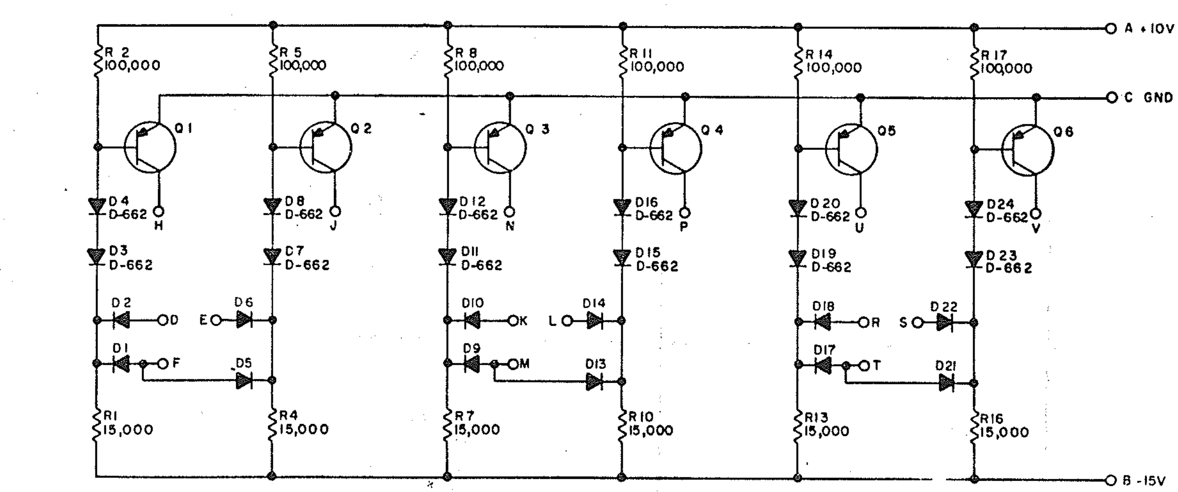
ANSISTOR & DIODE CONVERSION CHART			
	EIA	DEC	EIA
	2N3639		
	IN645		
	IN3605		

NOTES

D	RS-B-R111	2

DIODE GATE R111

RS-B-R123-1



UNLESS OTHERWISE INDICATED:
TRANSISTORS ARE DEC 3639-0
RESISTORS ARE 1/4 W, 5%
DIODES ARE D-664

TRANSISTOR & DIODE CONVERSION CHART			
DEC	EIA	DEC	EIA
3639-0	2N 3639		
62	IN 645		
64	IN 3606		

NOTES

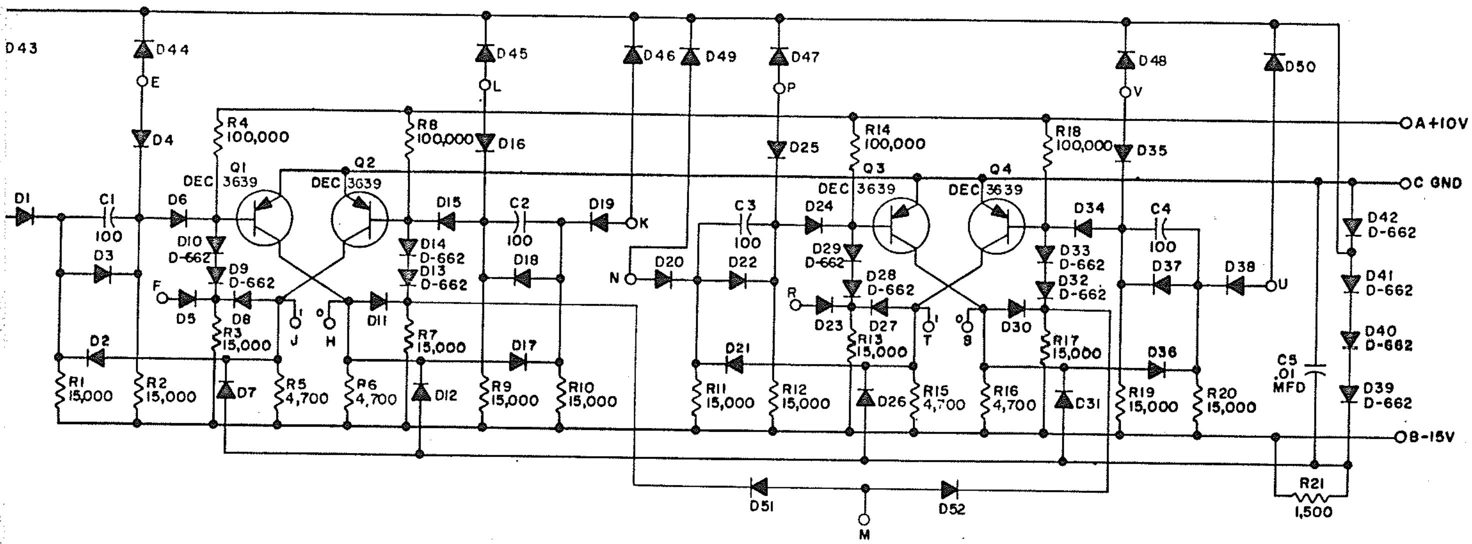
A	RS-B-R123	1

DIODE GATE R123

Fig. 8(c) R202 Dual Flip Flop

Fig.8(d) R302 One Shot Delay

3-R202-4



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 5%
CAPACITORS ARE MMFD
DIODES ARE D-664

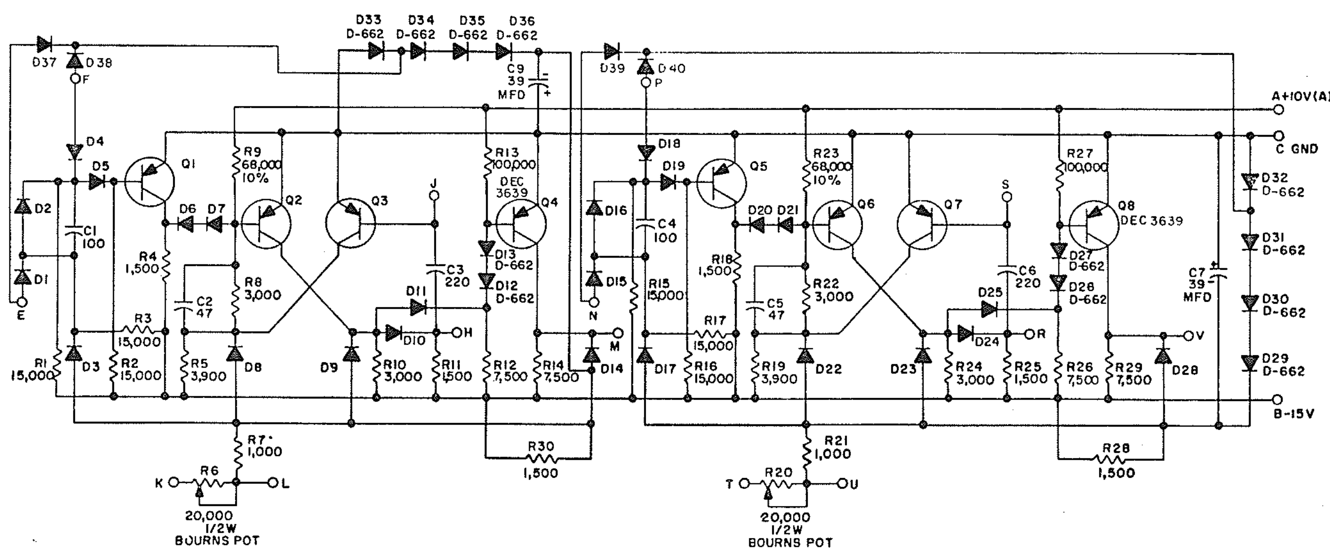
ISISTOR & DIODE CONVERSION CHART			
	EIA	DEC	EIA
	2N3639		
	IN 645		
	IN 3606		

NOTES

D	RS-B-R202	4
DUAL FLIP-FLOP R202		

)2

RS-B-R302-9



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 5%
CAPACITORS ARE MMFD
DIODES ARE D-664
TRANSISTORS ARE DEC 3639-0

TRANSISTOR & DIODE CONVERSION CHART			
DEC	EIA	DEC	EIA
DEC 3639-0	2N3639		
D-662	IN645		
D-664	IN3606		
DEC 3639	2N3639		

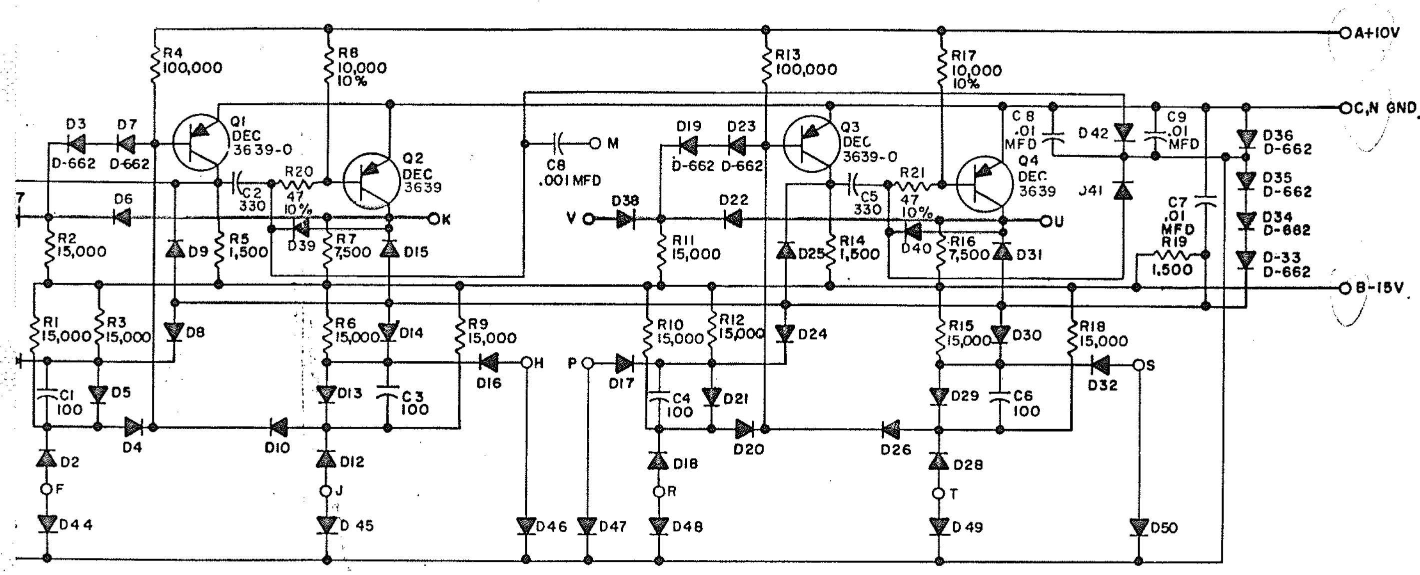
NOTES

G	RS-B-R302	9
DELAY (ONE SHOT) R302		

Fig. 8(e) R602 Pulse Amplifier

Fig. 8(f) B104 Inverter

602-7



OTHERWISE INDICATED:
ΊTORS ARE 1/4W; 5%
CITORS ARE MMFD
ΞS ARE D-664

'OR & DIODE CONVERSION CHART		
EIA	DEC	EIA
2N3639		
IN645		
IN3606		
2N3639		

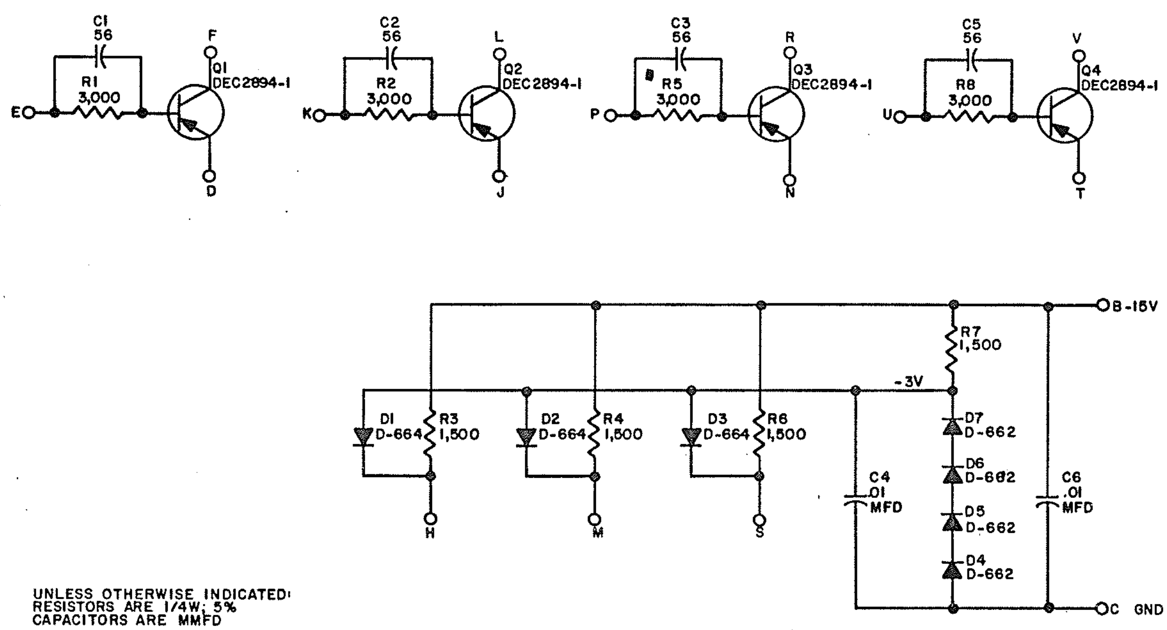
NOTES

THIS SCHEMATIC IS FURNISHED ONLY FOR TEST AND MAINTENANCE PURPOSES. THE CIRCUITS ARE PROPRIETARY IN NATURE AND SHOULD BE TREATED ACCORDINGLY.

H	RS-B-R602	7

PULSE AMPLIFIER R602

B104-1



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 5%
CAPACITORS ARE MMFD

STOR & DIODE CONVERSION CHART		
EIA	DEC	EIA
DEC2894		
IN645		
IN3605		

NOTES

THIS SCHEMATIC IS FURNISHED ONLY FOR TEST AND MAINTENANCE PURPOSES. THE CIRCUITS ARE PROPRIETARY IN NATURE AND SHOULD BE TREATED ACCORDINGLY.

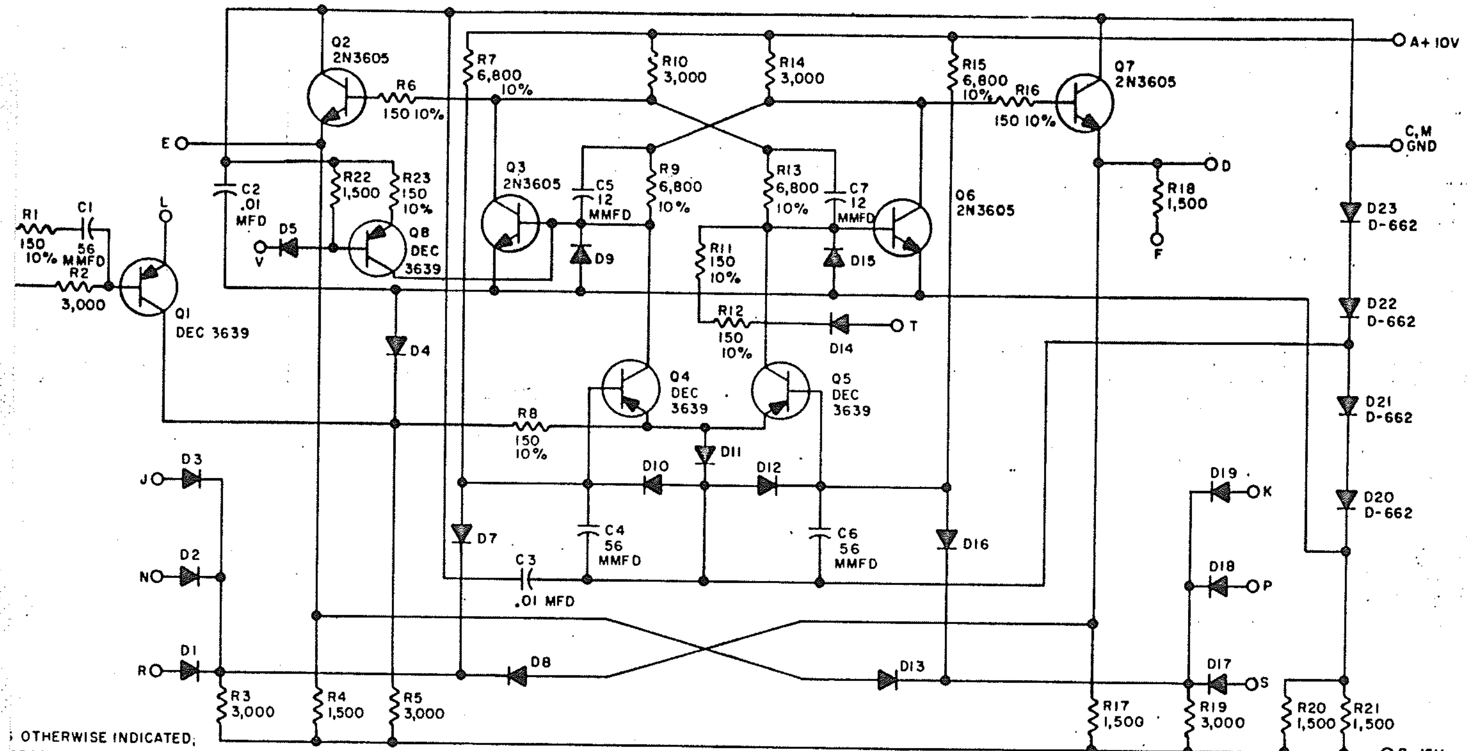
B	RS-B-B104	1

INVERTER B104

Fig. 8(g) B200 Flip Flop

Fig. 8(h) B602 Pulse Amplifier

32C0-2



UNLESS OTHERWISE INDICATED;
RESISTORS ARE 1/4W; 5%
DIODES ARE D-664

TRANSISTOR & DIODE CONVERSION CHART

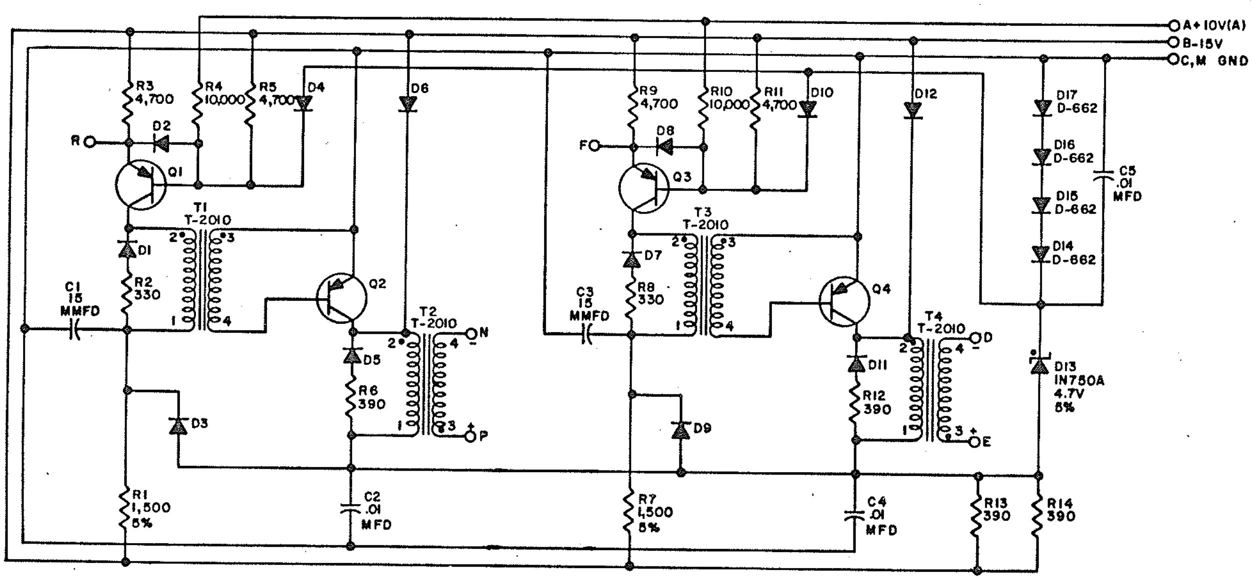
EIA	DEC	EIA
2N3605		
2N3639		
IN645		
IN3606		

NOTES

THIS SCHEMATIC IS FURNISHED ONLY FOR TEST AND MAINTENANCE PURPOSES. THE CIRCUITS ARE PROPRIETARY IN NATURE AND SHOULD BE TREATED ACCORDINGLY

B	RS-B-B200	2
FLIP-FLOP B200		

RS-B-B602



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 10%
TRANSISTORS ARE DEC2894-3
DIODES ARE D-664

TRANSISTOR & DIODE CONVERSION CHART

DEC	EIA	DEC	EIA
2894-3	DEC2894		
662	IN645		
664	IN3605		
750A	IN750A		

NOTES

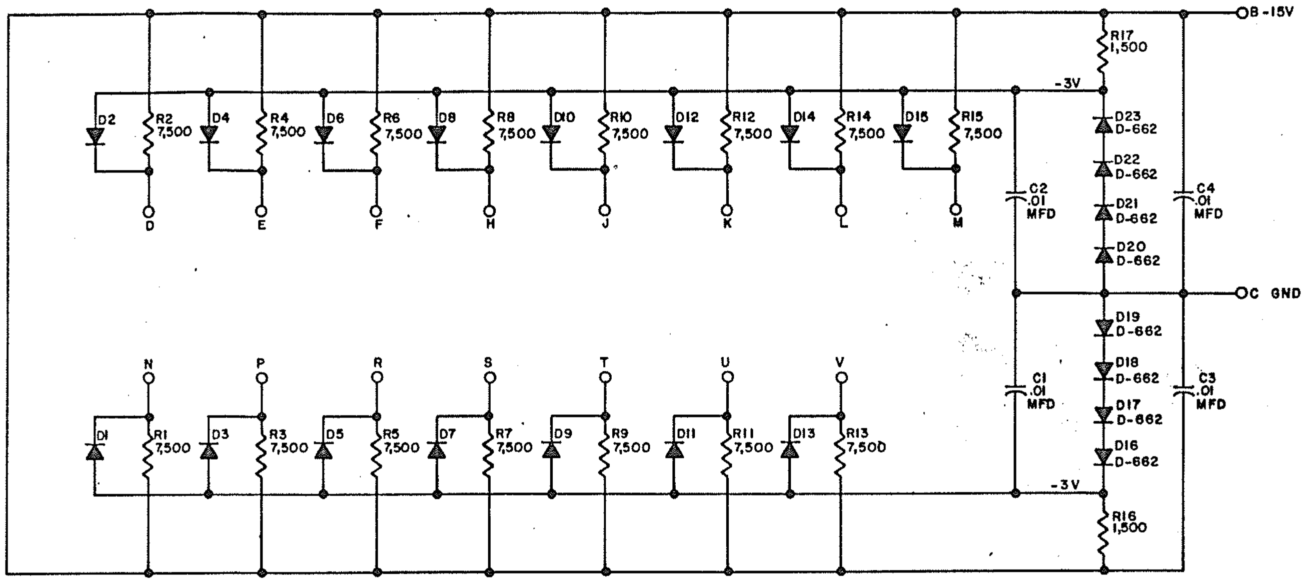
THIS SCHEMATIC IS FURNISHED ONLY FOR TEST AND MAINTENANCE PURPOSES. THE CIRCUITS ARE PROPRIETARY IN NATURE AND SHOULD BE TREATED ACCORDINGLY.

A	RS-B-B602	
10Mc PULSE AMPLIFIER B602		

Fig. 8(i) W002 Clamp Loads

Fig. 8(j) W501 Schmitt Trigger

RS-B-W002



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 5%
DIODES ARE D-664

USE THE ETCH BOARD OF THE W005

TRANSISTOR & DIODE CONVERSION CHART			
DEC	EIA	DEC	EIA
D-662	1N645		
D-664	1N3606		

NOTES

A	RS-B-W002	
CLAMP LOADS W002		

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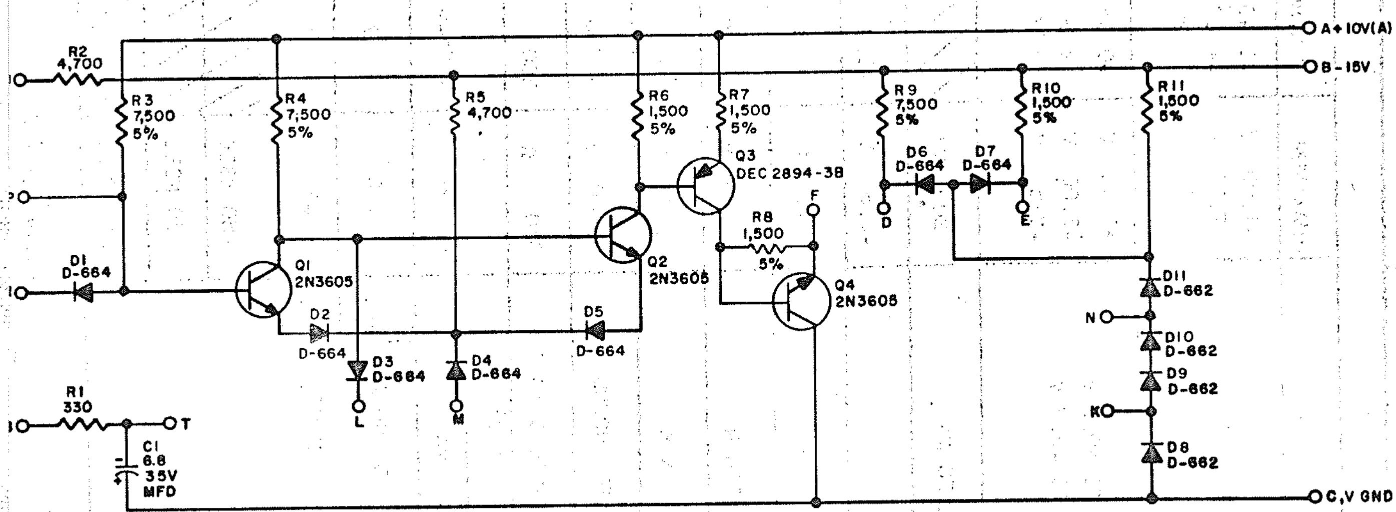
-W501-5



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 10%

TRANSISTOR & DIODE CONVERSION CHART			
DEC	EIA	DEC	EIA
-3B	DEC 2894-3B		
	1N645		
	1N3606		
	2N3605		

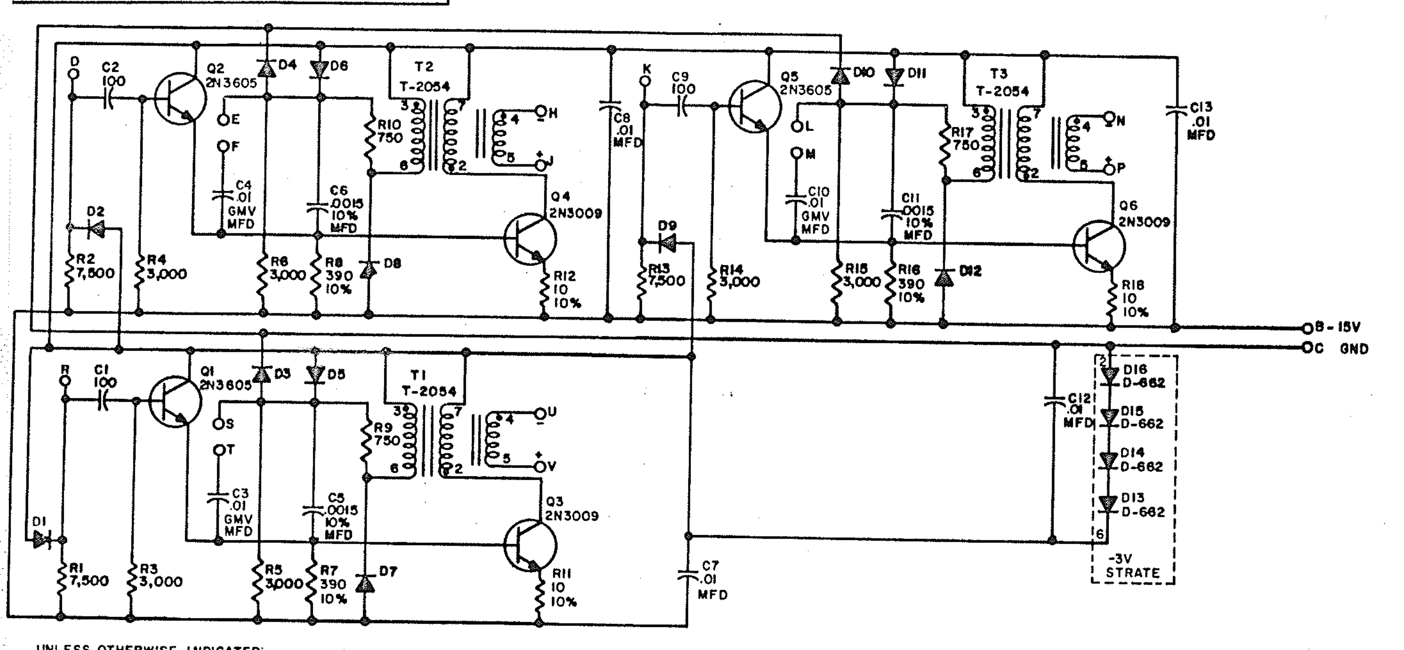
NOTES

F	RS-B-W501	5
SCHMITT TRIGGER W501		

Fig. 8(k) W640 Pulse Amplifier

Fig. 8(1) W800 Dual Relay

SIZE	CODE	NUMBER	REV
B	CS	W640-0-1	E



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 5%
CAPACITORS ARE MMFD
DIODES ARE D-664

REV	CHG NO	
4	DAW 5032	REV. BR. EDR. 5398

DRN.	DATE
H. PORTER	9-22-64
CHK'D N. PERRYMAN	9-29-64
ENG R. BANK	9-29-64
PROD. 2	DATE

TRANSISTOR & DIODE CONVERSION CHART

DEC	EIA	DEC	EIA
2N3009	SAME		
2N3605	SAME		
D662	IN645		
D664	IN3606		

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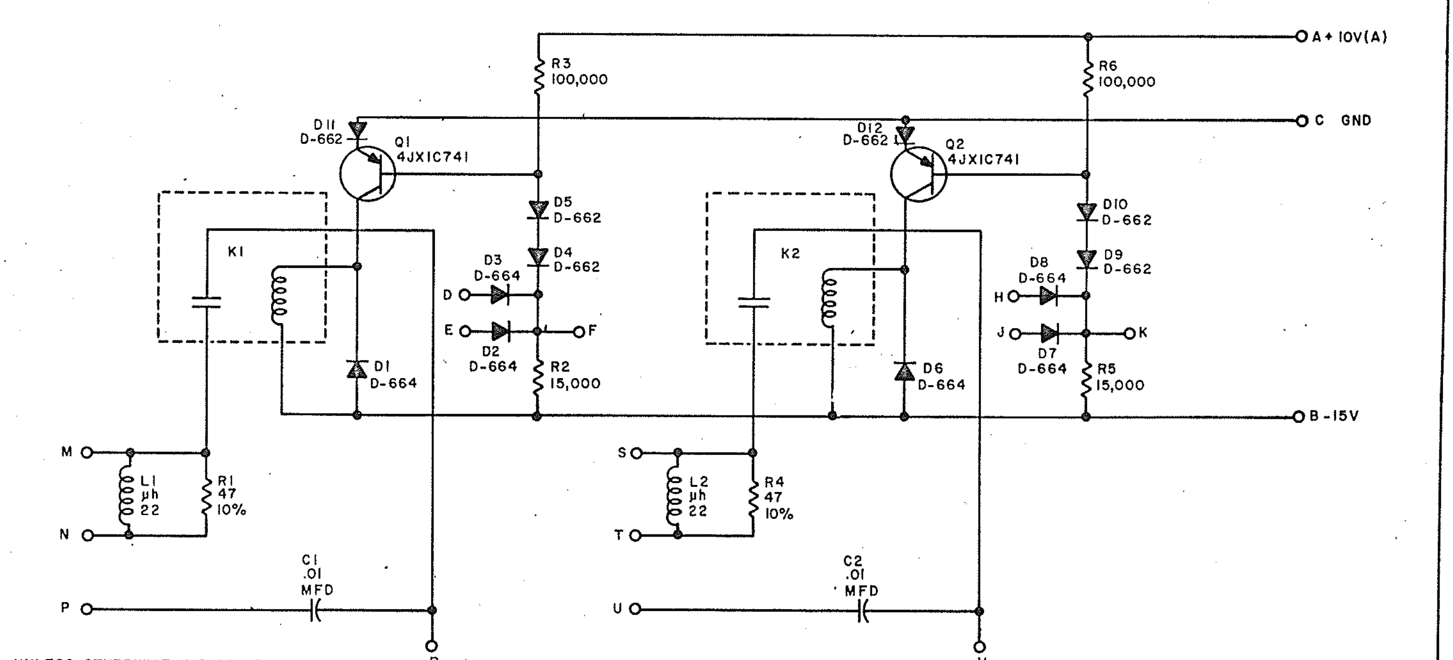
TITLE PULSE AMPLIFIER W640

SIZE	CODE	NUMBER	REV.
B	CS	W640-0-1	E

PRINTED CIRCUIT REV. D

FORM NO. 102

B-W800-2



UNLESS OTHERWISE INDICATED:
RESISTORS ARE 1/4W; 5%
K1 & K2 ARE WHEELOCK, 262-2A-X1, 12V DC
L1 & L2 ARE ESSEX, RFC-L, 10%

TRANSISTOR & DIODE CONVERSION CHART

DEC	EIA	DEC	EIA
	2N527		
	IN645		
	IN3606		

NOTES

B	RS-B-W800	2

RELAY W800

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APPENDIX 1

INSTRUCTION SUMMARY

MEMORY REFERENCE INSTRUCTIONS

Mnemonic Symbol	Octal Code	Machine Cycles	Operation Executed
CAL	00	2	Call subroutine. The address portion of this instruction is ignored. The action is identical to JMS 20.
DAC Y	04	2	Deposit AC. The content of the AC is deposited in the memory cell at location Y.
JMS Y	10	2	Jump to subroutine. The content of the PC and the content of the L are deposited in memory cell Y. The next instruction is taken from cell Y + 1.
DZM Y	14	2	Deposit zero in memory. Zero is deposited in memory cell Y.
LAC Y	20	2	Load AC. The content of Y is loaded into the AC.
XOR Y	24	2	Exclusive OR. The exclusive OR is performed between the content of Y and the content of the AC, with the result left in the AC.
ADD Y	30	2	Add (1's complement). The content of Y is added to the content of the AC in 1's complement arithmetic and the result is left in the AC.
TAD Y	34	2	Two's complement add. The content of Y is added to the content of the AC in 2's complement arithmetic and the result is left in the AC.
XCT Y	40	1+	Execute. The instruction in memory cell Y is executed.
ISZ Y	44	2	Increment and skip if zero. The content of Y is incremented by one in 2's complement arithmetic. If the result is zero, the next instruction is skipped.
AND Y	50	2	AND. The logical operation AND is performed between the content of Y and the content of the AC with the result left in the AC.

MEMORY REFERENCE INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Machine Cycles	Operation Executed
SAD Y	54	2	Skip if AC is different from Y. The content of Y is compared with the content of the AC. If the numbers are different, the next instruction is skipped.
JMP Y	60	1	Jump to Y. The next instruction to be executed is taken from memory cell Y.

EAE INSTRUCTION LIST

Mnemonic Symbol	Octal Code	Operation Executed
EAE	640000	Basic EAE command. No operation.
LRS	640500	Long right shift.
LRSS	660500	Long right shift, signed (AC sign = link).
LLS	640600	Long left shift.
LLSS	660600	Long left shift, signed (AC sign = L).
ALS	640700	Accumulator left shift.
ALSS	660700	Accumulator left shift, signed (AC sign = L).
NORM	640444	Normalize, unsigned. Maximum shift is 44_8.
NORMS	660444	Normalize, signed (AC sign = L).
MUL	653122	Multiply, unsigned. The number in the AC is multiplied by the number in the next core memory address.
MULS	657122	Multiply, signed. The number in the AC is multiplied by the number in the next core memory address.
DIV	640323	Divide, unsigned. The 36-bit content of both the AC and MQ is divided by the number in the next core memory location.
DIVS	644323	Divide, signed. The content of both the AC and MQ as a 1's complement signed number is divided by the number in the next core memory location.

EAE INSTRUCTION LIST (continued)

Mnemonic Symbol	Octal Code	Operation Executed
IDIV	653323	Integer divide, unsigned. Divide the number in the AC as an 18-bit unsigned integer by the number in the next core memory location.
IDIVS	657323	Integer divide, signed. Same as IDIV but the content of the AC is a 17-bit signed number.
FRDIV	650323	Fraction divide, unsigned. Divide the 18-bit fraction in the AC by the 18-bit fraction in the number in the next core memory location.
FRDIVS	654323	Fraction divide, signed. Same as FRDIV, but the content of the AC is a 17-bit signed number.
LACQ	641002	Replace the content of the AC with the content of the MQ.
LACS	641001	Replace the content of the AC with the content of the SC.
CLQ	650000	Clear MQ.
ABS	644000	Place absolute value of AC in the AC.
GSM	664000	Get sign and magnitude. Places AC sign in the link and takes the absolute value of AC.
OSC	640001	Inclusive OR the SC into the AC.
OMQ	640002	Inclusive OR AC with MQ and place results in AC.
CMQ	640004	Complement the MQ.
LMQ	652000	Load MQ.

INPUT/OUTPUT TRANSFER INSTRUCTIONS

Mnemonic Symbol	Octal Code	Operation Executed
		Program Interrupt
IOF	700002	Interrupt off. Disable the PIC.
ION	700042	Interrupt on. Enable the PIC.
ITON	700062	Interrupt and trap on. Enable PIC and trap mode.

INPUT/OUTPUT TRANSFER INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Operation Executed
		Real Time Clock
CLSF	700001	Skip the next instruction if the clock flag is set to 1.
CLOF	700004	Clear the clock flag and disable the clock.
CLON	700044	Clear the clock flag and enable the clock.
		Perforated Tape Reader
RSF	700101	Skip if reader is a 1.
RCF	700102	Clear reader flag, then inclusively OR the content of reader buffer into the AC.
RRB	700112	Read reader buffer. Clear reader flag and AC, and then transfer content of reader buffer into AC.
RSA	700104	Select reader in alphanumeric mode. One 8-bit character is read into the reader buffer.
RSB	700144	Select reader in binary mode. Three 6-bit characters are read into the reader buffer.
		Perforated Tape Punch
PSF	700201	Skip if the punch flag is set to 1.
PCF	700202	Clear the punch flag.
PSA or PLS	700204 700206	Punch a line of tape in alphanumeric mode.
PSB	700244	Punch a line of tape in binary mode.
		I/O Equipment
IORS	700314	Input/output read status. The content of given flags replace the content of the assigned AC bits.
TTS	703301	Test Teletype and skip if KSR 33 is connected to computer.
CAF	703302	Clear all flags.
SKP7	703341	Skip if processor is a PDP-7 or PDP-9

INPUT/OUTPUT TRANSFER INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Operation Executed
		Teletype Keyboard
KSF	700301	Skip if the keyboard flag is set to 1.
KRB	700312	Read the keyboard buffer. The content of the buffer is placed in AC10-17 and the keyboard flag is cleared.
		Teletype Teleprinter
TSF	700401	Skip if the teleprinter flag is set.
TCF	700402	Clear the teleprinter flag.
TLS	700406	Load teleprinter buffer. The content of AC10-17 is placed in the buffer and printed. The flag is cleared before transmission takes place and is set when the character has been printed.
		Types 30 and 34 Oscilloscope and Precision CRT Displays
DXC	700502	Clear the X-coordinate buffer.
DYC	700602	Clear the Y-coordinate buffer.
DXL	700506	Load the X-coordinate buffer from AC8-17.
DYL	700606	Load the Y-coordinate buffer from AC8-17.
DXS	700546	Load the X-coordinate buffer and display the point specified by the XB and YB.
DYS	700646	Load the Y-coordinate buffer and display the point specified by the XB and YB.
DSF	700701	Skip if display flag = 1.
DCF	700702	Clear display flag.
DLB	700706	Load the brightness register from AC15-17. (for Type 30)
--	700704	Load the brightness register from AC16-17. (for Type 34)

INPUT/OUTPUT TRANSFER INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Operation Executed
		Type 340C Precision Incremental Display
IDVE	700501	Skip on vertical edge violation.
IDSI	700601	Skip on stop interrupt.
IDSP	700701	Skip if light pen flag is set.
IDHE	701001	Skip on horizontal edge violation.
IDRS	700504	Continue display. After a light pen interrupt, this command causes the display to resume at the point indicated by the content of the DAC.
IDRA	700512	Read display address. Transfers the address in the DAC to AC5-17.
IDLA	700606	Load address and select. The content of AC5-17 are placed in the DAC and the display is started.
IDRD	700614	Restart display. After a stop code interrupt, this command causes the display to resume at the point indicated by the content of the DAC.
IDCF	700704	Clear display control. All flags and interrupts are cleared.
IDRC	700712	Read X and Y coordinates. The contents of bits XB0-8 is transferred into AC0-8 and the content of YB0-8 is transferred into AC9-17.
		Type 33 Symbol Generator
GCL	700641	Clear done flag (also done by GPL or GPR).
GSF	701001	Skip on done.
GPL	701002	Generator plot left.
GLF	701004	Load format (bit 15 for space, bits 16 and 17 for size).
GPR	701042	Generator plot right.
GSP	701044	Plot a space.

INPUT/OUTPUT TRANSFER INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Operation Executed
		Type 139E General Purpose Multiplexer Control
ADSM	701103	Select MX channel. The content of AC12-17 is placed in the MAR.
ADIM	701201	Increment channel address. The content of the MAR is incremented by 1. Channel 0 follows channel 77_8.
		Type 138E Analog-to-Digital Converters
ADSF	701301	Skip if converter flag is set.
ADSC	701304	Select and convert. The converter flag is cleared and a conversion is initiated.
ADRB	701312	Read converter buffer. Places the content of the buffer in the AC.
		Type DR09A Relay Buffer
ORC	702101	Clear output relay buffer flip-flop reigster.
ORS	702104	Set output relay buffer flip-flop register to correspond with the contents of the accumulator.
		Type 350 Incremental Plotter and Control
PLSF	702401	Skip if plotter flag is a 1.
PLCF	702402	Clear plotter flag.
PLPU	702404	Plotter pen up. Raise pen off of paper.
PLPR	702501	Plotter pen right.
PLDU	702502	Plotter drum (paper) upward.
PLDD	702504	Plotter drum (paper) downward.
PLPL	702601	Plotter pen left.
PLUD	702602	Plotter drum (paper) upward.
PLPD	702604	Plotter pen down. Lower pen on to paper.

INPUT/OUTPUT TRANSFER INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Operation Executed
		Type KF09A Automatic Priority Interrupt
SPI	705501	Skip on priorities inactive.
ISA	705504	Initiate selected activity.
DBK	703304	Debreak.
DBR	703344	Debreak and restore.
		Type RM09A Serial Drum
DRLCRD	706006	Load counter and read. Places the content of AC2-17 in the DCL and prepares the drum system for reading a block for reading a block into core memory.
DRLCWR	706046	Load counter and write. Loads the DCL from AC2-17 and prepares the drum system for writing a block to be received from core memory.
DRSF	706101	Skip if drum transfer flag is set.
DRCF	706102	Clear drum transfer and error flags.
DRLBLK	706106	Load sector and select. Places the content of AC9-17 in the DTR, clears both drum flags, and initiates the block transfer.
DRSOK	706201	Skip if drum error flag is not set.
DRCONT	706204	Continue select. Clears the flags and initiates a transfer as specified by the content of the DCL and DTR.
		Type 647 Automatic Line Printer
LPDF	706501	Skip if printing done flag = 1.
LPCB	706502	Clear printing done flag. Clear printing buffer; set done flag.
LPL1	706566	Load one character into printing buffer.
LPL2	706526	Load two characters into printing buffer. Clear done flag.

INPUT/OUTPUT TRANSFER INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Operation Executed
		Type 647 Automatic Line Printer (continued)
LPLD	706546	Load printing buffer (three characters).
LPSE	706506	Select printer and print.
LSSF	706601	Skip if spacing flag = 1.
LSCF	706602	Clear spacing flag.
LSLS	706606	Load spacing buffer, space, and clear spacing flag.
		Type CR01E Card Reader
RCSF	706701	Skip (the next instruction in sequence) on data ready flag.
RCSD	706721	Skip on card done flag.
RCSR	706741	Skip on reader ready.
	706702	Clear data flag, and inclusively OR column into AC12-17 in alphanumeric mode.
RCRA	706712	Clear AC; clear data ready flag and read column AC12-17 in alphanumeric mode.
	706742	Clear data ready flag, and inclusively OR column into AC6-17 in binary mode.
RCRB	706752	Clear AC; clear data ready flag and read column into AC6-17 in binary mode.
RCSE	706704	Select card reader and initiate card motion if reader is ready; clear card done flag.
RCLD	706724	Clear card done flag.
		Type CR02B Card Reader
CRSF	706701	Skip if the card reader flag is set.
CRSA	706704	Select and read a card in alphanumeric mode. A card is started through the reader and 80 columns are read, interpreted, and translated into 6-bit character codes.

INPUT/OUTPUT TRANSFER INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Operation Executed
		Type CR02B Card Reader (continued)
CRRB	706712	Read the card reader buffer. The content of the CRB is placed in AC6-17.
CRSB	706744	Select and read a card in binary mode. A card is started through the reader and 80 columns are read as 12-bit numbers.
		Type TC59 Tape Control IOT Instructions
MTSF	707301	Skip on error flag or magnetic tape flag (EF and MTF).
MTCR	707321	Skip on tape control ready (TCR).
MTTR	707341	Skip on tape transport ready (TTR).
MTAF	707322	Clear status and command registers and EF and MTF.
	707324	Inclusively OR content of AC_{0-11} into command register.
MTLC	707326	Load content of AC_{0-11} into command register.
MTCC	707356	Terminate write continuous mode.
	707342	Inclusively OR content of status register into AC_{0-11}.
MTRS	707352	Read content of status register into AC_{0-11}.
	707302	Inclusively OR content of command register into AC_{0-11}.
MTRC	707312	Read command register into AC_{0-11}.
MTGO	707304	Set "go" bit to execute command in command register.
		TC02 DECtape Control IOT Instructions
DTCA	707541	Clear status register A.
DTRA	707552	Read status register A.
DTXA	707544	XOR status register A.
DTLA	707545	Load status register A.

INPUT/OUTPUT TRANSFER INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Operation Executed
		TC02 DECtape Control IOT Instructions (continued)
DTEF	707561	Skip on error flag.
DTRB	707572	Read status B.
DTDF	707601	Skip on DECtape flag.
		Memory Extension Control
SEM	707701	Skip if in extend mode.
EEM	707702	Enter extend mode.
LEM	707704	Leave extend mode.

OPERATE INSTRUCTIONS

Mnemonic Symbol	Octal Code	Event Time	Operation Executed
OPR or NOP	740000	---	Operate group or no operation. Causes a 1-cycle program delay.
CMA	740001	3	Complement accumulator. Each bit of the AC is complemented.
CML	740002	3	Complement link.
OAS	740004	3	Inclusive OR ACCUMULATOR switches. The word set into the ACCUMULATOR switches is OR combined with the content of the AC, the result remains in the AC.
RAL	740010	3	Rotate accumulator left. The content of the AC and L are rotated one position to the left.
RAR	740020	2	Rotate accumulator right. The content of the AC and L are rotated one position to the right.
HLT	740040	---	Halt. The program is stopped at the conclusion of the cycle.
SMA	740100	1	Skip on minus accumulator. If the content of the AC is negative (2's complement) number the next instruction is skipped.

OPERATE INSTRUCTIONS (continued)

Mnemonic Symbol	Octal Code	Event Time	Operation Executed
SZA	740200	1	Skip on zero accumulator. If the content of the AC equals zero (2's complement), the next instruction is skipped.
SNL	740400	1	Skip on non-zero link. If the L contains a 1, the next instruction is skipped.
SKP	741000	1	Skip. The next instruction is unconditionally skipped.
SPA	741100	1	Skip on positive accumulator. If the content of the AC is zero (2's complement) or a positive number, the next instruction is skipped.
SNA	741200	1	Skip on non-zero accumulator. If the content of the AC is not zero (2's complement), the next instruction is skipped.
SZL	741400	1	Skip on zero link. If the L contains a 0, the next instruction is skipped.
RTL	742010	2,3	Rotate two left. The content of the AC and the L are rotated two positions to the left.
RTR	742020	2,3	Rotate two right. The content of the AC and the L are rotated two positions to the right.
CLL	744000	2	Clear link. The L is cleared.
STL	744002	2,3	Set link. The L is set to 1.
RCL	744010	2,3	Clear link, then rotate left. The L is cleared, then the L and AC are rotated one position left.
RCR	744020	2,3	Clear link, then rotate right. The L is cleared, then the L and AC are rotated one position right.
CLA	750000	2	Clear accumulator. Each bit of the AC is cleared.
CLC	750001	2,3	Clear and complement accumulator. Each bit of the AC is set to contain a 1.
LAS	750004	2,3	Load accumulator from switches. The word set into the ACCUMULATOR switches is loaded into the AC.
GLK	750010	2,3	Get link. The content of L is set into AC17.
LAW N	76XXXX	---	Load the AC with 76XXXX.

APPENDIX 2
PDP-9 I/O CODES

MODEL 33, 35 ASR/KSR TELETYPE CODE (ASCII) IN OCTAL FORM

Character	8-Bit Code (in Octal)	Character	8-Bit Code (in Octal)
A	301	!	241
B	302	"	242
C	303	#	243
D	304	$	244
E	305	%	245
F	306	&	246
G	307	'	247
H	310	(	250
I	311	)	251
J	312	*	252
K	313	+	253
L	314	,	254
M	315	-	255
N	316	.	256
O	317	/	257
P	320	:	272
Q	321	;	273
R	322	<	274
S	323	=	275
T	324	>	276
U	325	?	277
V	326	@	300
W	327	[	333
X	330	/	334
Y	331	]	335
Z	332	↑	336
0	260	→	337
1	261	Leader/Trailer	200*
2	262	Line-Feed	212*
3	263	Carriage-Return	215
4	264	Space	240
5	265	Rub-out	377*
6	266	Blank	000*
7	267	ALT Mode	373
8	270		
9	271		

* Ignored by the operating system

APPENDIX 3

ISOTOPE ABUNDANCE RATIO DATA OUTPUT AND ANALYSIS

```
GONE,       TIN
            TCR
            LAW TITLE
            TSR
            TCR
ALPHA,      LAC (10000
            DAC 10
            LAC (777600
            DAC TEMP
            SKP
BETA,       705004
GAMMA,      705001
            JMP GAMMA
            705012
            DAC I 10
            JMS INDEL
            ISZ TEMP
            JMP BETA
            LAC (10000
            DAC 10
            LAC (777776
            DAC PAR
            LAC (777600
            DAC TEMP
            LAC (2000
            DAC 11
DELTA,      LAC I 10
            DAC EASY
            ISZ TEMP
            JMP . 5
            TCR
            LAW ERROR2
            TSR
            JMP FOX
            CLL
            CLA
            LMQ
            LAC I 10
            DIV
EASY,       XX
            SNL
            JMP TAL
            ISZ PAR
            JMP UNDER
SOLO,       LAC 10
            ADD (777775
            DAC 10
            LAC I 10
            DAC LWF1
```

```
          LAC I 10
          DAC LWF2
          LAC 10
          ADD (777775
          DAC 10
          LAC LWF2
          DAC I 10
          LAC LWF1
          DAC I 10
          LAC 10
          ADD (777775
          DAC 10
          LAC (777777
          DAC PAR
          LAC TEMP
          ADD (777776
          DAC TEMP
          JMP DELTA
UNDER,    TCR
          LAW ERROR1
          TSR
          JMP SOLO
TAL,      LACQ
          DAC I 11
          ISZ TEMP
          JMP DELTA
FOX,      LAC (777701
          DAC HOLD
          LAC (2000)
          DAC 10
          DZM OVRFLO
          CLL
          LAC I 10
GEORGE,   TAD I 10
          SZL
          JMS HOW
ITEM,     ISZ HOLD
          JMP GEORGE
          LMQ
          LAC OVRFLO
          CLL
          DIV
          100
          DAC REMAVE
          LACQ
          DAC AVERAT
          LAC (2000
          DAC 10
          LAC (4000)
          DAC 11
```

```
         LAC (777700
         DAC TEMP
KING,    LAC AVERAT
         CMA
         ADD I 10
         SMA
         SKP
         CMA
         DAC I 11
         ISZ TEMP
         JMP KING
         LAC (4000
         DAC 10
         LAC (5000
         DAC 11
         LAC (6000
         DAC 12
         LAC (777700
         DAC TEMP
LOVE,    CLL
         LAC I 10
         DAC HOLD
         LAC HOLD
         DAC . 3
         LAC HOLD
         MUL
         XX
         DAC I 11
         LACQ
         DAC I 12
         ISZ TEMP
         JMP LOVE
         LAC (777701
         DAC TEMP
         LAC (1
         DAC CARRY
         LAC (6000
         DAC 10
         DZM FULL
         LAC I 10
MIKE,    CLL
         TAD I 10
         SNL
         JMP . 6
         DAC STORE
         LAC FULL
         TAD CARRY
         DAC FULL
         LAC STORE
         ISZ TEMP
```

```
                JMP MIKE
                DAC SUM1
                LAC (777700
                DAC TEMP
                LAC (5000
                DAC 10
                LAC FULL
                TAD I 10
                ISZ TEMP
                JMP .-2
                DAC SUM2
                LAC SUM1
                CMA
                DAC CSUM1
                LAC SUM2
                CMA
                DAC CSUM2
                LAC (1
                DAC INC
                CLL
                CLA
NOMAD,          LAC INC
                DAC OBOE
                LAC INC
                MUL
OBOE,           XX
                ADD CSUM2
                SZA
                JMP UNFIN
                LACQ
                ADD CSUM1
                SZA
                JMP UNFIN
                JMP AHEAD
UNFIN,          SMA
                JMP AHEAD
                ISZ INC
                JMP NOMAD
AHEAD,          LAC (-3+1
                DAC TEMP
                LAC INC
                RCR
                ISZ TEMP
                JMP .-2
                DAC SIGMA
                TCR
                LAW CLMNHD
                TSR
                TCR
                LAC (10000
```

```
          DAC 10
          LAC (2000
          DAC 11
          LAC (777700
          DAC PAR
PETER,    LAC I 10
          JMS I10OUT
          LAC I 10
          JMS I10OUT
          LAC I 11
          JMS D10OUT
          TCR
          ISZ PAR
          JMP PETER
          TCR
          LAW AVE
          TSR
          LAC AVERAT
          JMS D10OUT
          TCR
          LAW SIG
          TSR
          LAC SIGMA
          JMS D10OUT
          TCR
          HLT
I10OUT,   XX
          DAC WAIT
          LAC (-6+1
          DAC MNCNT
          LAC (303240
          DAC FTRD
SET,      LAC WAIT
          CLL
          IDIV
FTRD,     XX
          DAC WAIT
          LACQ
          TDIGIT
          LAC FTRD
          CLL
          IDIV
          12
          LACQ
          DAC FTRD
          ISZ MNCNT
          JMP SET
          LAC (-10+1)
          DAC TEMP
          TSP
```

```
            ISZ TEMP
            JMP .-2
            JMP I I10ØOUT
D10ØOUT,    XX
            DAC WAIT
            LAC (-5+1
            DAC MNCNT
            CLA
            TDIGIT
            LAC (17
            TY1
            LAC WAIT
HERE,       CLL
            MUL
            12
            TDIGIT
            LACQ
            ISZ MNCNT
            JMP HERE
            JMP I D10ØOUT
INDEL,      Ø
            LAM -226Ø
            DAC 7
            CLON
            CLSF
            JMP .-1
            CLOF
            JMP I INDEL
ERROR1,     TEXT /
DIVIDEND GREATER THAN DIVISOR, RATIO INVERTED, NUMBER ORDER REVERSED /
ERROR2,     TEXT /
ODD NUMBER OF DATA WORDS
EXAMINE LAST RATIO FOR ERROR /
HOW,        XX
            DAC SUM
            CLA
            GLK
            TAD OVRFLO
            DAC OVRFLO
            CLL
            LAC SUM
            JMP I HOW
CLMNHD,     TEXT /
MASS 1        MASS 2          RATIO /
TITLE,      TEXT /
          ISOTOPIC ABUNDANCE RATIO MEASUREMENT /
AVE,        TEXT /
AVERAGE RATIO = /
SIG,        TEXT /
SIGMA = /
PAUSE GONE
```

APPENDIX 4

```
ISOTOPE ABUNDANCE RATIO DATA OUTPUT AND ANALYSIS
/PDP-4/7 BTA
OTY, NONINTERRUPT VERSION


SUM          1Ø72
MNCNT        1Ø73
WAIT         1Ø74
SIGMA        1Ø75
INC          1Ø76
CSUM2        1Ø77
CSUM1        11ØØ
SUM2         11Ø1
SUM1         11Ø2
STORE        11Ø3
FULL         11Ø4
CARRY        11Ø5
AVERAT       11Ø6
REMAVE       11Ø7
OVRFLO       111Ø
HOLD         1111
LWF2         1112
LWF1         1113
PAR          1114
TEMP         1115
```

AHEAD	315
ALPHA	27
AVE	572
AVERAT	1106
BETA	34
BTATAB	1022
CARRY	1105
CLMNHD	534
CSUM1	1100
CSUM2	1077
DELTA	54
D100UT	416
EASY	71
ERROR1	447
ERROR2	477
FOX	135
FTRD	374
FULL	1104
GAMMA	35
GEORGE	144
GONE	22
HERE	427
HOLD	1111
HOW	523
INC	1076
INDEL	437
ITEM	147
I100UT	363
KING	167
LOVE	210
LWF1	1113
LWF2	1112
MIKE	235
MNCNT	1073
NCT	766
NOMAD	274
OBOE	300
OCL	1001
OCS	1002
OCU	1000
OTY	1061
OVRFLO	1110
PAR	1114
PETER	336
REMAVE	1107
RL6	761
SET	371
SIG	601
SIGMA	1075
SOLO	76
STORE	1103

SUM	1072
SUM1	1102
SUM2	1101
TAL	131
TBC	1067
TCR	100651
TCRA	1016
TDIGIT	100732
TEMP	1115
TEMY	1070
TEMY1	1066
TIN	100716
TITLE	551
TSP	100665
TSR	100743
TTAB	10
TYEXIT	600755
TYSVAC	1071
TYT	100677
TY1	100605
TY1A	613
TY1B	1003
TY1C	1012
TY1D	1010
TY2	635
TY3	100637
UNDER	125
UNFIN	311
WAIT	1074
XIT	100000

TTAB	10
GONE	22
ALPHA	27
BETA	34
GAMMA	35
DELTA	54
EASY	71
SOLO	76
UNDER	125
TAL	131
FOX	135
GEORGE	144
ITEM	147
KING	167
LOVE	210
MIKE	235
NOMAD	274
OBOE	300
UNFIN	311
AHEAD	315
PETER	336
I100UT	363

SET	371
FTRD	374
D100UT	416
HERE	427
INDEL	437
ERROR1	447
ERROR2	477
HOW	523
CLMNHD	534
TITLE	551
AVE	572
SIG	601
TY1A	613
TY2	635
RL6	761
NCT	766
OCU	1000
OCL	1001
OCS	1002
TY1B	1003
TY1D	1010
TY1C	1012
TCRA	1016
BTATAB	1022
OTY	1061
TEMY1	1066
TBC	1067
TEMY	1070
TYSVAC	1071
SUM	1072
MNCNT	1073
WAIT	1074
SIGMA	1075
INC	1076
CSUM2	1077
CSUM1	1100
SUM2	1101
SUM1	1102
STORE	1103
FULL	1104
CARRY	1105
AVERAT	1106
REMAVE	1107
OVRFLO	1110
HOLD	1111
LWF2	1112
LWF1	1113
PAR	1114
TEMP	1115
XIT	100000
TY1	100605
TY3	100637
TCR	100651
TSP	100665
TYT	100677
TIN	100716
TDIGIT	100732
TSR	100743
TYEXIT	600755

APPENDIX 6

ISOTOPIC ABUNDANCE RATIO MEASUREMENT

SEPT.12, 1967 RUN ~~XX~~ #6
PREPARED SAMPLE CO_2 (44/46)
BASE TIME = 6 ADDED TIME ON HIGH MASS = 7
TO FIND THE CORRECT RATIO MULTIPLY MEASURED RATIO BY 0.28639
THIS NUMBER ARISES FROM UNEQUAL COUNTING TIMES AND WAS MEASURED
IN RUN #5

MASS 1	MASS 2	RATIO
002672	000306	0.11451
002688	000274	0.10193
002735	000250	0.09140
002707	000262	0.09678
002732	000286	0.10468
002787	000316	0.11338
002664	000252	0.09459
002743	000272	0.09915
002695	000240	0.08905
002784	000278	0.09985
002683	000346	0.12895
002783	000282	0.10132
002719	000276	0.10150
002471	000286	0.11574
002459	000294	0.11956

REFERENCES

1. J. S. Allen, Phys. Rev. 55, 966, (1939)
2. C. R. McKinney, et al, Rev. Sci. Instr., 21, 724, (1950)
3. A. I. Akishin, Sov. Phys. Uspekhi, 66, 113-123, (1)
4. L. A. Dietz, Rev. Sci. Instr., 36, 1763, (1965)
5. T. L. Collins and F. A. White, App. Spect., 8, 17, (1954)
6. A. O. Nier, Rev. Sci. Instr., 11, 212, (1940)
7. A. O. Nier, Rev. Sci. Instr., 18, 294, (1947)
8. J. H. Beynon, "Mass Spectrometry and its Applications to Organic Chemistry" Elsevier Publishing Company, (1960)
9. H. E. Duckworth, "Mass Spectroscopy", Cambridge University Press, (1958)
10. C. A. McDowell, "Mass Spectrometry", McGraw-Hill Book Company, Inc. (1963)
11. G. P. Barnard, "Modern Mass Spectrometry", The Institute of Physics, London, (1953).