FINAL REPORT

Contract No.: NAS 9-12117

Submitted by: Orion Research Incorporated
11 Blackstone Street
Cambridge, Massachusetts 02139

Submitted to: National Aeronautics and
Space Administration
Houston, Texas

Date: December 14, 1973

(NASA-CR-134373) AUTOMATED POTENTIOMETRIC ELECTROLYTE ANALYSIS SYSTEM Final Report (Orion Research, Inc.)

N74-30491

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G3/05 46342

AUTOMATED POTENTIOMETRIC ELECTROLYTE ANALYSIS SYSTEM

FINAL REPORT

9-12117

ORION RESEARCH INCORPORATED

MSC-14627

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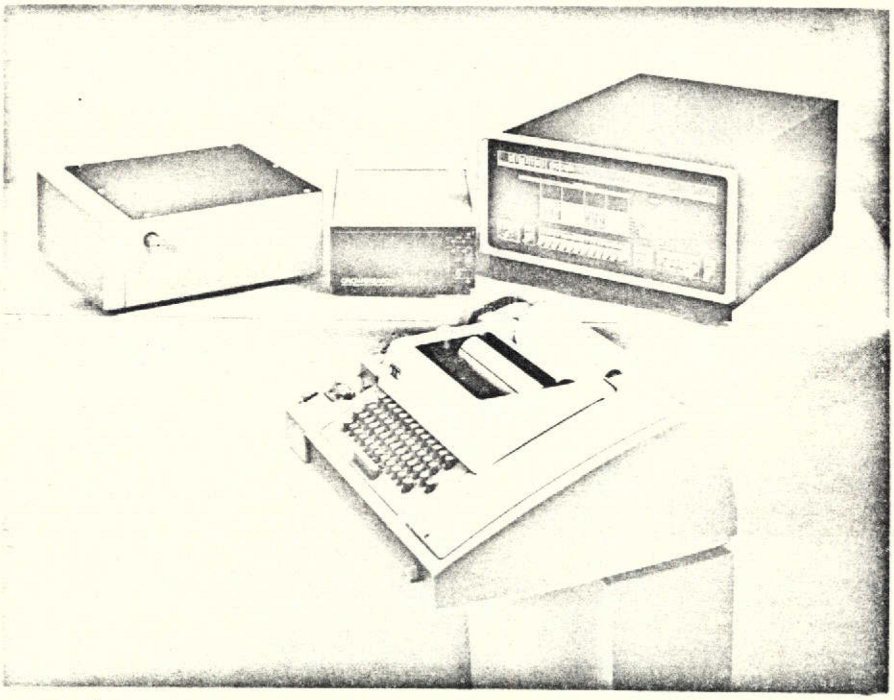
CHAPTER I

INTRODUCTION

This final report is submitted by Orion Research Incorporated to describe work performed on Contract NAS 9-12117. The purpose of this undertaking was to demonstrate the feasibility of utilizing chemical sensing electrode technology as the basis for an automatically-controlled system for blood gas and electrolyte analyses under weightless conditions. The specific measurements required by the contract are pH, pCO_2, sodium (Na^+), chloride (Cl^-), potassium (K^+), and ionized calcium (Ca_I^{++}). In addition to these parameters, Orion has added total calcium (Ca_T^{++}) at no additional cost to NASA.

A photograph of the Automated Potentiometric Electrolyte Analysis System (A.P.E.A.S.), designed and built by Orion to meet the contract specifications, is shown in Figure 1.1. This system consists of a fluid transport unit, an electronics unit, a controller and a teletypewriter. The system is flight packaged, but not flight qualified, in accordance with the contract requirements.

1.1 Automated Potentiometric Electrolyte Analysis System



CHAPTER II

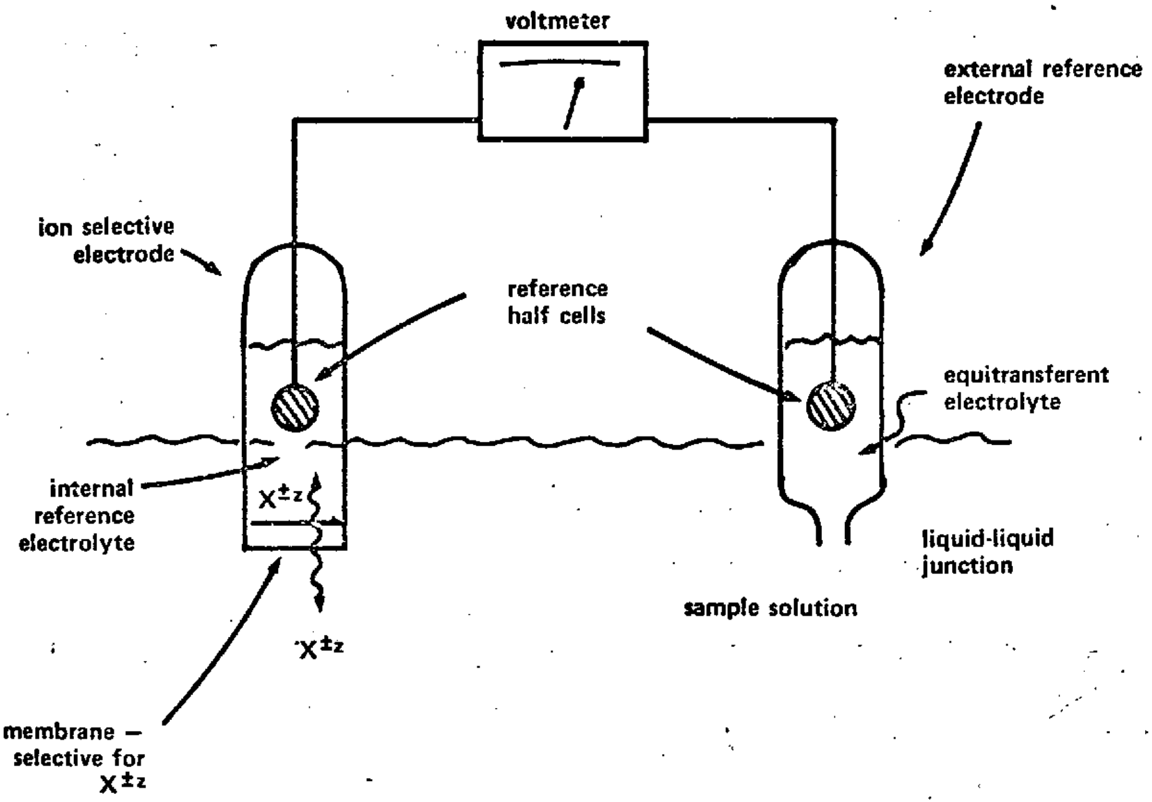
ELECTRODES

2.1. Introduction

This section has been included as a brief outline of general electrode theory for the non-specialist, so that the sections discussed later will be rendered more intelligible. A more complete review can be found in a paper written for the National Bureau of Standards Symposium on Ion-Selective Electrodes, by J.W. Ross, entitled, ''Solid and Liquid Membrane Ion-Selective Electrodes,'' January, 1969, (NBS special publication 314).

The basic equipment required for an electrode measurement of a single ionic species in a sample solution is shown in Figure 2.1. Two probes are required: the ion-selective electrode and a reference electrode. For the present, the reference electrode can be considered simply as an electrical contact to the sample solution whose potential relative to the solution is independent of the solution composition. The second probe, the ion-selective electrode, is an insulating barrel sealed across one end with a membrane. The membrane, which can be made from a variety of materials, is an ionic conductor across which only one ionic species, the ion to be measured,

2.1 Basics of Ion-Selective Electrode Measurement



is capable of migration. Inside the barrel is an electrolyte, either solid or liquid, which contains a fixed level of the ion to be measured and, in addition, an ion to which a reference half cell is reversible.

If the two probes are connected to a high impedence voltmeter and placed in a solution containing the ion to be measured, there will be a momentary flux of the ion across the membrane. Electrical charge will, as a result, be carried across the membrane until a potential is developed which is exactly that required to inhibit further net ionic migration across the membrane. In the equilibrium state, the potential measured by the voltmeter is given by the Nernst equation:

$$E = E_0 + 2.3 \frac{RT}{zF} \log A$$

where the constant E_0 is dependent on the choice of reference electrode, the level of the ion in the internal electrolyte, and the internal reference half cell. R is the gas constant, T the absolute temperature, z the charge (including sign) of the ion and F the Faraday constant. A represents the ionic activity of the transported ion in the sample solution. (At 25°C, 2.3 RT/F has a value of 59.16 mv.)

The number of ions which moves across the membrane to establish the equilibrium potential is vanishingly small, so that neither the ion concentration of the sample solution nor the internal electrolyte is perturbed in this process. (The cell potential, E, is therefore a direct measure of the ion activity in the sample solution.)

It is important to note that the level of the ion is measured by its ''ionic activity'' and not in terms of the more familiar ''concentration.'' Ion activity may be thought of as the thermodynamically effective concentration of an ion. In electrolyte solutions of high ionic strength an ion activity may differ significantly from its stoichiometric concentration. In very dilute solutions the activity and concentration scales converge. In general, ionic activity is more significant than concentration. Activities, not concentrations, determine positions of chemical equilibria and rates of chemical reactions.

Compared with other analytical techniques, electrode measurements have an impressive list of advantages. Although an electrode senses ionic activity, it can also be used to determine free ion and total concentrations through methods such as titration, known addition, and ionic strength buffering.

Electrode measurements are rapid, virtually instantaneous in many cases. Response times are frequently as fast as ten milliseconds, and even under unfavorable conditions, a reading can be obtained within three minutes.

An electrode measurement is non-destructive. The number of ions transported across the membrane in order to establish equilbrium is miniscule relative to the number present in even the most dilute samples. In addition, with appropriate electrode geometry, very small samples of only a few tenths of a milliliter can be handled. These advantages can be very important in biological applications, where several determinations must be performed on a single small sample.

In most cases, no sample pretreatment is necessary. Opaque solutions and even viscous slurries can be measured directly. Time-consuming filtration and distillation operations are eliminated. Automated analytical methods based on electrode measurements are therefore relatively simple to design. The equipment required is simple and, relatively inexpensive.

All electrodes exhibit a drift in the magnitude of the constant term in the Nernst equation, at a rate which depends primarily on the temperature variation in the surroundings. An electrode in an average laboratory will show a noncumulative drift of about two millivolts per day. Under field conditions or in process control applications, even larger fluctuations can occur. The presence of drift requires periodic restandardization at a frequency which depends on the accuracy required and the rate of temperature variation. Under the most favorable conditions, in an air-conditioned laboratory with samples and standards all at the same temperature, a precision of 0.2 mv can be attained on replicate measurements of the same sample. Under typical field conditions, a precision of 4.0 mv is more usual. The following table translates the uncertainty in the potential reading into the corresponding percent uncertainty in ion activity as determined from the Nernst equation.

PRECISION IN E	PRECENT UNCERTAINTY MONOVALENT ION	PERCENT UNCERTA DIVALENT ION
0.2 mv	0.4%	0.8%
4.0 mv	7.5%	15.0%

For a given uncertainty in E, the accuracy of a divalent ion measurement is poorer than that of a monovalent ion because of the presence of the charge term, z, in the Nernst equation. Because it is a logarithmic device, an electrode gives a constant precision throughout its dynamic range. Therefore, the accuracy of determinations at low levels is comparable to those performed in more concentrated solutions.

2.2 Membranes

The usefulness of an ion-selective electrode is determined primarily by the ability of the membrane to pass only the ion to be measured and to exclude all others. Several classes of materials have been found to be adaptable to this function.

2.2.1. Glass Systems

Historically, silicate glass membranes permeable to hydrogen ions formed the first ion-selective electrodes to be studied. The technology in this area is over 40 years old, beginning with the development of pH electrodes in the 1930's. More recently (1957), it was discovered that certain glasses could be formulated which were selectively permeable to sodium, and to a lesser extent, potassium and other alkali metal ions.

Glass membranes for the measurement of pH are highly developed and pH electrodes are available whose potentials rigorously follow the Nernst equation, at least in the pH range of biological interest. The major difficulties with pH glasses are their high electrical resistance and the ease with which they devitrify during fabrication operations. Their high resistance requires the use of sophisticated electronic measuring systems. Devitrification problems restrict to some extent the range of shapes which can be fabricated.

In addition to pH selective glasses, a number of other composition systems are known which are useful for alkali metal ion analysis. Although not ideally selective to a given alkali metal ion, they can still be used in a given application where interfering ion levels are sufficiently low. Such electrodes obey an equation of the form

$$E = E_o + 2.3 \frac{RT}{zF} \log (A + S_i A_i)$$

where A is the sample ion activity to be measured and the A_i's are the activity levels of interfering ions which have some mobility in the glass membrane, and S_i's are the selectivity constants, which differ for each interfering ion and each glass composition.

Selectivity constant tables provide a convenient method of comparing the properties of different glass compositions and predicting whether a given glass will make a useful electrode in a given application. At the present time, glasses are known which will satisfactorily measure sodium in biological samples, without significant interference from potassium or hydrogen ions at the levels normally encountered. Glasses are also known which can be used to measure potassium in some samples such as urine, but not in blood serum, because of the high background sodium levels. No glasses are available with significant selectivity for divalent cations or anions of any charge.

2.2.2. Liquid Membrane Systems

In 1965, the first liquid membrane electrode was developed at Orion [Ross, J.W., Science 156, 1378 (1967)]. Liquid membrane electrodes are fabricated from a porous, inert plastic substrate which is saturated with a water-immiscible organic solvent. A high molecular-weight organic salt of the ion of interest is dissolved in the organic solvent. A calcium-selective electrode for example, can be made from a solution of calcium bis-2-diethylhexyl phosphate, $Ca(DEHP)_2$ in a solvent such as dioctylphenylphosphonate. The neutral, undissociated molecules of the salt are free to diffuse into the solvent-saturated pores of the membrane and are free to exchange calcium ions with the sample solution. Since the salt itself is water-insoluble, the organic DEHP groups act to transport calcium ions back and forth through the membrane. The selectivity of the membrane depends upon the fact that the DEHP groups form more stable complexes with calcium ions than with sodium, magnesium, or other ions present in the sample solution.

The example cited employs a negatively charged organic anion to selectivity transport a cation. Positively charged cationic organic groups can be found with high selectivities for anions. A highly effective nitrate electrode utilizes a cationic organic group for transport of nitrate anions. Organic groups containing sulfur have proven to have high selectivities for heavy metals, such as copper and lead.

Liquid electrodes are described by an equation similar to that for the alkali ion glass membrane systems:

$$E = E_0 + 2.3 \frac{RT}{ZF} \log [A + S_i A_i{}^{z/z_i}]$$

where z and z_i are the charges on the ion to be measured, and on the interfering ion, respectively. The selectivity constants, S_i, have the same significance as described previously and are equally useful in cataloging membrane characteristics. A typical calibration curve for a calcium selective electrode is shown in Figure 2.2.

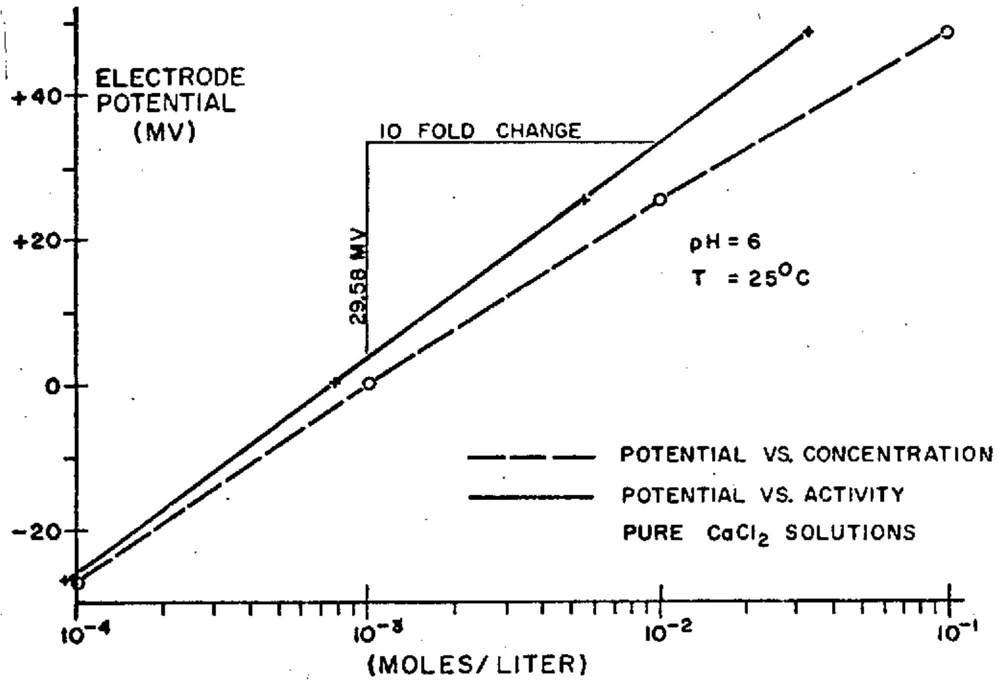
2.2.3. Solid State Crystalline Systems

A still newer class of membranes showing ion selective properties was developed at Orion beginning with the discovery that lanthanum fluoride single crystals showed a high level of fluoride ion conductivity [Frant, M.S. and Ross, J.W., Science 154, 1553 (1966)]. An electrode membrane fabricated from a thin section of LaF_3 crystal behaves in an ideal Nernstian manner toward changes in solution fluoride activity.

Subsequently, other ionic solid state conductors were discovered which permit electrode measurements of a variety of ions.

Unlike glass and liquid membrane systems, interference resulting from ion transport through the membrane phase does not occur with crystalline lattice membranes. The crystal in this sense is an ideal ion ''sieve'' for the ion to be measured.

2.2 Calcium Electrode Calibration Curve



Interference can occur due to solid phase reactions at the membrane-sample interface. A chloride ion sensitive membrane made from a silver-chloride crystal section may experience interference from iodide as a result of the reaction:

$$AgCl_{(s)} + I^- = AgI_{(s)} + Cl^-$$

Here the silver chloride surface is converted to silver iodide with a loss of chloride response. Reactions of this type can only occur if the ratio of the activity of the interfering ion to that of the ion to be measured exceeds a critical value which can be calculated from the solubility products of the pertinent solid phases. In the case just discussed, iodide interference will occur if

$$\frac{A_{I^-}}{A_{Cl^-}} \frac{\text{Ksp AgI}}{\text{Ksp AgCl}} = 10^{-6.33}$$

where Ksp is the solubility product constant. If this ratio is exceeded, the electrode becomes completely inoperative as a chloride sensing device until the surface layer of AgI is removed by abrasion or chemical treatment. In samples in which the ratio I^-/Cl^- is less than the critical, the electrode will function as an ideal chloride sensing device with no interference from iodide.

2.3 Reference Electrodes

Reference electrode theory has grown concomitantly with the development of the glass pH electrode for a number of years. Two factors are important in the selection of a given design, the nature of the internal half cell, and the choice of the solution which forms the liquid junction to the sample solutions.

Half cells of the type $M^{x+} + xCl^- = MCl_x$ (s) $+ xe^-$ are universally used to make the connection between the metal wire from the meter and the solution forming the liquid junction. Excellent stability is obtained where M is either silver, mercury, or thallium. In our experience, silver has been the best choice, because it shows a smaller temperature hysteresis effect on the half cell potential than the other two metals do.

Overall system stability under conditions where temperature is subject to change can be improved if the temperature coefficient of the internal half cell in the reference electrode can be matched to that of the ion-selective electrode. Under these conditions the constant ''E_0'' in the Nernst equation can be made temperature invariant.

In general, this matching is possible for any reference electrode, ion-selective electrode pair with a suitable choice of internal electrolyte composition in the ion-selective electrode, and suitable reference electrode filling solution.

In addition to fixing the half cell potential and temperature coefficient of the reference electrode half cell, the liquid junction solution should result in a constant (and preferably zero) liquid-liquid junction potential at the sample-solution interface. The liquid-liquid junction potential is determined by the concentrations and relative mobilities of all the ions present in solution at the interface, and will, in general, vary in response to changes in sample composition. Classically, the solution to this problem has been to make the reference electrode filling solution very concentrated in an electrolyte whose cations and anions have very nearly equal mobilities (KCl or NH_4NO_3 for example). Since the electrolyte concentration is very high relative to the sample solution, the effect of sample ions on the liquid-liquid junction potential can be ignored. The potential is therefore independent of sample composition. In addition, the equality of mobilities for the two ions present in large excess ensures that the potential will be nearly equal to zero.

2.4. Speed of Measurement

The response time of an ion-selective electrode depends on the time required to establish a steady state of ion flux across the membrane in response to a change in ion activity at the electrode surface. Response rate can be limited by either the membrane characteristics, or by the time required to bring fresh sample to the membrane surface.

In the absence of interfering ions, the membrane response is quite rapid, on the order of milliseconds for the glass and solid state membrane materials and less than 5 seconds for liquid membrane systems. In the presence of high levels of interfering ions, the response times for all types of membranes will increase to several minutes for liquid systems and to as much as 15 minutes for glass membranes.

Under normal operating conditions, where ion interference terms are small, the system response is determined by the rate at which a sample ion activity can be changed at the membrane surface. Sample flow velocity, viscosity, and the hydrodynamic flow pattern of the system all affect this rate.

With viscous samples, such as blood serum, fastest responses are obtained under high velocity, laminar flow conditions which can be achieved by using small diameter capillary tube geometries, in the electrode and interelectrode ducting.

2.5. A.P.E.A.S. Electrodes

2.5.1. General:

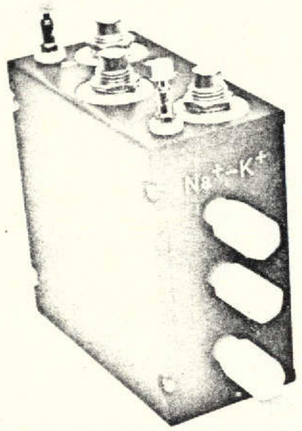
The system employs four electrode modules to perform the seven measurements. A photograph of a typical module is shown in Figure 2.3. Three of these modules each contain two sensing electrodes and a reference electrode. The fourth contains a combination pCO_2 electrode and circuitry for monitoring temperatures in the electrode area.

2.5.2. $pCO_2/^{o}C$ Module:

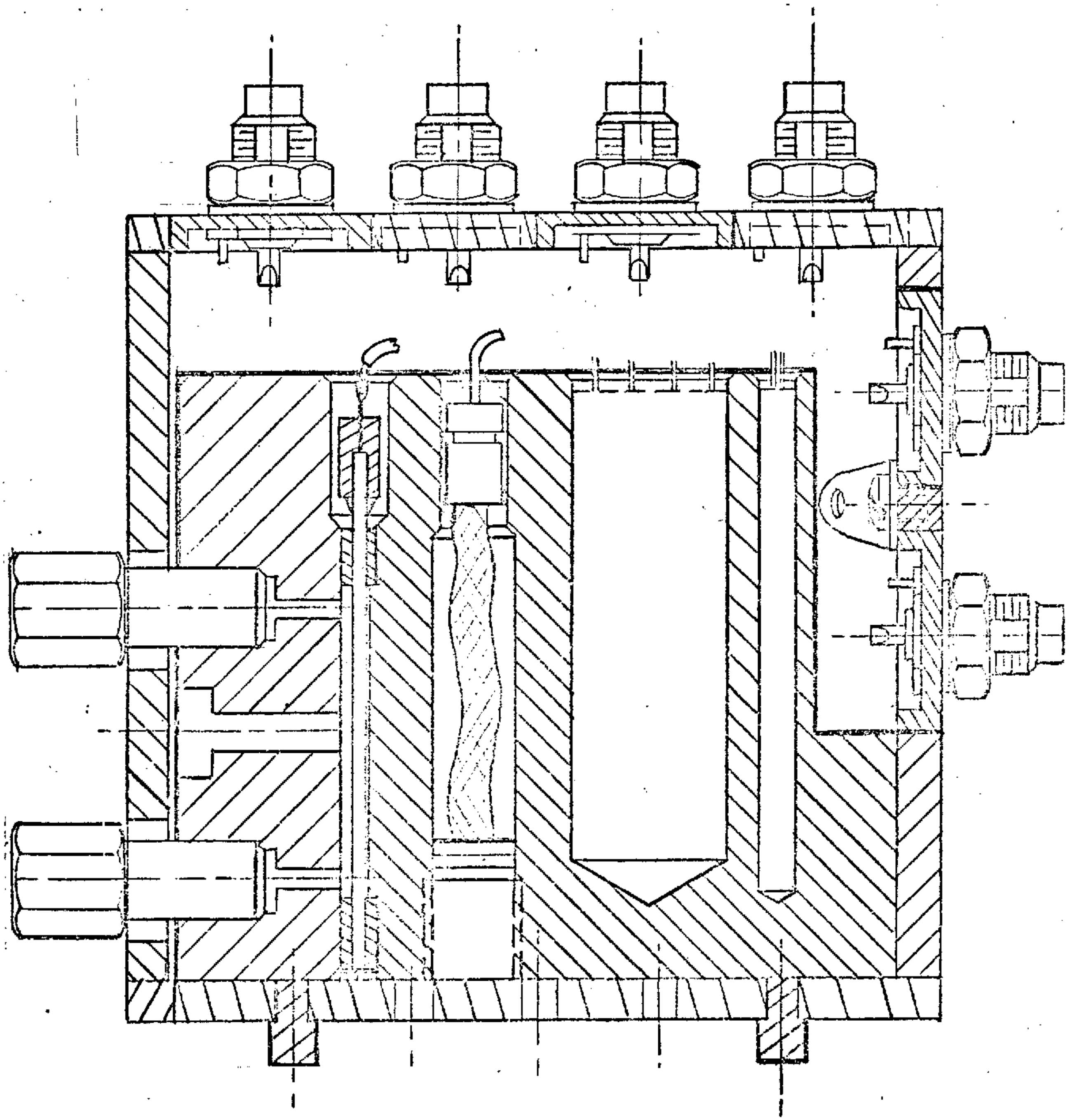
A drawing, in cross section, of the $pCO_2/^{o}C$ module is shown in Figure 2.4.

A combination gas-sensing electrode and the circuitry for monitoring temperature are employed in the measurement of the partial pressure of carbon dioxide in samples introduced into the system. The principles of operation of this device can best be illustrated

2.3 A.P.E.A.S. Electrode Module



2.4 pCO$_2$/°C Module in Cross-Section



by referring to Figure 2.5. The CO_2 electrode uses a hydrophobic gas-permeable membrane to separate the sample from the electrode internal filling solution. Equilibrium between the sample pCO_2 and the partial pressure of CO_2 in the bicarbonate filling solution is achieved by the diffusion of carbon dioxide across the membrane. The CO_2 dissolving in the bicarbonate internal filling solution reacts with water to form carbonic acid according to the following reaction:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

The relationship between CO_2, H^+, and HCO_3^- is given by the following equation:

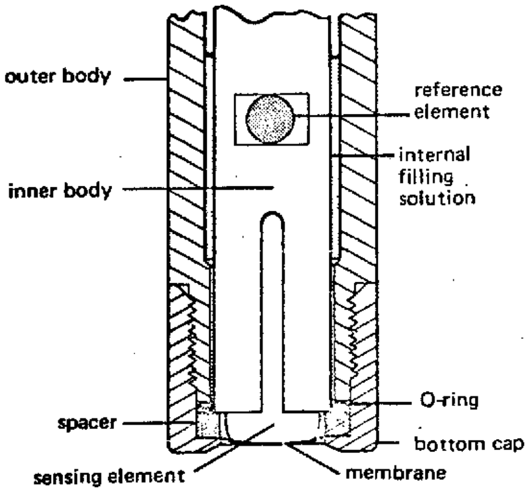
$$\frac{[HCO_3^-][H^+]}{[CO_2]} = \text{constant}$$

The internal filling solution contains HCO_3^- at such a high level that the term $[HCO_3^-]$ can be considered a constant. Thus:

$$[H^+] = [CO_2] \cdot \text{constant}$$

The potential of the pH sensing element varies in a Nernstian manner with changes in the H^+ level:

2.5 Construction of a Gas-Sensing Electrode



$$E = E_0 + 2.3\frac{RT}{F}\log A_{H^+}$$

By defining a new constant, E, the response to CO_2 is described as:

$$E = E_1 + 2.3\frac{RT}{F}\log [CO_2].$$

The change in pH is measured by the glass electrode. Since the pH response of the glass electrode is a function of the ratio $[HCO_3^-]/[CO_2]$, the pH measured is a function of the partial pressure of CO_2 in the sample.

This electrode can respond only to a gas, and therefore is free from any ionic interferences in physiological samples.

Circuitry for the temperature readout is also enclosed in the module with the CO_2 electrode. This module was selected as the temperature sensing and control site because the CO_2 electrode is approximately five times more sensitive to temperature changes than the remainder of the electrodes in the system. This can be explained by the sensitivity to changes in temperature of the partial pressure of a gas, in addition to the Nernstian dependence of the pH sensor on temperature.

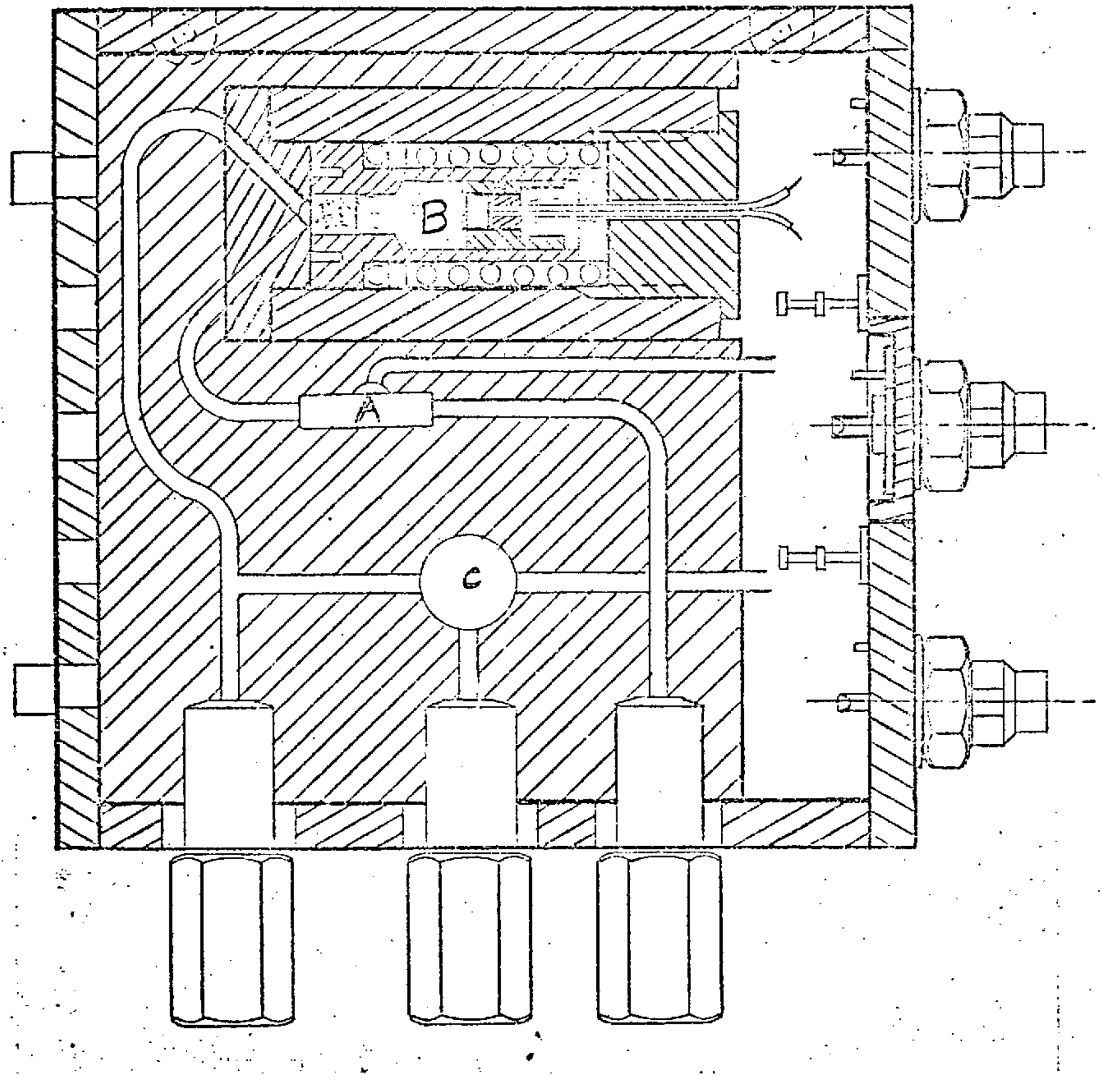
2.5.3. Na^+/K^+ Module:

A cross-sectional drawing of the Na^+/K^+ module is shown in Figure 2.6.

Sodium is measured in this module using a sodium selective glass capillary with a solid state electrolyte backing (A). The electrode develops a potential proportional to the logarithm of the activity of the free sodium ion in the sample. The response of this electrode is described by the Nernst equation, as discussed in Section 2.1.

Although the electrode detects very low levels of sodium ion, it is a logarithmic device and cannot be used to detect very small changes in ionic activity at high concentration levels. Factors such as temperature variation, drift, and noise, limit the precision. With frequent calibration, however, measurements should be reproducible to ±1% of the sample sodium ion activity.

2.6. Na⁺/K⁺ Module in Cross-Section



The electrode response to sodium ion in solution, as a function of pH, is shown in Figure 2.7. This figure shows that near the normal blood pH of 7.4, there is negligible hydrogen ion interference. However, correction for hydrogen ion interference should be made for urine samples which have a pH in the range 5.5 to approximately 6.0.

In general, for solutions containing sodium ion and an interfering monovalent cation, electrode behavior is given by the equation:

$$E = E_0 + 2.3\frac{RT}{F} \log(A_{Na^+} + S_{x^+}A_{x^+})$$

Where: S_{x^+} = selectivity constant for the interfering ion

A_{x^+} = activity of the interfering ion

Table 2.1 gives selectivity constants (electrode response to interfering ion in proportion to electrode response to sodium ion) for the common interfering cations. These values are only approximate since S_x varies somewhat with the ratio of the interfering cation to the level of total sodium ion. S_x also differs slightly from the value listed if more than one interfering ion is present in the sample.

2.7 Sodium Electrode Response vs. pH

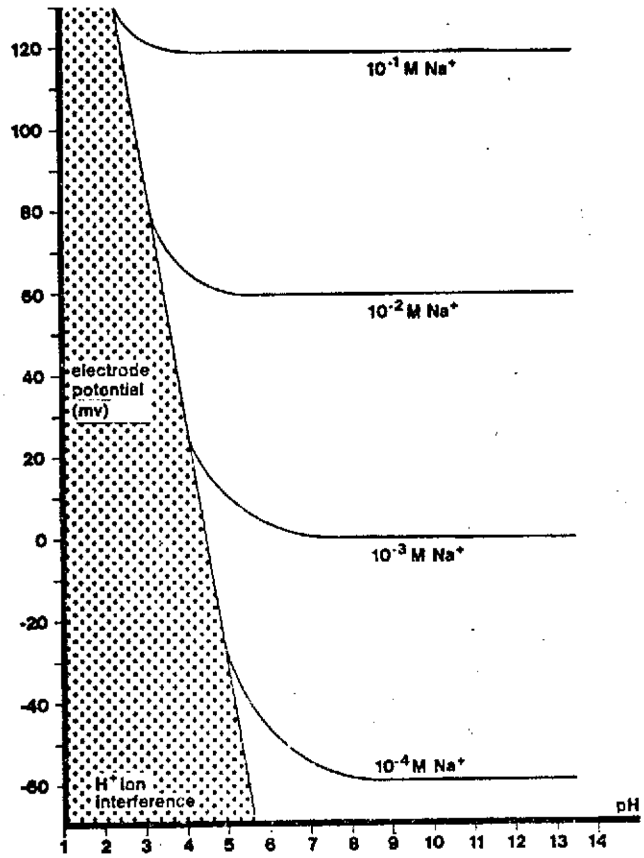


Table 2.1 Approximate Cation Selectivity Constants for the Sodium Electrode:

Cation	Selectivity Constant
Li^+	2×10^{-3}
K^+	1×10^{-3}
Rb^+	3×10^{-5}
Cs^+	1.5×10^{-3}
NH_4^+	3×10^{-5}
$N(C_2H_5)_4^+$	5×10^{-4}
Ag^+	350
Tl^+	2×10^{-4}

Whether significant interference occurs depends on the level of interfering ion and sodium ion present in the sample and the selectivity constant for the interfering ion. A concentration of 10^{-1} M potassium, for example, will cause virtually no error in the 5×10^{-2} M sodium solution, a 1% error in a 10^{-2} M solution, and substantial error in a solution more dilute than 10^{-3}M sodium.

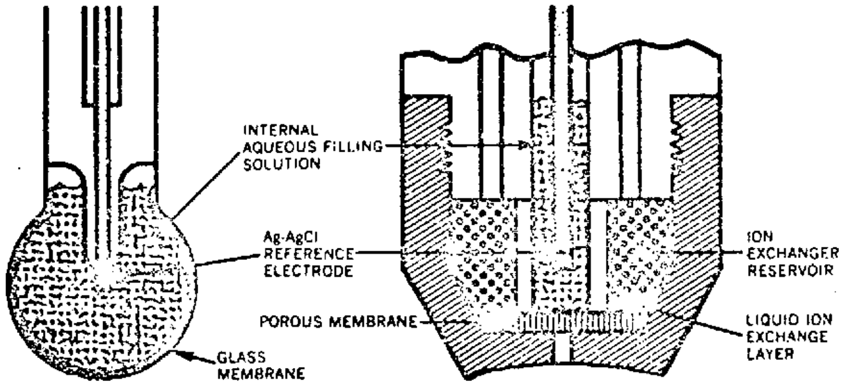
Typical response time varies from several seconds in 10^{-1} M sodium ion solutions, to several minutes near the limit of detection. Response time is more rapid when going from dilute to concentrated solutions. Electrode response is also more rapid in solutions of

low viscosity, and in solutions which are stirred during measurement.
The potassium electrode is of the liquid membrane type (see Figure 2.8.) (B). The liquid membrane employed is valinomycin, an antibiotic whose structure is an eighteen amino acid ring. This neutral, macrocyclic compound acts as a ''ferry'' to selectively transport potassium across the hydrophobic membrane.

The electrode detects potassium ion much as a conventional glass pH electrode detects hydrogen ion, but instead of developing a potential across a glass membrane, it develops a potential across a thin layer of water-immiscible liquid ion exchanger.

An aqueous filling solution containing fixed levels of potassium ion and chloride ion contacts the inside surface of the membrane disc, which is saturated with the ion exchanger. The potassium ion in the filling solution provides a stable potential between the inside surface of the membrane and the internal filling solution, and the chloride ion provides a constant potential between the filling solution and the internal Ag/AgCl reference element. Thus, changes in electrode potential are due to changes in sample potassium ion activity, and can be described by the Nernst equation.

2.8 Potassium Electrode, right, shown with pH Electrode



CONVENTIONAL GLASS pH ELECTRODE

LIQUID MEMBRANE ELECTRODE

The electrode responds to certain other cations as well as to potassium ion. In solutions containing potassium ion and an interfering monovalent cation, electrode behavior is given by the equation:

$$E = E_0 + 2.3\frac{RT}{F}\log\left[A_{K^+} + S_{X^+}A_{X^+}\right]$$

Table 2.2 gives selectivity constants for the common interfering cations. These values are only approximate since S_X varies with the ratio of the level of the interfering cation to the level of total potassium ion. S_X also differs slightly from the value listed if more than one interfering ion is present in the sample.

Table 2.2: Approximate Cation Selectivity Constants for the Potassium Electrode

Cation	Selectivity Constant
Cs^+	1.0
NH_4^+	3×10^{-2}
H^+	10^{-2}
Tl^+	10^{-2}
Ag^+	10^{-3}
Na^+	2×10^{-4}
Li^+	10^{-4}
Tris	10^{-4}

This electrode is sufficiently selective that no significant interferences occur in biological samples, including serum and urine.

The reference electrode for the Na^+/K^+ module (C) consists of a solid-state AgCl/AgS sensor through which 0.3 M KCl is pumped. This reference electrode is identical in construction to the chloride measuring electrode which is described more fully in section 2.5.5.

2.5.4 pH/Ca_I^{++} Module

The pH/Ca_I^{++} is similar in construction to the Na^+/K^+ module shown in Figure 2.5. The only differences are that a hydrogen selective capillary is substituted for the sodium selective capillary and the liquid membrane electrode employs a calcium selective ion exchanger and internal filling solution.

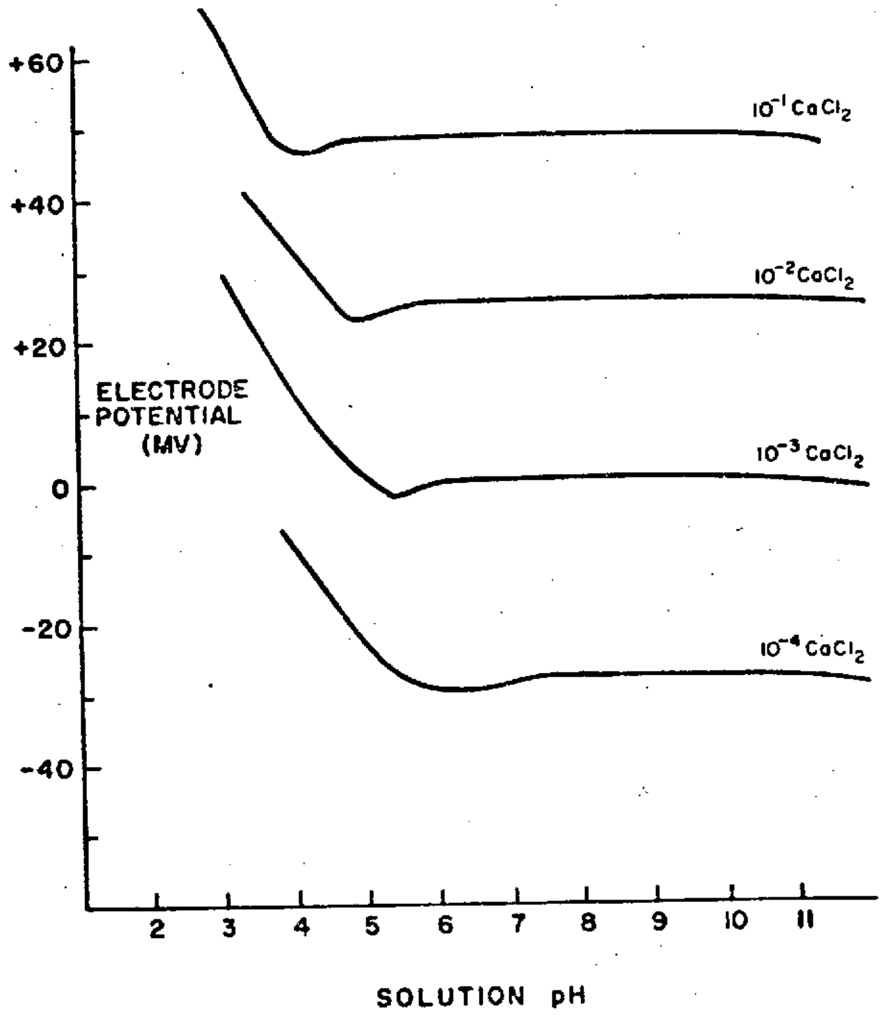
The pH capillary is a lithium-barium-cesium silicate glass formulation with a higher lithium concentration than used in commercial pH electrodes. This formulation produces a glass which shows poorer sodium selectivity at high pH (over pH 10.5), but gives a much lower volume resistivity glass. Since the pH of the samples of interest for this system is much lower than pH 10, the small sacrifice in sodium rejection is of no importance. The lower resistance capillary, however, is more responsive and is less subject to perturbations due to electrical noise.

The theory and practice of pH measurements is well known and will not be treated in more detail in this chapter.

The calcium electrode ion-exchanger is a calcium salt of an organophosphoric acid, which exhibits a high selectivity for calcium over other cations. An internal filling solution of calcium chloride contacts the inside surface of the membrane. The calcium ion in this solution provides a stable potential between the internal reference electrode and the filling solution. Thus, changes in potential are due only to changes in sample calcium ion activity. The electrode responds only to the ionized or unbound calcium in the sample. It has been shown that, in serum, the ionized fraction is the physiologically active form and is therefore, in many cases, more significant than the total calcium parameter obtained by conventional techniques such as flame photometry or colorimetry.

Over the range pH 5.5 to 11, the electrode exhibits little error due to changes in pH (see Figure 2.9.). The electrode is believed to give correct readings of calcium activity above pH 11, but difficulties are experienced in interpretation of the data due

2.9 Calcium Electrode Response vs. pH



to formation of $Ca(OH)_2$. In the acid regions (below pH 5), The electrode responds to hydrogen ion and no longer measures calcium ion.

The electrode will respond, to some extent, to all divalent cations. The electrode behavior in solutions containing calcium and a second divalent cation is given by the following equation:

$$E = E_0 + 2.3 \frac{RT}{2F} \log(A_{Ca^{++}} + S_{x^{++}} A_{x^{++}})$$

where $S_{x^{++}}$ = selectivity constant for the divalent cation X^{++}.

Values shown in Table 2.3 for $S_{x^{++}}$ are only approximate and may vary depending on the ratio of X^{++} to Ca^{++}.

Table 2.3

Approximate Divalent Cation Selectivities ($S_{x^{++}}$) For The Calcium Electrode (pH = 6)

Ion	$S_{x^{++}}$	Ion	$S_{x^{++}}$
Zn^{++}	3.20	Ni^{++}	0.080
Ca^{++}	1.00	Sr^{++}	0.017
Fe^{++}	0.80	Mg^{++}	0.014
Pb^{++}	0.63	Ba^{++}	0.010
Cu^{++}	0.27		

The interfering divalent cation error relative to the amount of calcium present in the sample is given by the following equation:

$$\text{ERROR} = S_{x^{++}}(A_{x^{++}}/A_{Ca^{++}})$$

For example, in a solution with a calcium activity of 10^{-3} moles/liter, and about twice as much magnesium the error is about 0.014 $(2 \times 10^{-3}/10^{-3}) = 0.028$.

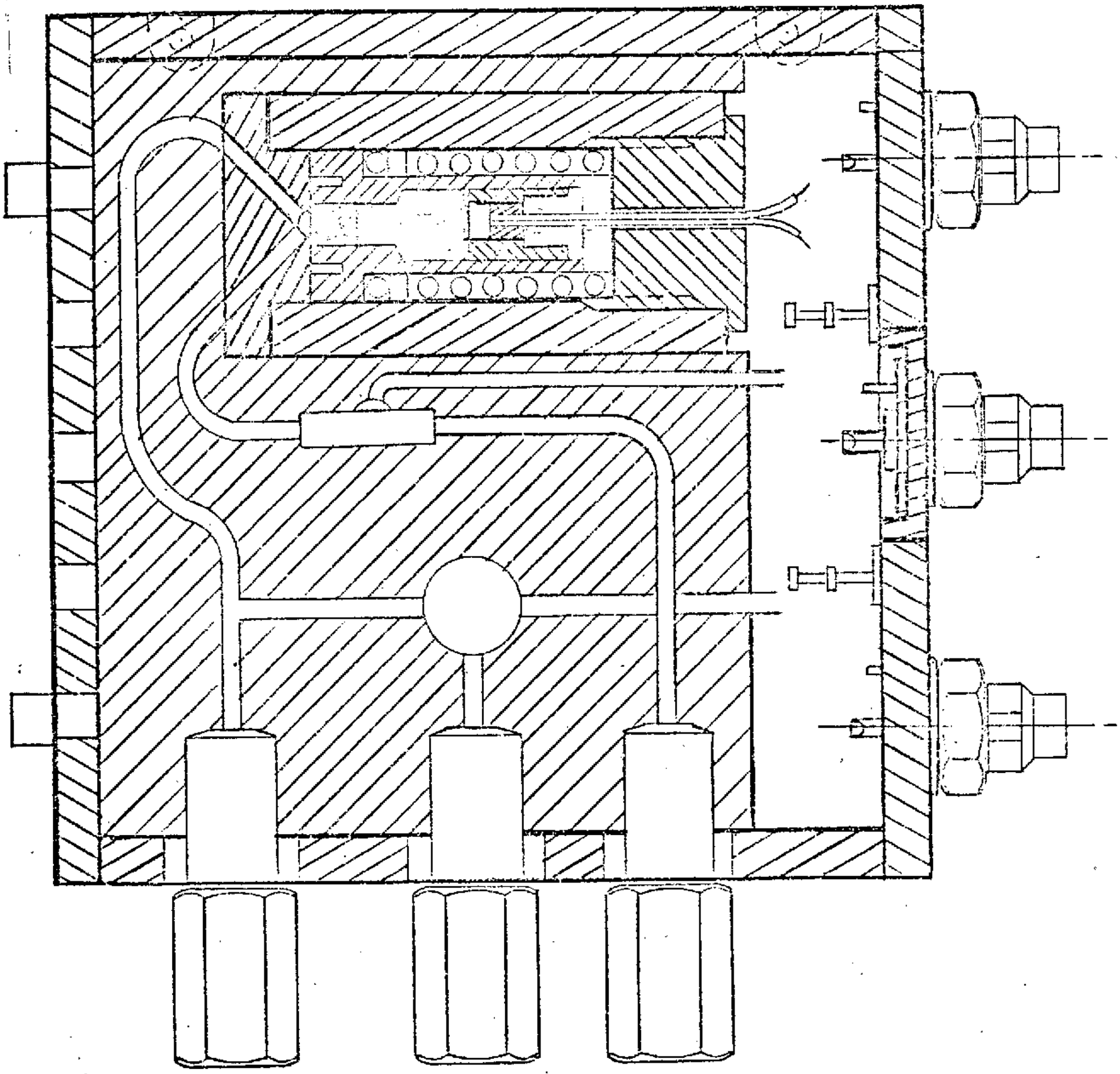
In other words, the apparent calcium activity level will read high by about 2.8% in the presence of a two-fold excess of magnesium ion.

Correction for the interference errors with the calcium electrode was made by preparing standard mixtures with levels of the interfering ion equal to those expected in the samples. Additional corrections can be made by programmed corrections for sample background variations.

2.5.5. Ca_T^{++}/Cl^- Module

A cross-sectional drawing of the Ca_T^{++}/Cl^- module is shown in figure 2.10. This module employs a flow-through $AgCl/Ag_2S$ solid-state membrane for the measurement of chloride, which has a solid-state silver

2.10. Ca_T^{++}/Cl^- Module in Cross-Section



backing, and therefore contains no liquid internal reference solution.

The potential developed by the electrode is due to changes in the silver ion activity at the surface of the membrane, and is described by the Nernst equation. The sample is not required to contain silver ions because the limited solubility of the membrane provides sufficient ions for this purpose. Silver ions are mobile through the membrane as a consequence of lattice defects in the crystalline structure.

The calcium portion of this module is identical to the calcium electrode described in 2.5.4. Total calcium is obtained by acidifying the sample stream, causing hydrogen ion displacement of protein-bound Ca^{++}.

2.6. Effect of Mechanical Stresses On Electrodes

High accelerations (5-10 g) and high sound levels experienced during take-off do not permit the use of conventional, commercial electrode formats.

High accelerations could easily force air bubbles into critical positions plugging the liquid junction of the reference electrode and displacing the internal liquid electrolytes inside the ion-selective electrodes from their required contact with the membrane surfaces.

Redesigns, incorporating solid internal references have been necessary to avoid these problems.

Adequate time response requires the use of thin membranes which, particularly in the case of the glass and liquid membrane electrodes, will be subject to rupture at high sound levels. A combination of sound shielding for the entire system, and mechanical ''backing'' of the membranes will be required to avoid difficulties from this source. By using the large variety of solid internal electrolytes developed at Orion, a considerable increase in rigidity and strength has been achieved which would not be possible using conventional construction techniques.

The electrodes which have been designed and built for the A.P.E.A.S. system appear to be capable of surviving rigorous stresses. All components have been incorporated into rigid epoxy bodies with solid-state and solid internal references being used wherever possible. Those electrodes requiring liquid internal electrolytes have been designed to prevent loss of liquids during severe stresses.

CHAPTER III

CHEMISTRY

3.1 Introduction

Theoretically, one could use electrodes to measure absolute activity of any ionic species. To do this would require an absolute measurement or calculation of the constant E_o in the Nernst equation. However, it is impossible to measure or calculate from thermodynamic data the half cell potentials and liquid-liquid junction potential included in the E_o term. As a result, from a practical standpoint, ion activity measurements can only be made relative to an arbitrary standard.

In the case of hydrogen ion activity measurements, the problem has been solved via the National Bureau of Standards pH scale in which several selected buffers have been arbitrarily assigned ''reasonable'' pH values. All pH values are understood to be relative to these defined, arbitrary standards. In the case of the other ions, there is no generally accepted activity scale presently available, although work is beginning.

In the absence of a standard scale, most analytical work in relatively concentrated electrolytes is presently being done using standard solutions of strong electrolytes with ionic strengths approximating those of the samples. Relative activity measurements made in this way have the advantage that the numerical value of the result approximates the value of the concentration of the free ion in the sample solution.

In addition to having an appropriate ionic strength, a standard solution must also satisfy more obvious requirements: the activity level of the ion to be measured should be close to that expected in the sample, the solution should contain no ion in sufficient concentration to cause interference, and the solution must be stable with respect to chemical and biological degradation.

In general, two standard solutions with activity values bracketing those expected in the sample solutions are used in calibrating an electrode. Frequency of standardization depends on the drift rate of the electrodes. For maximum accuracy, however, standardization should be repeated for each sample measurement.

3.2. APEAS Standards

Development of suitable standard mixtures for the APEAS system has required a significant fraction of the total time expended on the contract. The major reason is the fact that very little, if any, prior work had been done in the are of formulating gas/electrolyte mixtures. Standards for a system of this type must meet several requirements. Among these are:

1. The standards must provide for two-point calibration, where possible, for each of the seven electrodes in the system.
2. The activities of the individual species should bracket the expected physiological range of the samples which will be most frequently introduced into the system.
3. The standards must be buffered with respect to pH and pCO_2.
4. The ionic strengths of the standards must closely approximate the ionic strength of serum.
5. The mixtures must be stable.
6. No more than two sample containers should be required for system standardization.

The formulations for a pair of standards which meet the above requirements are shown below:

Component	STD/A ml/l	STD B ml/l
1 M NaCl	100	125
0.1 M KCl	20	60
0.1 M $CaCl_2$	30	10
1 M $NaHCO_3$	16.5	16.5
1 M HCl	45	40
1 M Tris	50	50

The concentrations for the individual ions in the above mixtures are shown below:

Species	STD A, meq/l	STD B, meq/l
Na^+	116.5	141.5
Cl^-	153.0	173.0
K^+	2.0	6.0
Ca^{++}	6.0	2.0
pCO_2	46.0 mm	29.5 mm
pH	7.07	7.35

Tris (hydroxymethyl aminomethane) was selected as the buffer for these solutions because there is no known interaction between tris and the cations being determined in the system. Also, tris is the basis for a new series of physiological pH buffers recently proposed by the National Bureau of Standards.

CHAPTER IV

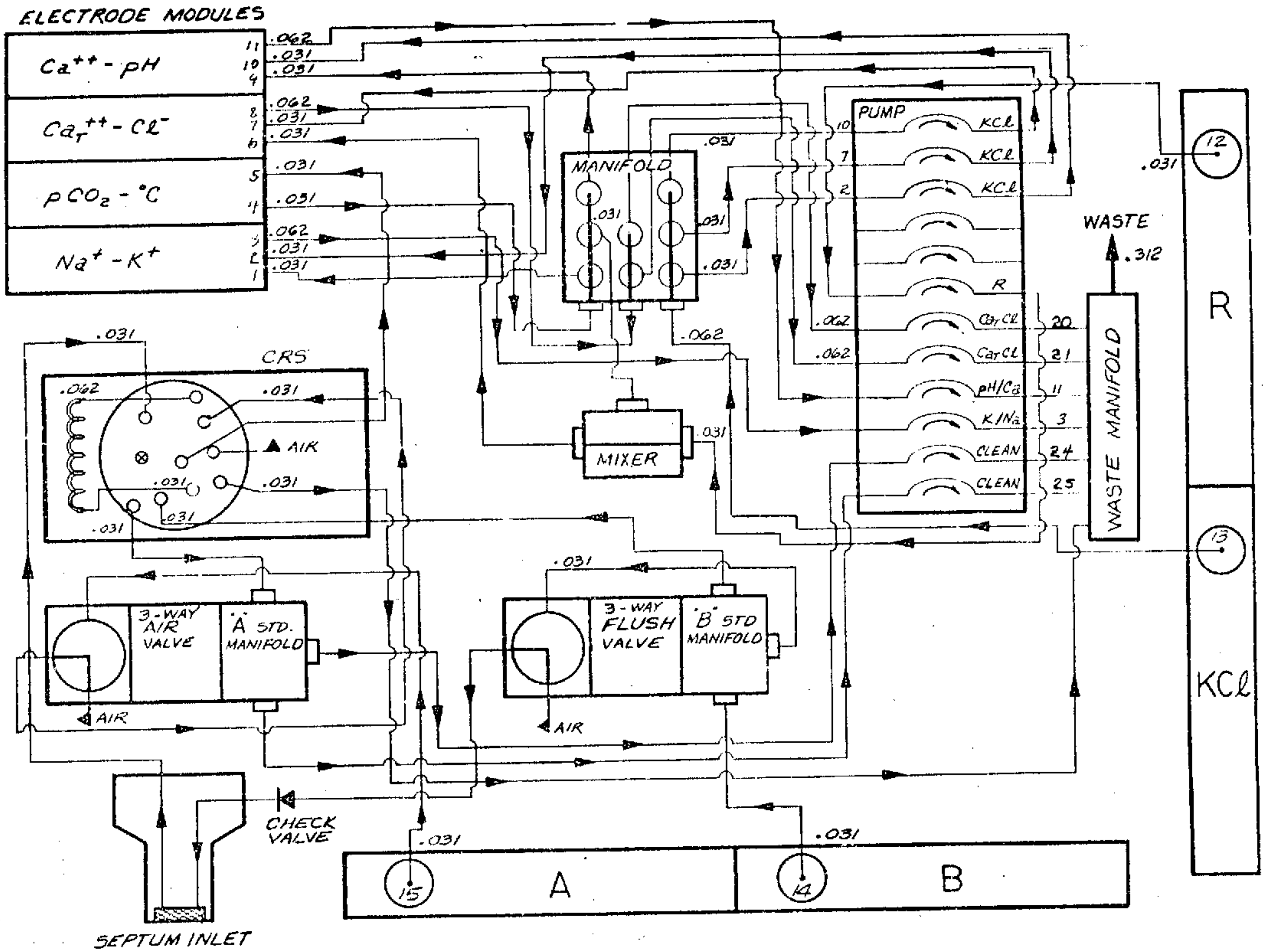
FLUID TRANSPORT PACKAGE

4.1 Introduction

The fluid transport section of the APEAS system contains all the essential elements to standardize, inject, store, deliver, measure, and dispose of standards and samples. These elements are standard solution bags, septum inlet port, chromatographic switching valve, sample holding loop, KCl and acid reagent bags, electrodes, pump, and waste bag, respectively (Figure 4.1). A brief description of each of these, and related elements follows.

4.2 Fluid Containers

Standardizing solutions, reagents and system waste for multiple measurements are contained in flexible, gas impermeable bags. These containers were developed specifically for the APEAS system to meet the following requirements:



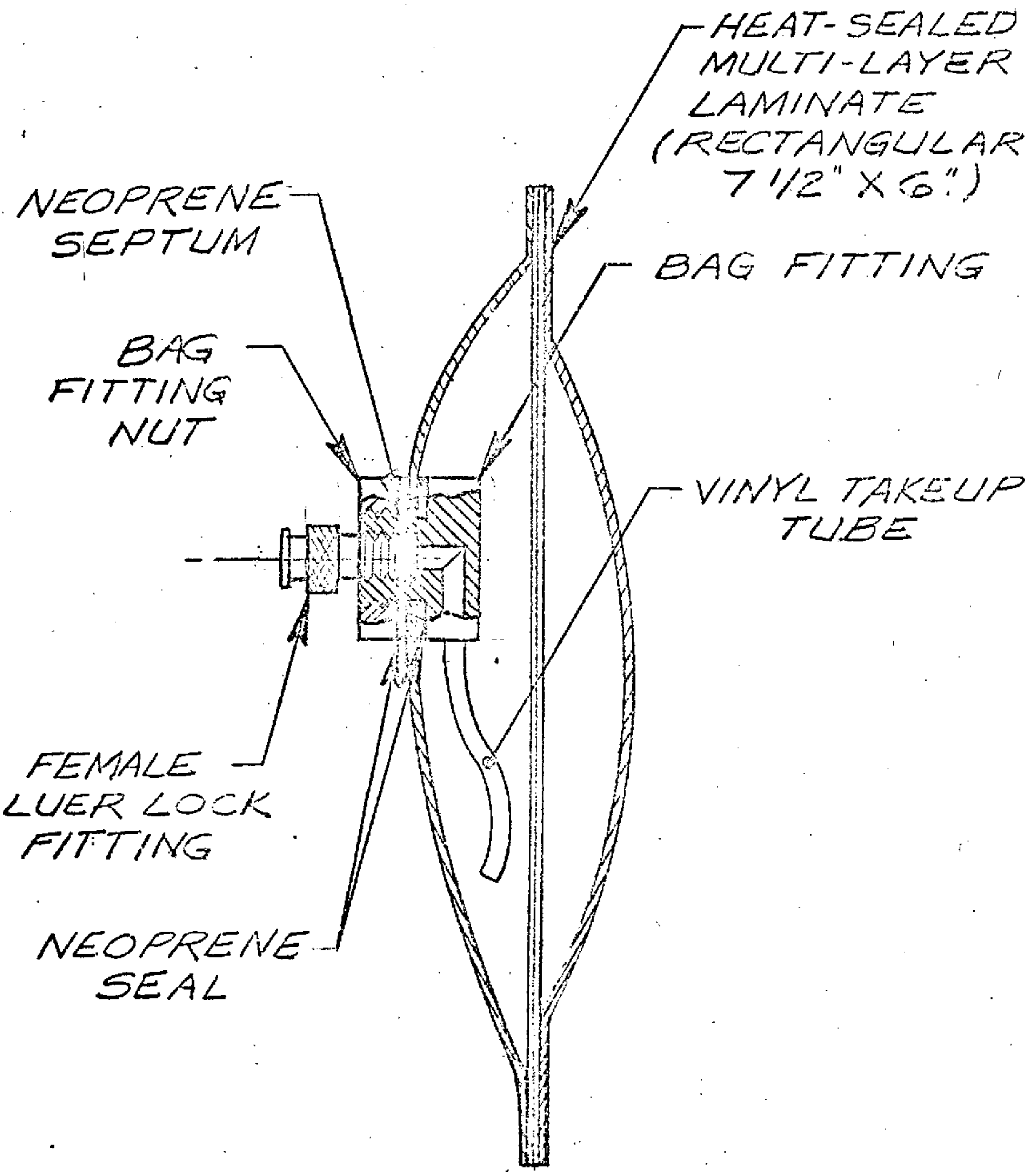
4.1. Fluid Transport Block Diagram

1. They must collapse under aspiration;
2. They must be gas impermeable;
3. They should possess a wide range of chemical resistance to organic and inorganic solutions;
4. They should be replaceable with a minimum of operator skills, with no spillage;
5. They must be amenable to flight hardened design and ''0'' g operation under a broad spectrum of shock and vibration;
6. They must utilize available space within the fluid transport package.

Various approaches were studied, and a flexible, heat sealed, foil container was selected. The standards, KCl and reagent containers are of flat, heat-sealed laminate construction with puncturable septum fittings on each bag (see Figure 4.2).

The modified polyphenylene oxide fittings contain a neoprene septum held in place with a chrome plated locking Luer fitting. The bags are initially filled with fluid and folded by the operator on an anodized aluminum frame. The containers are firmly secured with plastic clips and are removed or inserted into the appropriate card-guided compartment in the fluid transport unit. The waste container is placed flat in its tray at the top of the unit, filling under positive pressure from all channels of the peristaltic pump.

4.2 Fluid Container



All sample and reagent bags contain an internal vinyl tube which takes fluid from the bottom of the bags, thus ensuring maximum utilization of the approximately 250 ml within. The bag is adaptable to tear drop construction for ''0''g environments, thus allowing air or equilibrated gas to reside away from the internal tube. The tube is presently open, but could contain a wick element to exclude gas in the bag.

When the bag is positioned on a frame, the septum is easily accessible to the appropriate numerically-coded Luer locked needle. After being quarter turned into the fitting, the bag contents are available for system use. Each bag is labelled to prevent inadvertent misplacement in the unit.

4.3 Injection Port:

Anaerobic sample introduction to the fluid transport is accomplished via syringe and needle through a septum injection port. The following were the criteria for the port design:

1) Sample introduction must be anaerobic
2) The fluid transport must be capable of internally cleaning all fluid passages after each sample and standardizing sequence

3) Use of standard laboratory equipment to introduce samples was required

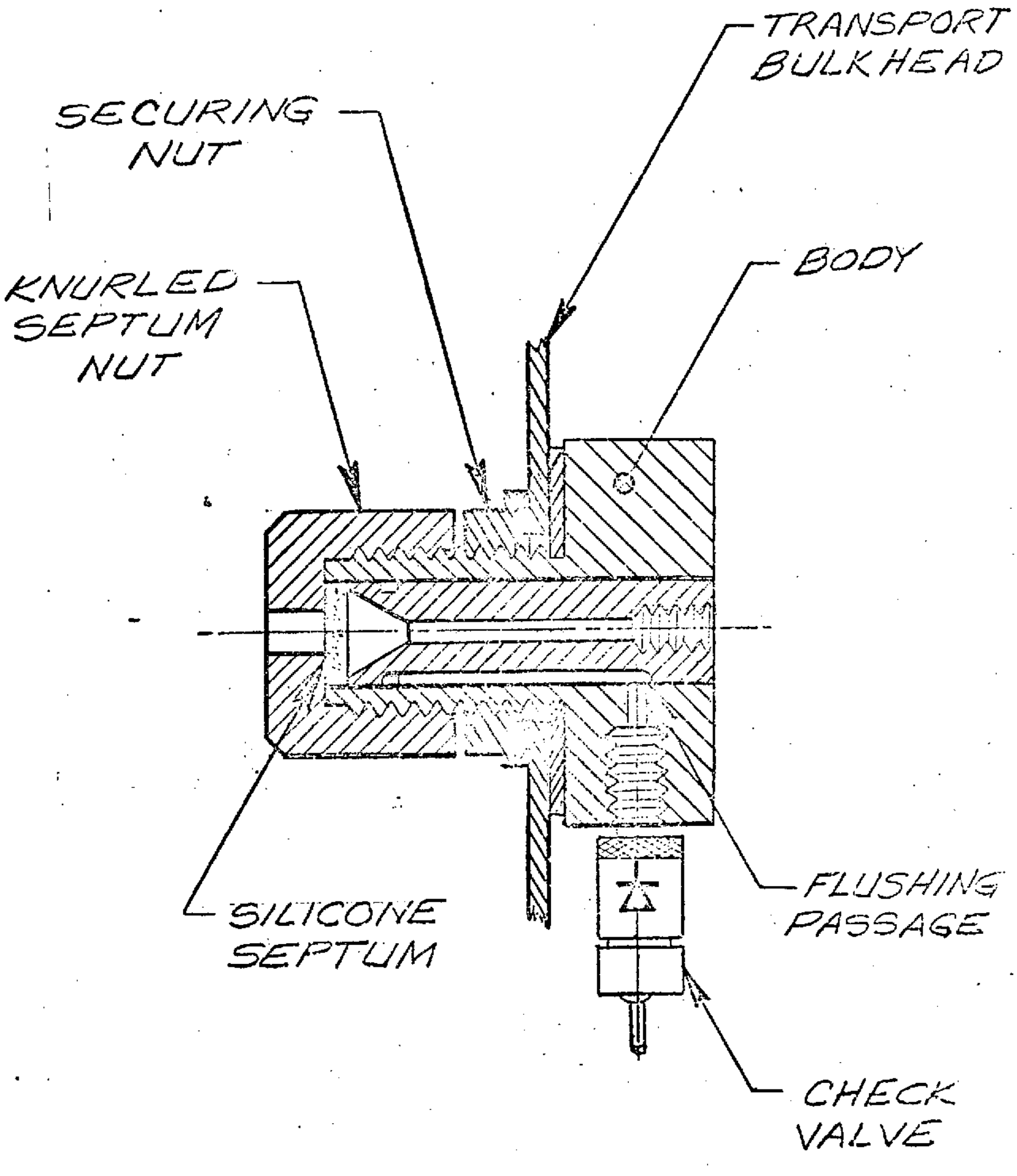
4) Capable of at least 100 sample introductions without leaking or fouling

5) Chemically unreactive to the sample and internal solutions

6) Small internal dead volume

The sample injection port designed to meet these criteria is a PVC screw threaded body mounted to the transport case. (See Figure 4.3). It contains a stainless steel insert with internal fluid passages exiting to a cone in front, on which a replaceable silicone septum rests. The knurled stainless steel retaining nut can be unscrewed to remove the septum, without opening the box. A syringe with a 21 gauge 1-1/2 inch Huber point needle punctures the septum through the access hole and is guided by the conical surface of the insert to the main passage to the CRS valve and holding coil. The needle fit in this passage insures sufficient back pressure, thus allowing the bulk of the sample to enter the holding coil. Any residual left on the walls is washed out to waste by an internal solution - air purge cycle, thus making the inlet ready for another sample. The 3/16'' diameter septum puncture area is statistically correct for 100 random punctures with minimum chance of coring out the septum. The alternative of punctu ing a small

4.3 Injection Port



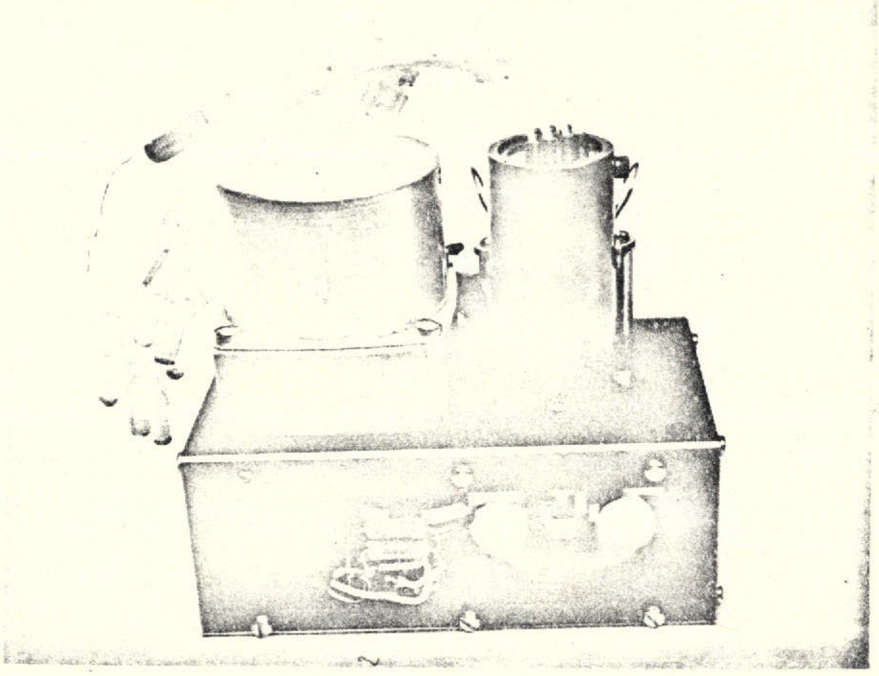
area repeatedly in tests showed a high probability of introducing particulate elastomer into the fluid passages, with subsequent blockage. The port contains a one-way check valve to prevent back-up into the purging system.

4.4 Valves

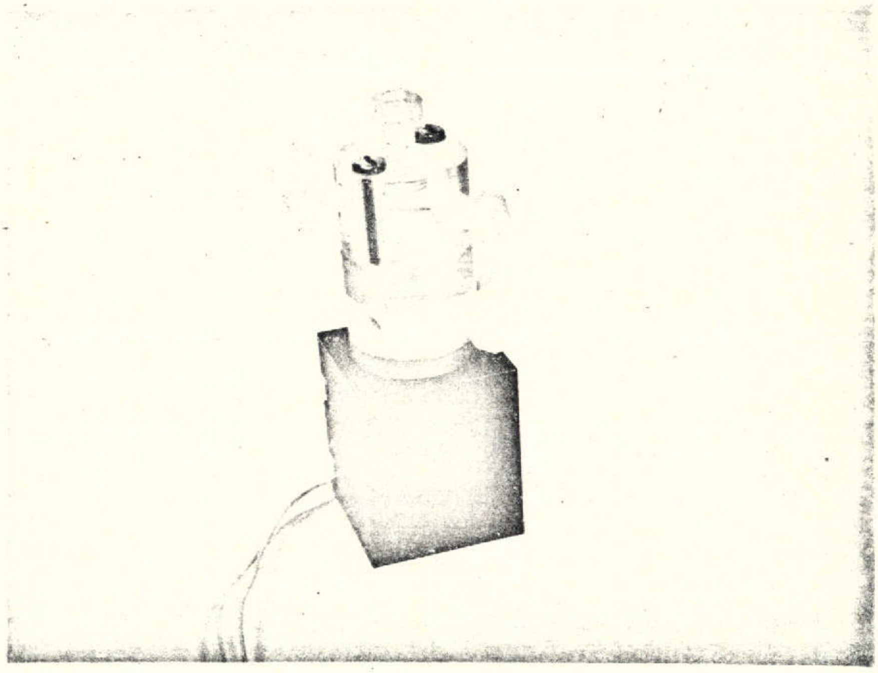
There are two types of valves in the fluid transport package, a multiport chromatographic rotary switching (CRS) valve, (see Figure 4.4.), and solenoid operated diaphragm valves, (see Figure 4.5). The function of the CRS valve is to direct the proper fluids (i.e., standardizing or sample) to the measuring electrodes. A diagram of the port function is shown in Figure 4.6. As can be seen in the diagram, there are three functions being utilized simultaneously in some positions. The valve has six basic positions with four added function ports. Figure 4.6. describes briefly the functions taking place at each of the six basic positions. The valve materials in contact with the fluid stream are teflon (TFE) and stainless steel. The valve body and other parts not in fluid contact are brass and carbon steel.

The valve is driven through its stations by a six position ''geneva'' indexing mechanism. The driver

4.4 Chromatographic Rotary Switching (CRS) Valve

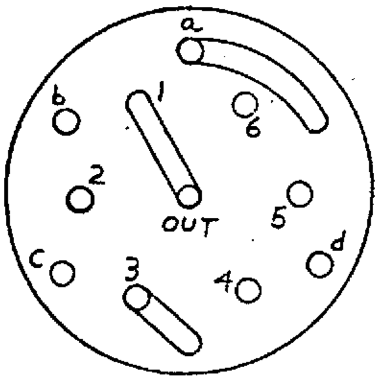


4.5 Solenoid Valve

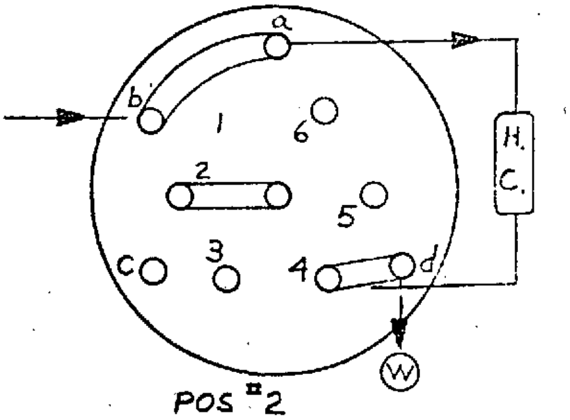


4.6 Valve Port Function Diagram

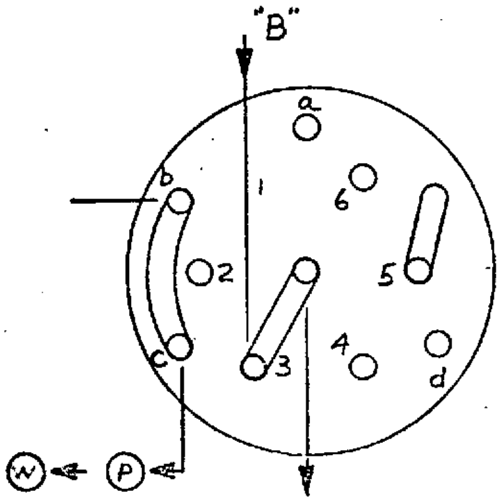
VALVE PORT FUNCTION



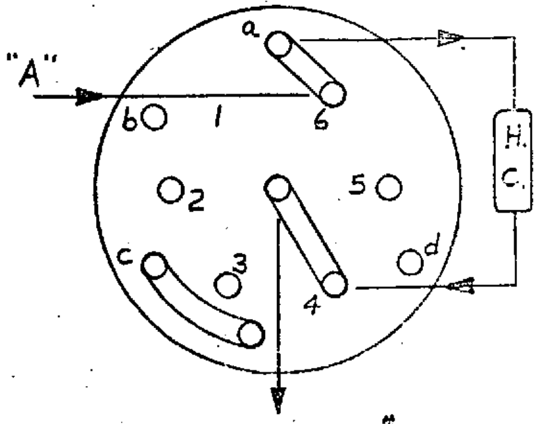
POS #1
ALL CLOSED



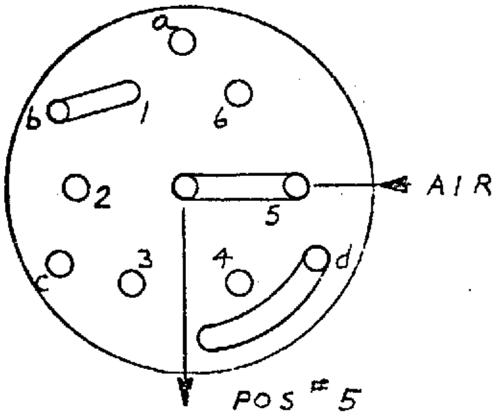
POS #2
1. SAMPLE INJECT
(b-a-4-d)
2. NOT USED
(2-OUT)



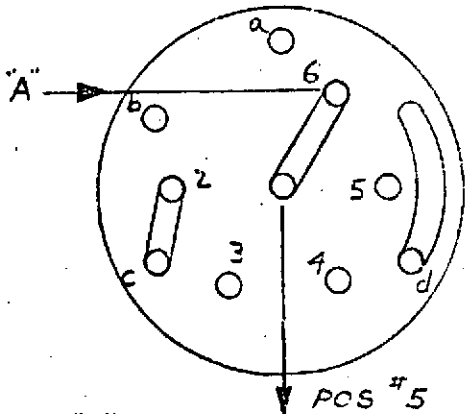
POS #3
1. SEPTUM CLEAN OUT
(b-c)
2. "B" STD TO ELECTRODES
(3-OUT)



POS #4
1. SAMPLE TO ELECTRODE
FOLLOWED BY AIR
OR "A" STD
(6-a-4-OUT)



POS #5
1. AIR TO ELECTRODES
(5-OUT)
2. NOT USED (b) (d)



POS #5
1. "A" STD TO ELECTRODES
IN CHECK MODE WITH
"AIR" VALVE IN "ON" POS.

of the geneva has two stations so that only 180° of driver motion is required for each driven station. The geneva is driven via a 1:1 ratio gear train by a 150 in-0z synchronous motor of 20 rpm.

Other functions on the valve assembly are the binary switch cam and motor logic cams. The binary switch cam is a rotating disc attached to the valve drive shaft that actuates four switches. These switches indicate, by binary code, the valve station currently in use. The coding scheme is addressed in the electronics section. The motor logic cams are on the geneva drive wheel shaft and they control the input displacement of the geneva (i.e.,180°). One of the two is also a motor interlock cam to prevent pump motion while the valve is in motion.

The other valves in the fluid package are three way, 24 VDC, diaphragm valves. These valves are of minimum internal volume and are teflon constructed in the fluid contact section. The ''flush'' valve serves to direct air or ''B'' standard solution to the septum inlet port for cleaning that device during the appropriate period. The other, ''air'' valve serves to direct air bubbles or ''A'' standard to the holding coil during the ''A'' standardizing cycle.

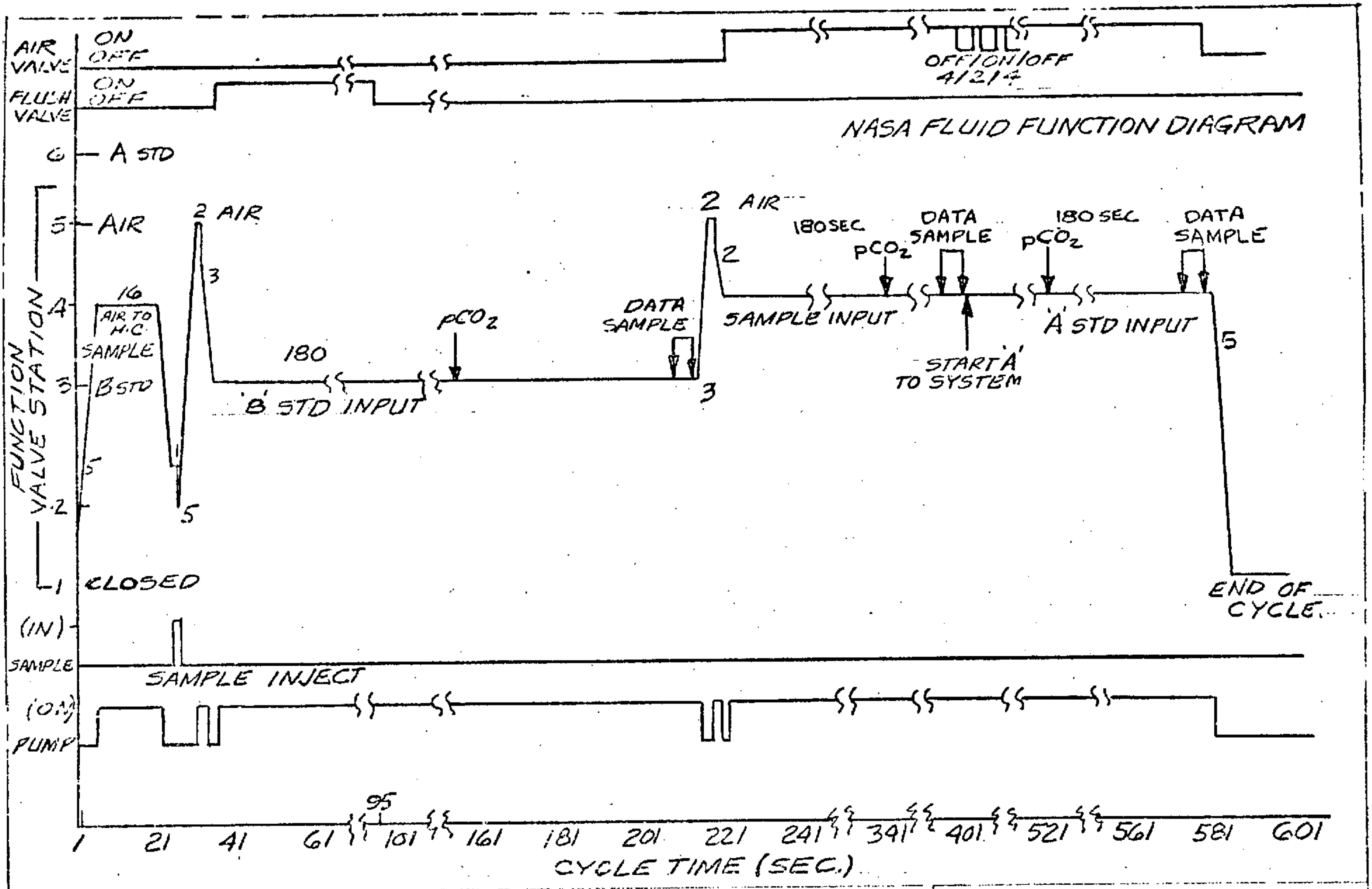
The timing sequence of all three valves can be seen in the ''Fluid Timing Diagram'' of Figure 4.7.

4.5. Sample Holding Coil

The holding loop is a coil of approximately 1 ml volume that stores the sample and allows it to come to near temperature equilibrium with the package before measurement. It is made of teflon tube and is connected to ports ''A'' and '4' of the CRS valve. The holding coil is washed after extraction of sample by following it with alternate bubbles of air and ''A'' standard solution. This mixture remains in the loop until new sample is inducted and pushes the mixture to waste.

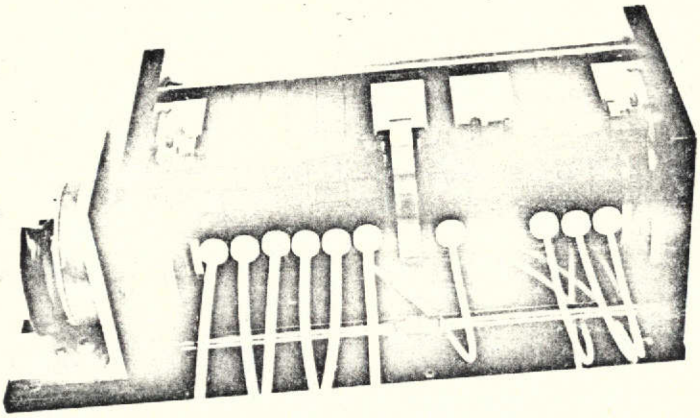
4.6. Pump

The fluid package pump is a specially designed peristaltic pump of twelve channels (Figure 4.8.). The pump is constructed of aluminum and stainless steel. The design features include planetary gear driven rollers for precise roller speed relative to tube motion, thereby increasing tube life, and flow precision, and minimizing pulsing in the flow tube. The rollers in contact with the flow tubing are wear resistant teflon ''S'' coated to increase tube life. Each flow tube is individually adjustable for spring pressure so that optimum flow



4.7. Timing Diagram

4.8 System Pump



rates and tubing life can be obtained.

The flow tube cassettes are machined so as to minimize the pulsing inherent in the peristaltic pump design. Each cassette will accept up to 1/4'' OD tubing. The cassettes are also teflon ''S'' coated to increase tube life. The cassettes are arranged in two groups of six by system function.

The pump is driven by a high torque instrument A.C. syncronous speed motor. The motor speed was selected to match the flow requirements of the electrodes. The volume flow requirements are varied in each channel by using different tube internal diameters.

The pump tubing is silicone rubber, a compound that is highly chemical resistant and has long life under peristaltic pumping conditions.

4.7 Thermal Control

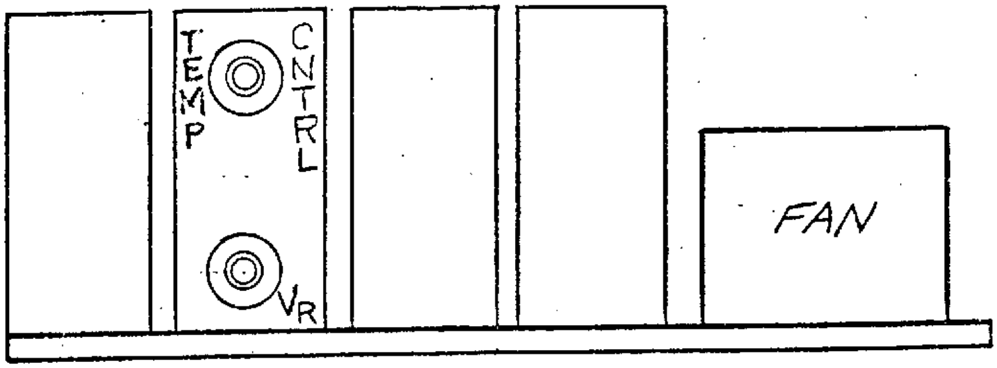
The thermal system for the fluid package is designed for the following criteria: (1) The system operates at 37.0°C in a laboratory enviroment, (2) The pCO_2 electrode be controlled at ± 0.1°C, (3) The electrodes must be at or near operating temperature within 30 minutes of start up.

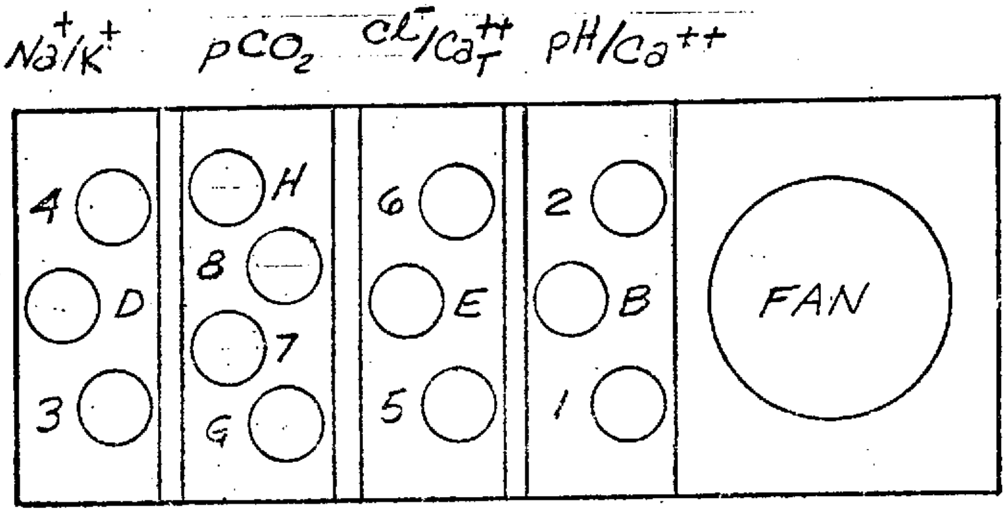
The approach selected to meet the above criteria is to use the pCO_2 electrode as the system control point. The electrodes are heated using a feedback control system from a hot plate on which they are mounted (Figure 4.9.). In addition, the excess heat generated in heating the electrodes is circulated via a forced air fan over the electrodes thereby equalizing the temperature of the electrodes and moving the heat throughout the fluid package. This approach would allow meeting the 30 minute warm up for the electrodes using minimum power, since the thermal mass is much smaller.

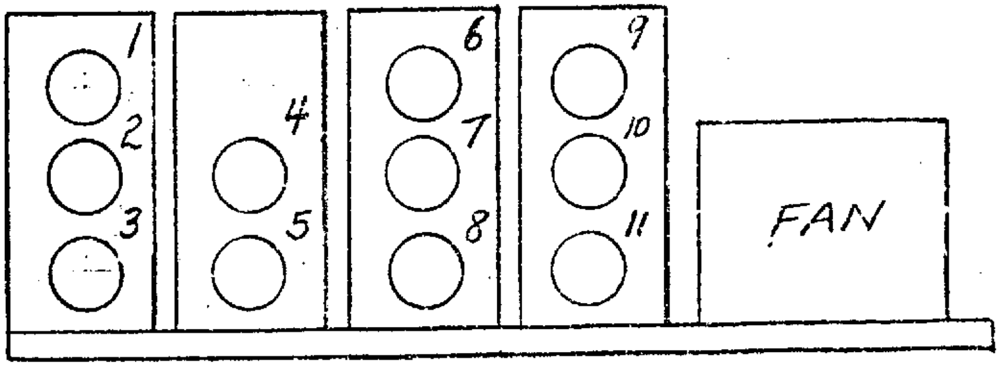
However, using this approach the system fluids do not stabilize in temperature for several hours. This trade off is acceptable because the fluids entering the electrode modules have sufficient time to equalize temperature within the module prior to measurement.

The temperature control point and read-out networks are located within the pCO2 electrode module. The proportioni control unit thereby maintains the most temperature critical module at the set point. Temperature tests have been run to optimize the feedback control element position for best response characteristics. By this method, control was established within the required ± 0.1^c during the 10 minute test period.

4.9 Electrode Mounting

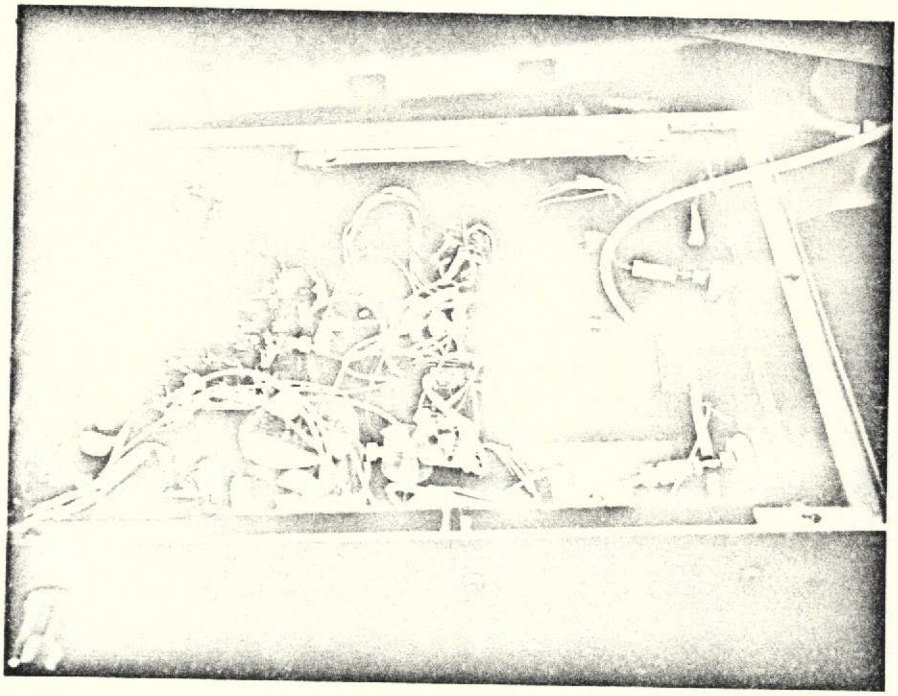






By circulating the heated air in the system, and by additional component heat, the fluid temperature will reach 37.0°C after several hours running time. Thermal insulation of ''Pyrel foam'' has been provided throughout the fluid package to maintain thermal isolation from the environment. Figure 4.10. shows a top view of the assembled Fluid Transport Unit.

4.10 Fluid Transport Unit, without Cover, Top View



CHAPTER V

ELECTRONICS UNIT

5.1. Preface:

All electronic circuitry, designed and fabricated for the A.P.E.A.S., is located in a section of the Fluid Transport Unit (F/T), and a separate Electronics Unit (E/U). The F/T houses eight amplifiers, one for each parameter, an eight input analog multiplexer to select a specific amplifier output, and temperature measurement and control functions. This circuitry, which is best located in close proximity to the sensing electrodes, is contained on a single removable printed circuit board. A 0.09 cu. ft. compartment, separated from the fluid section, is utilized for this portion of the electronics system.

Electronic logic and control functions, required for this Fluid Transport Unit to dialogue with a general purpose digital computer, are provided in the electronics unit. It is in this unit that standard 5 volt logic control signals from the computer are converted to the appropriate driving voltages for the valves, pump, mixer and multiplexer in the F/T. In addition to providing all power required by both E/U and F/T, the E/U digitizes the analog electrode data, provides pump and valve safety interlocks, and feeds complete system status information back to the computer. Three push button switches allow the operator total system control with minimum complexity. An array of status indicators keep the user posted on the actual system operation. Behind a service door, the individual F/T component control switches and indicators enable individual selection of fully automatic or fully manual operation of each device. A digital display of the multiplexed electrode output is also provided. the E/U occupies 0.35 cu. ft., weighs 16 lbs., is powered by 120 VAC, 60 Hz at 120 watts, and utilizes plug-in printed circuit boards and integrated circuits for ease in servicing. A summary of design objectives follows.

5.2. Design:

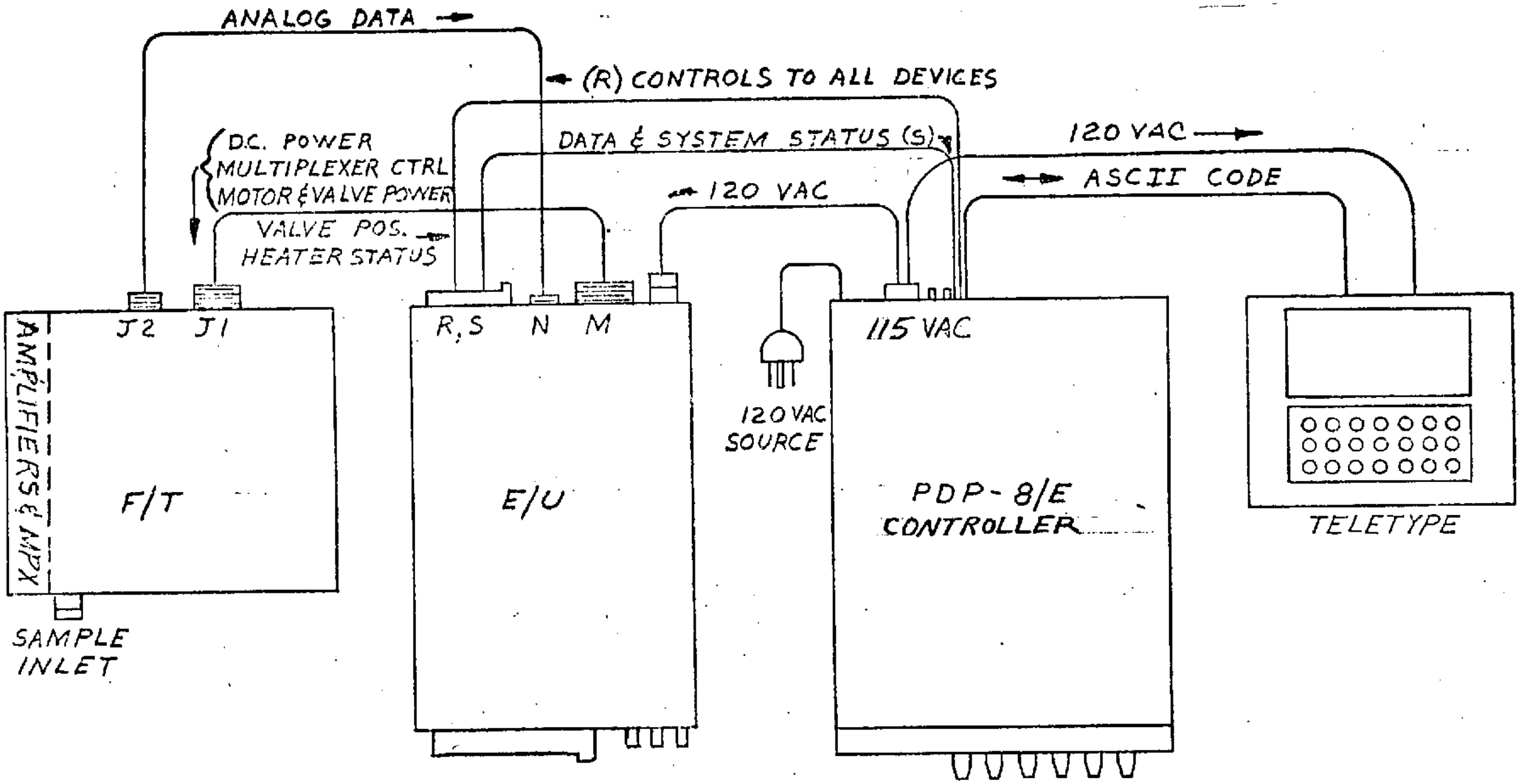
It is anticipated that the actual flight system will incorporate a low power dedicated hardware controller in conjunction with a data telemetry link or on-board data processor. For this reason it was unrealistic to design control electronics hardware which would be directly applicable in a flight system. Instead, the main design goal was to produce a laboratory evaluation unit which would maximize operational flexibility and serviceability. Extensive, although not difficult, modification will be required for flight electronics. These changes are summarized in Chapter 9,

One design objective was to minimize circuitry in the F/T, providing only those elements required for suitable electrical dialogue to a separate electronics unit. By using a high impedance differential input amplifier for each parameter, it was possible to incorporate an analog multiplexer for rapid data acquisition with a single analog to digital converter. Without such amplification, the high impedances of some electrodes would cause settling times approaching 10 seconds. Locating the multiplexer in the F/T allows all measurement data to be transmitted via one low impedance conductor pair. Temperature control of the electrode modules is provided in the F/T for maximum control stability. A completely independent temperature measuring circuit is connected to one of these eight amplifiers, allowing the monitoring of this control function. Backup over-temperature heater shutdown is also provided in the event of control failure. Appropriate location of F/T insulation causes the amplifier section to be effectively temperature stabilized by the electrode system, improving amplifier performance. Minimal changes to this area would be necessary for a flight design.

The E/U is designed to provide all the necessary power drive circuits, decoding and encoding logic, and analog to digital conversion, without predetermining actual system operation. All system sequencing and timing is determined by the computer software, referenced to a one pulse per second hardware clock. The result is a truly flexible control system where the operation of any device or the entire system may be altered by simple changes to a software control table. The addition of device and status indicators, and automatic/manual control switches, permit the user to over-ride the computer control at any time for tests or evaluation. This approach has proven to be considerably more flexible than a hardware controller, and best suits a prototype system of this type. Other design features include spare control functions for possible future modifications, extensive use of plug-in components for servicibility, and minimum size, consistent with laboratory instrument construction. Test fixtures and programs as well as complete annotated schematics and layouts are provided to facilitate system maintenance.

5.3. Description:

the relationship pf the electronics unit to the fluid transport and computer is shown in Figure 5.1. As previously indicated, the E/U serves as the control and data transfer agent between the PDP-8/E and the F/T. Cables between the E/U and F/T carry the actual



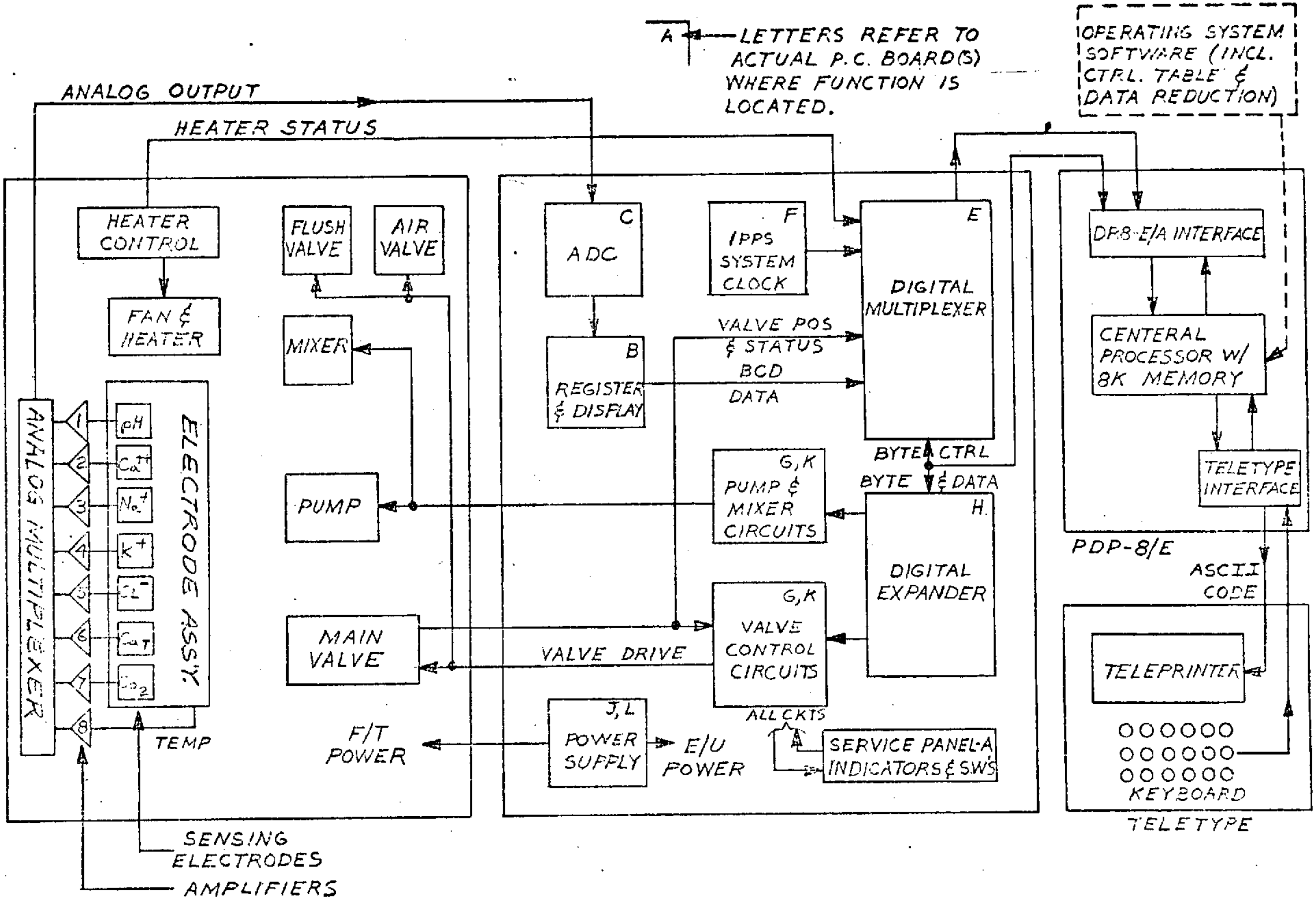
5.1. A.P.E.A.S. Unit Connections

motor and solenoid power, multiplexer control, and return analog signal data from the sensing electrodes. Digital signal cables between the E/U and controller transmit encoded parallel 12 bit information, including all data and control. A cable from the controller to the teletype carries ASCII code to the teleprinter, and back from the keyboard.

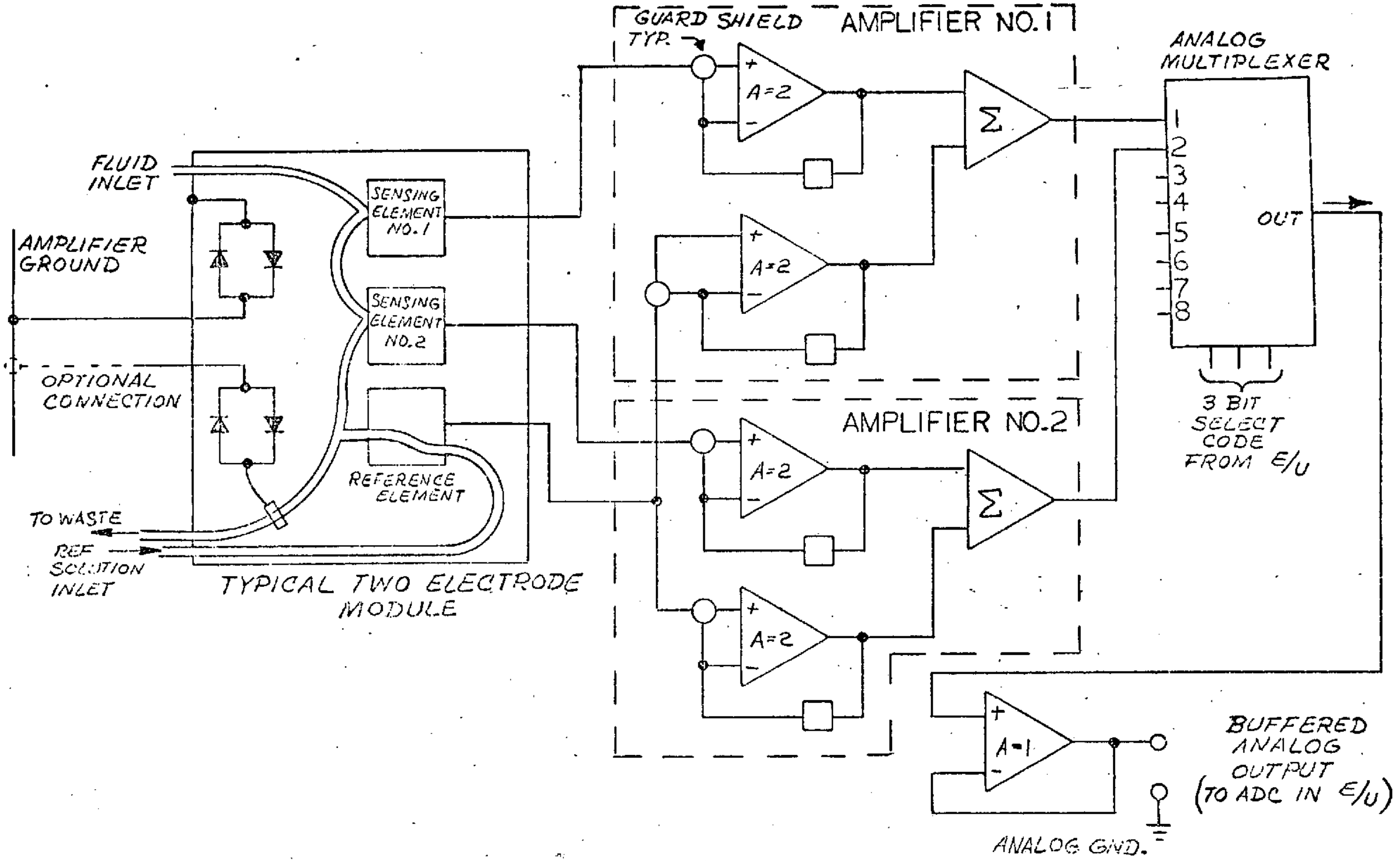
An overall block diagram of the system is given in Figure 5.2. Although simplified, this traces the basic control and data transfer paths between major functional areas. Letters are used in the upper right hand corner of E/U functions to identify actual board location in the E/U. The following more detailed description of electronics operation is keyed to partial block diagrams. These diagrams provide reference to annotated schematics which show the actual circuitry.

5.3.1 Electrodes, Amplifiers, and Multiplexer (Figure 5.3.)

The sensing electrodes used in the F/T require specialized amplifiers and grounding systems for proper operation. Potentiometric measurements of the electrode outputs must be made to several tenths of a millivolt accuracy, in spite of the fact that some electrode impedances approach 300 to 500 megohms. In addition to impedance and offset current considerations, it is understandable that very small potentials introduced by the fluid stream or ground wiring could cause signi-



5.2. Overall System Block Diagram

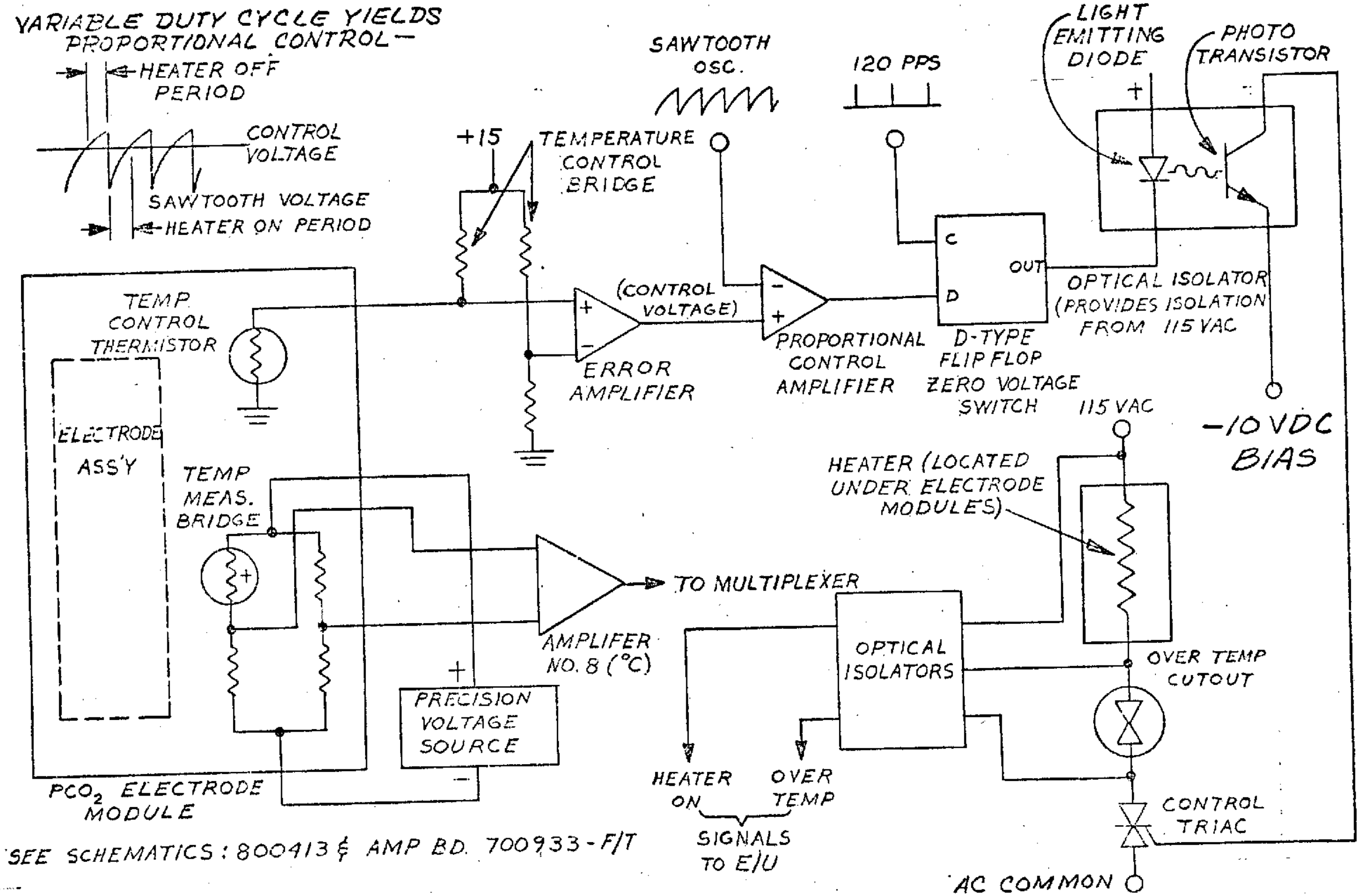


5.3. Electrodes, Amplifiers, and Multiplexer ficant errors. The problem is solved in two ways. First, very high impedance differential input amplifiers allow measurement between a sensing electrode and reference without regard to common mode voltage. Clamp diode pairs are used as shown to limit the common mode voltage. This diode technique provides a voltage ''window'', but by allowing small offset potentials, does not induce currents in this fluid system. Coaxial cable shields, driven by guard potentials, improve response and virtually eliminate stray pickup. The amplifier design incorporates low pass filtering to reject any AC voltages. Secondly, all analog signal and power grounds are referenced to a single point in the F/T, eliminating errors due to ground currents. The temperature stabilized environment of the F/T further improves amplifier performance. A nominal gain of two is provided to permit 50 microvolt per bit resolution at the input. This additional sensitivity is desireable for calcium measurement with typical 30 millivolt/decade slopes.

Amplifier outputs are selected by a F.E.T. type analog multiplexer, buffered by a single unity gain amplifier, and fed to the E/U ADC. A separate cable which shields both the signal and signal return lines is used for maximum noise immunity. Multiplexer channel control comes from the computer control software, or the E/U manual override if utilized.

5.3.2. Temperature Control System (Fig.5.4.)

Temperature control and measurement circuitry account for the balance of F/T electronics. Temperature sensors are located in the pCO_2 module because that parameter is the most sensitive to thermal variations. For heater control, the output of the control thermistor bridge is amplified and then fed to a proportional control amplifier. The function of this second amplifier requires some explanation. For the fastest warmup time, an on/off type controller is preferable. However, at the control point, a proportional controller provides greater stability. A second problem is that proportional control usually means high thermal dissipation (transistor) or R.F.I. (SCR) from the control device, when not fully on or off. By using a constant amplitude sawtooth signal, and a second amplifier functioning as a comparator, it is possible to achieve proportional control with on/off duty cycle variation. As illustrated by the waveform in Figure 5.4., a change in control voltage causes a proportional change in on/off duty cycle. The proportional control band is kept narrow by limiting the sawtooth amplitude. Output from the second amplifier is syncronized to AC heater power by 120 pps and a D-type



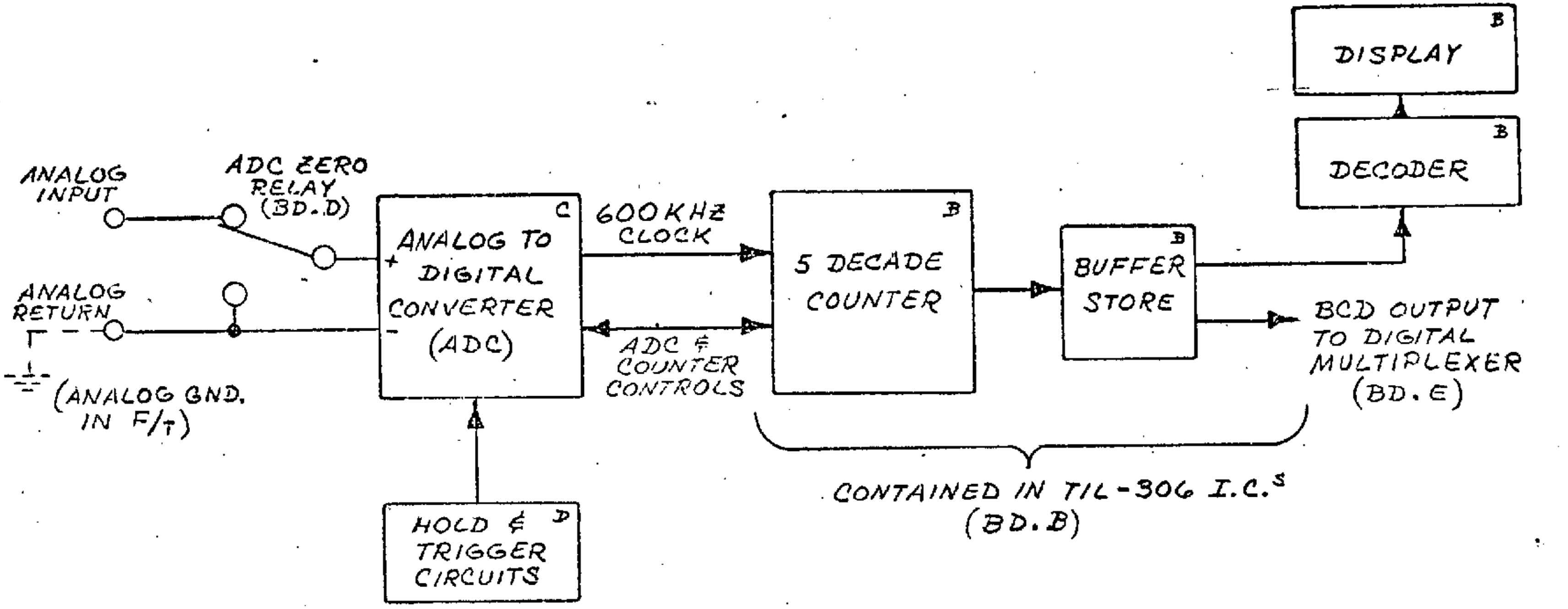
5.4. Temperature Control System

flip-flop, so that all on/off switching occurs at zero volts. This technique is used to eliminate RFI from the control TRIAC. Optical isolators are used as shown to avoid any electrical connection between control logic and 115 VAC. A thermal switch in series with the heater provides over-temperature protection. If activated, the ''THERM-FAIL'' indicator will light on the E/U (note Fig. 5.13.). The adjacent ''NORM'' indicator is illuminated whenever power is actually applied to the heater.

A separate circuit, consisting of a precision voltage and a second thermistor bridge, is used for temperature measurement. The output of this circuit is fed to the eighth amplifier, and is calibrated to read degrees centigrade directly, to 0.01 degree. The ''LO-TEMP-HI'' indicators on the E/U are controlled from this measurement via the computer software.

5.3.3 Analog to Digital Conversion (Fig. 5.5.)

Analog output from the F/T is connected to a single analog to digital converter (ADC) in the E/U. This dual slope integrating ADC digitizes its ± 4v. input to a precision of 0.1 millivolt, displays the result on the E/U, and provides BCD data for the computer. It is important to remember that the input amplifiers



SEE SCHEMATICS:

700887 - BD.B
700943 - BD.C
700892 - BD.D

ADC SPECIFICATIONS:

TYPE	DUAL SLOPE INTERGRATION WITH AUTO ZERO
INPUT	± 4 VDC
OUTPUT	± 40,000 COUNTS
CONVERSION RATE	10/SEC (MAX)

5.5. Analog to Digital Conversion

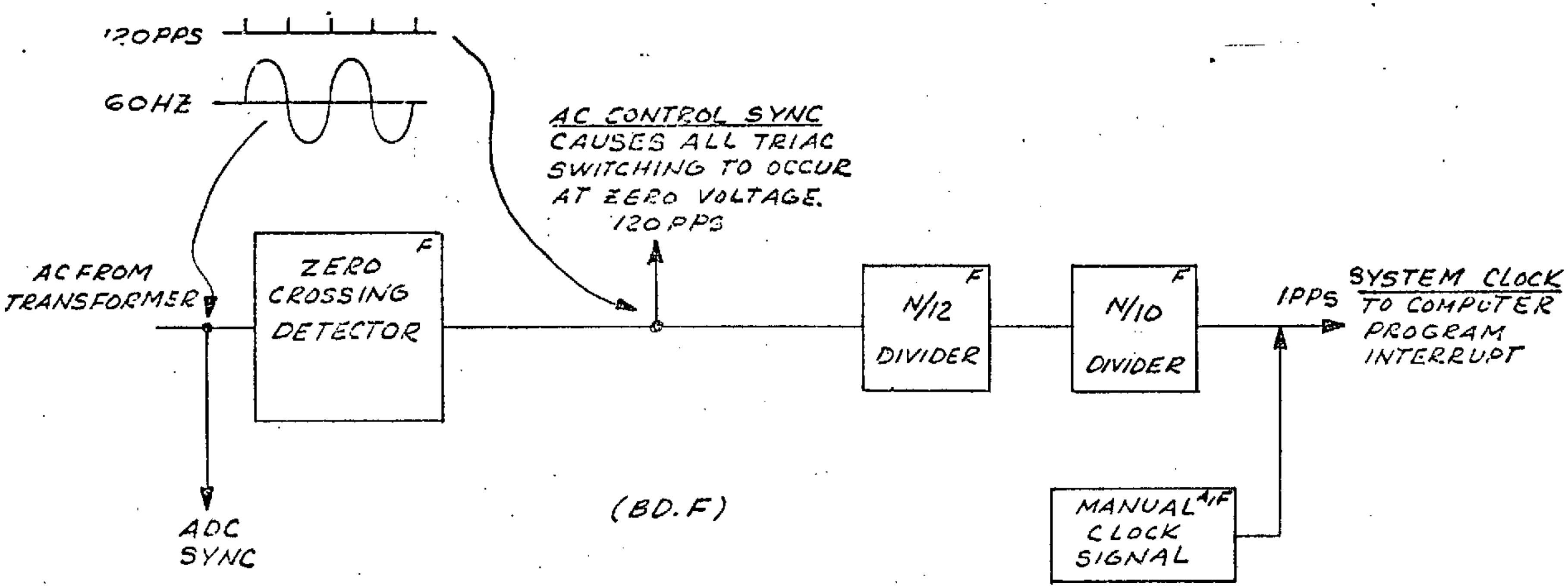
have gain of 2. This means that, at the electrodes, the maximum input is ± 2v. with a measurement precision of 0.05 mv. Except for temperature, the ADC display and BCD data must be divided by two for actual electrode potential.

An input ''ZERO'' relay is provided for testing the ADC and display functions. It may be operated manually at the E/U or by the computer program. For additional ADC testing, a precision voltage source may easily be attached at connector ''N'' on the E/U.

5.3.4. System Timing Circuitry (Fig. 5.6.)

In order to prevent R.F.I. from AC power switching and possible ADC instability due to hum pickup, synchronization to AC power is necessary. This is accomplished using a low voltage AC signal from the transformer secondary. The ADC uses this AC directly to synchronize the start of each conversion, with a constant phase relationship to line power. For power control, a zero crossing detector produces 120 pps from the same signal. The pulses occur at zero line voltage, as indicated, and are used as an update command for D-Flip-Flops controlling AC power loads.

The 120 pps is divided to one pulse per second for the



SEE SCHEMATIC 700897-BD.F

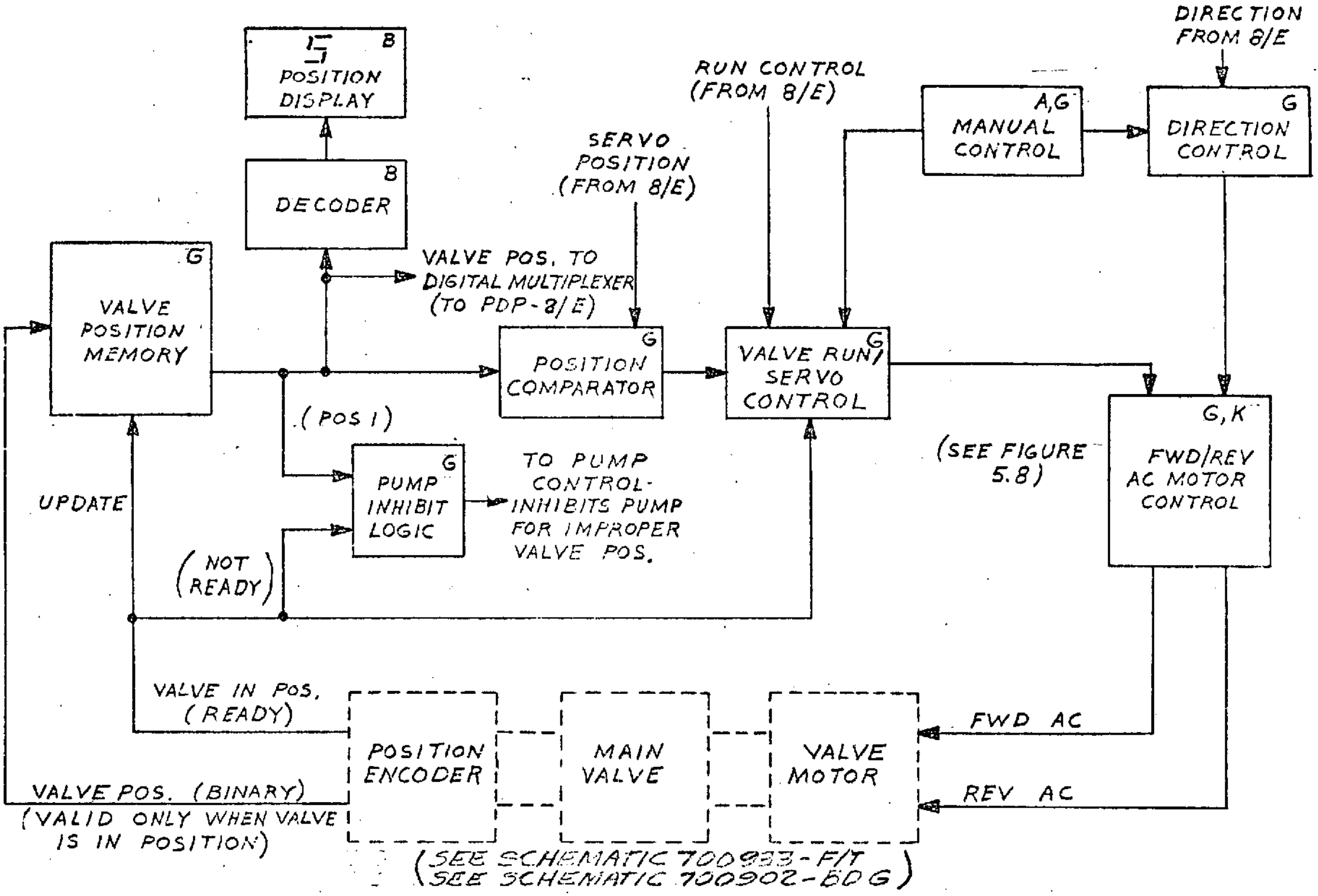
5.6. System Timing Circuitry

main system clock. Software registers, in the computer program, accumulate the 1 pps signal for system timekeeping. All software control timing originates from this clock, which may be stopped and manually incremented at the E/U for test purposes.

5.3.5. Main Valve Control (Fig. 5.7.)

The main valve control incorporates all circuitry required to run the valve to any position, forward or reverse, with manual or computer control. A position encoder, located on the valve, provides binary position indication when the valve is locked in a position. During the valve transit between positions, this code is not valid and must be stored. The output of the position memory is displayed and made available to the computer.

Two modes of computer control are possible. First, the program may issue a direction and a run command, causing the valve to run one position and stop. Alternately, the control program may specify a desired position and direction. The latter case, most often used, will cause the valve to servo to the desired setting. If an illegal servo code is used (such as position 7) the valve will be automatically shut down after two and one half complete rotations. This servo mode is not



5.7. Main Valve Control

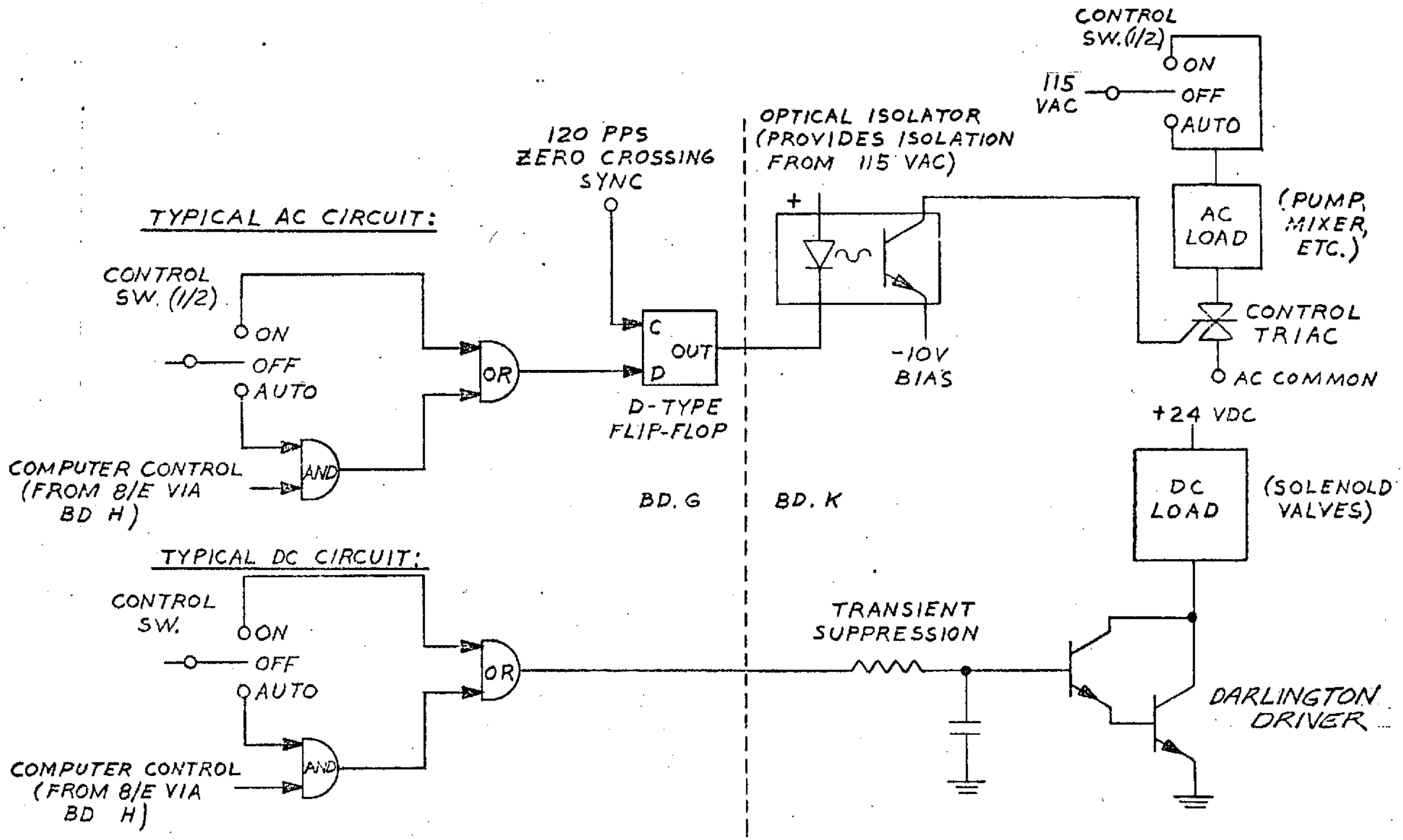
available for manual operation. Refer to Chapter 8 for operating guidelines.

When the valve is in position No.1 or in transit, fluid lines are not connected for operation and the pump must not be run. Pump inhibit logic in the valve control detects this condition, preventing pump operation. Backup protection is provided with valve microswitches in series with pump motor power. A warning indicator near the pump motor in the F/T will be on if this backup system is employed. The E/U provides full indication of normal valve and pump status.

5.3.6. Power Control Circuits (Fig. 5.8.)

Circuits used for controlling high current loads are designed to avoid transient or RFI generation. This is done by switching AC loads at zero voltage utilizing the 120 pps sync. Optical isolation between AC and [illegible] logic circuits further reduce noise problems. For DC controls, the load is switched with a R-C time delay to slow voltage changes.

All controls feature automatic operation (control from computer software) or manual control (from the E/U). The selected operating mode completely overrides the

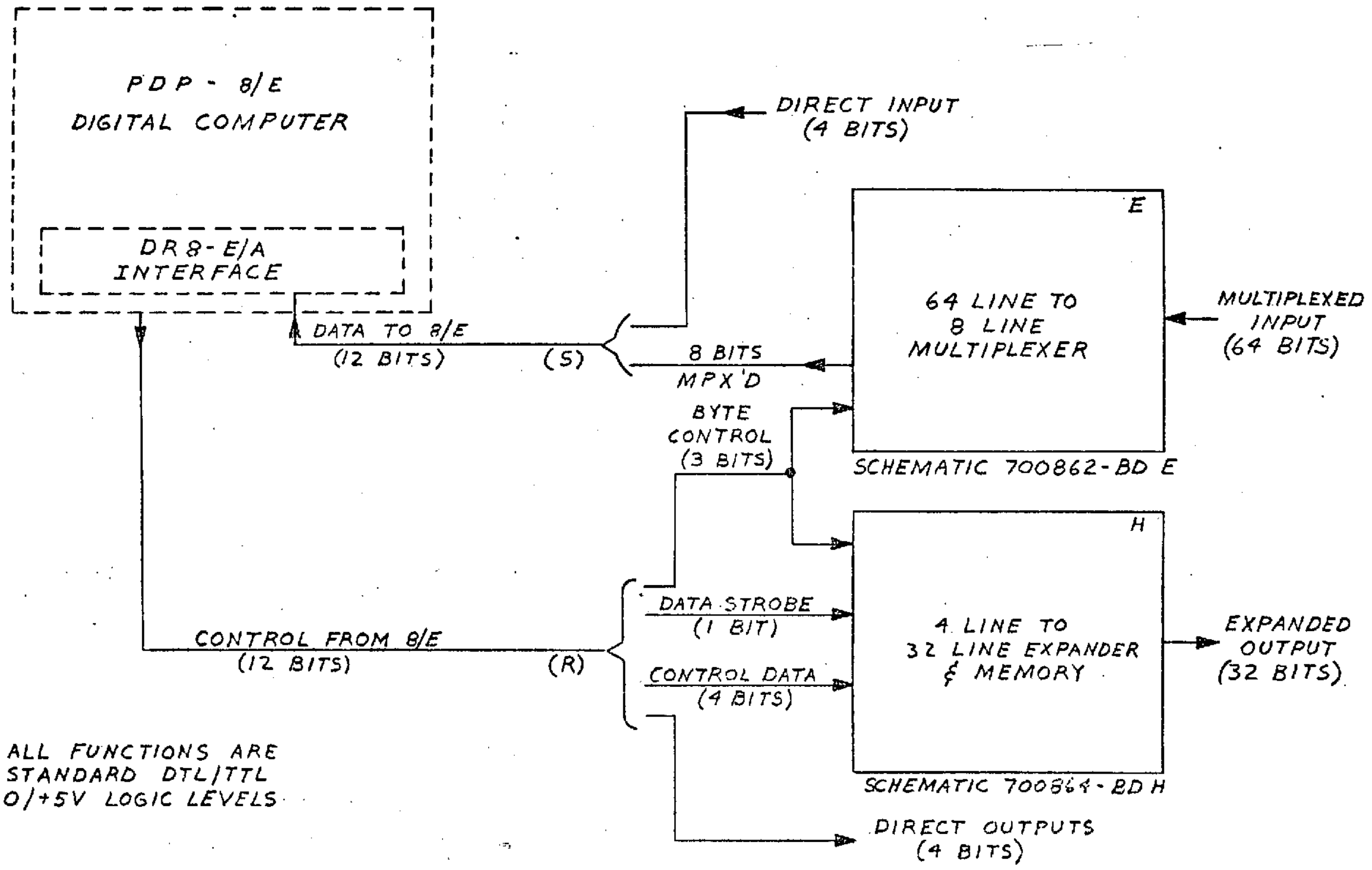


5.8. Power Control Circuits

non-selective mode. Because control functions are independent, some may be in automatic mode while others are in manual. An E/U front panel indicator (''MANUAL MODE'') cautions the user when any control is set for manual operation. A similar caution is typed, if required, at the start of an ''ANALYSIS'' or ''CHECK'' sequence.

5.3.7. Digital Multiplexer and Expander (Fig. 5.9.)

The PDP-8/E computer and DR8-E/A interface provide 12 bit parallel data transfer to and from the E/U. In order to accomodate the numerous system data and control lines, it is necessary to provide a secondary expansion interface in the E/U. Simply, a 64 data bit capability from the E/U is multiplexed into 8 bytes of 8 bits each, and 32 control bits are demultiplexed (expanded) in the form of 8 bytes of 4 bits each. Input and output bytes are selected by a common 3 bit byte code from the computer. A data strobe allows setting the expander byte prior to updating the stored outputs. Direct inputs and outputs are used for high priority functions such as the system clock, user control, error flags, and ADC controls.



ALL FUNCTIONS ARE
STANDARD DTL/TTL
0/+5V LOGIC LEVELS

5.9. Digital Multiplexer and Expander

5.3.8. Power Supplies and Grounding (Fig. 5.10)

All power supplies are located in a shielded compartment of the Electronics Unit. Except for 115 VAC and -10 VDC TRIAC bias, all voltages are isolated from the AC power line. Special grounding practices are used, as indicated, to ensure proper system performance. The 15 volt and 5 volt supplies are protected from short circuits because of the large amount of circuitry they service.

5.3.9. Electronics Unit Layout (Fig. 5.11)

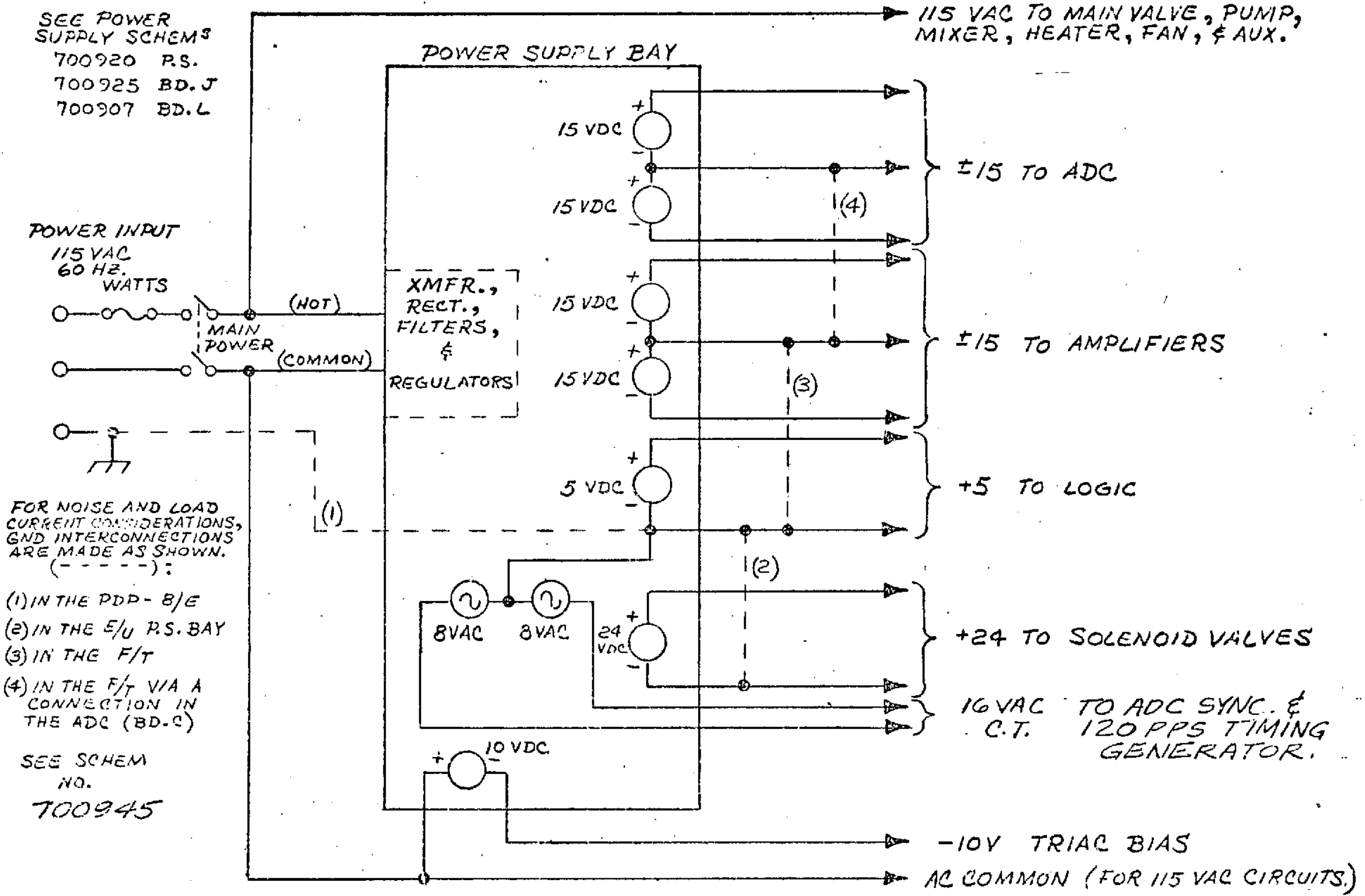
This top view of the Electronics Unit shows the plug-in printed circuit board layout. The unit offers adequate size for serviceability without being a cumbersome part of the system. It is anticipated that a flight electronics system would be no larger than this, including the hardware system controller.

5.3.10. Electronics System Photographs (Figs. 5.12 to 5.18)

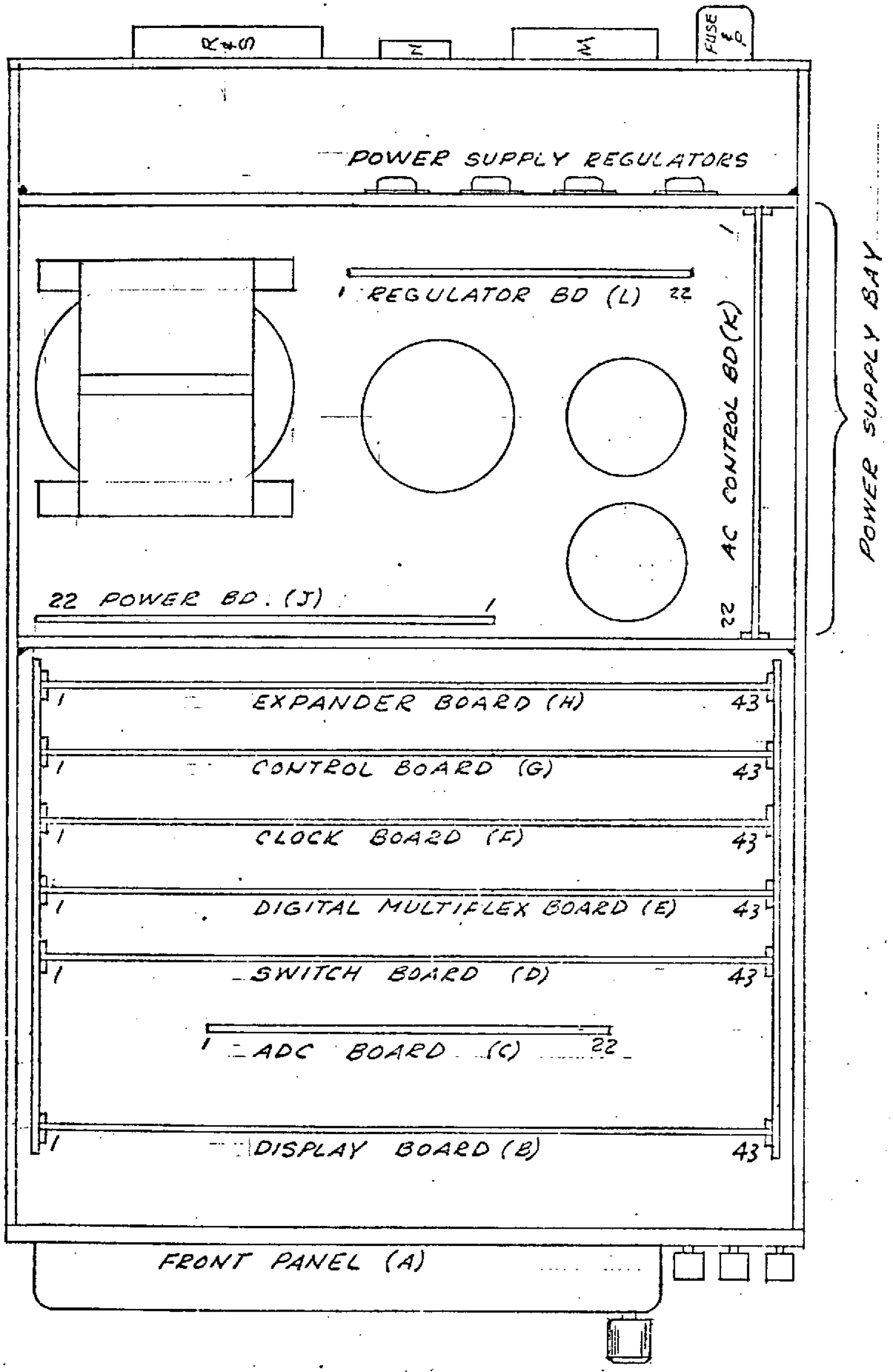
These photographs show the actual system components.

5.4. Summary

The A.P.E.A.S. electronics has been designed to provide



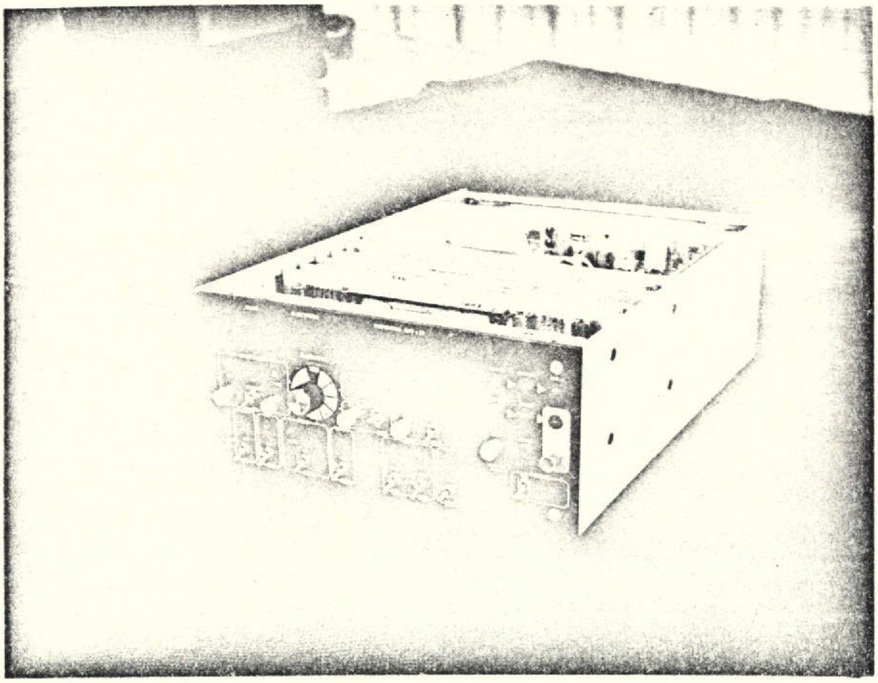
5.10. Power Supplies and Grounding



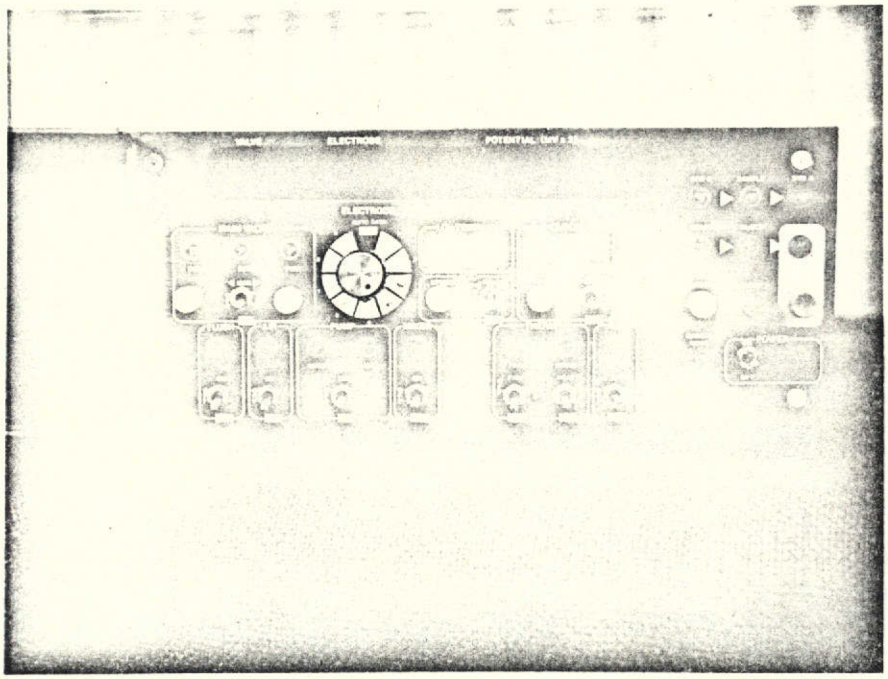
5.11. Electronics unit layout

all necessary data and control transfer functions between the fluid handling section and a controller, with minimum operational restrictions. This allows maximum flexibility of system test and evaluation by simple changes to a software control table. Wherever possible, circuitry has been designed to be easily tested or replaced. Chapter 8 provides additional information regarding the setup, operation, and maintenance of this system.

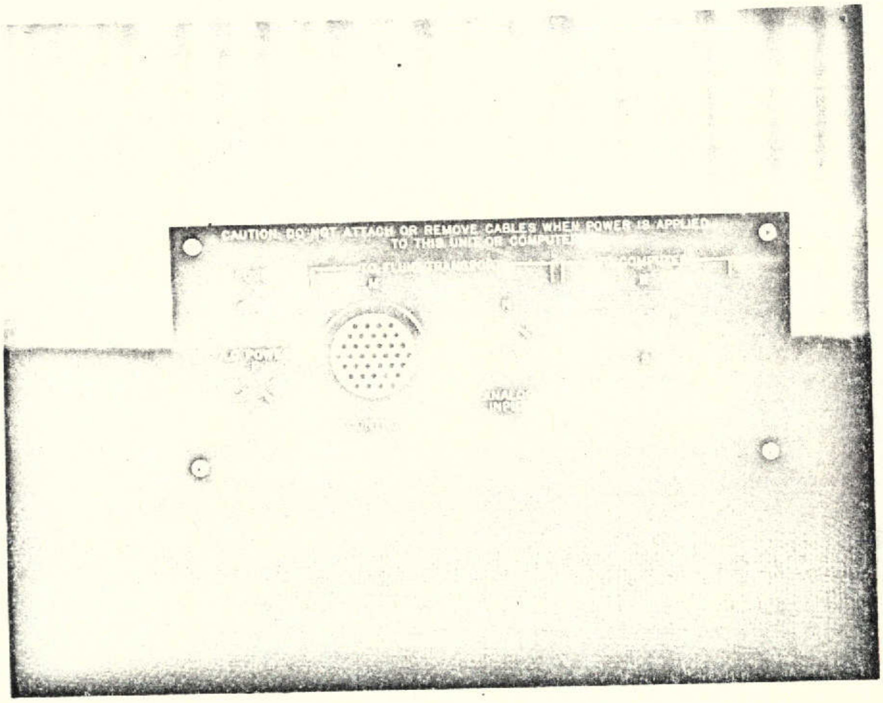
5.12 Electronics Unit



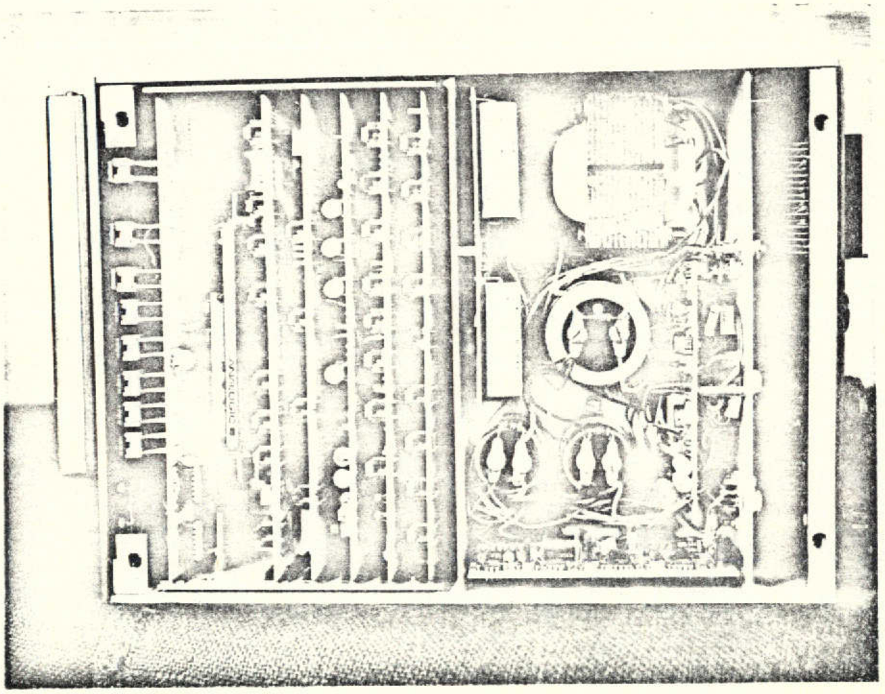
5.13 Electronics Unit Front Panel



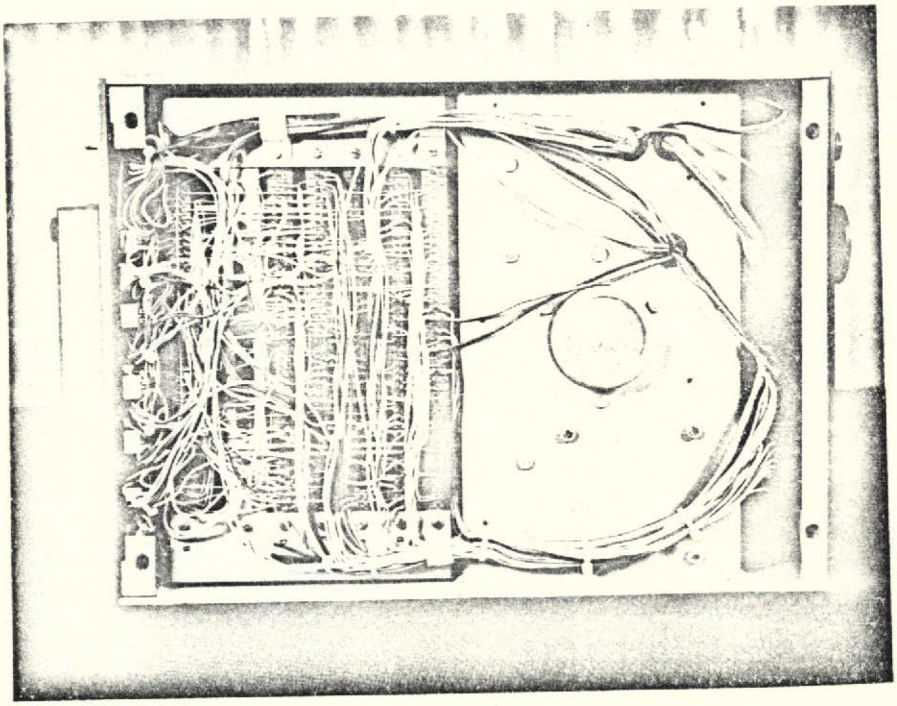
5.14 Electronics Unit Rear Panel



5.15 Electronics Unit Top View

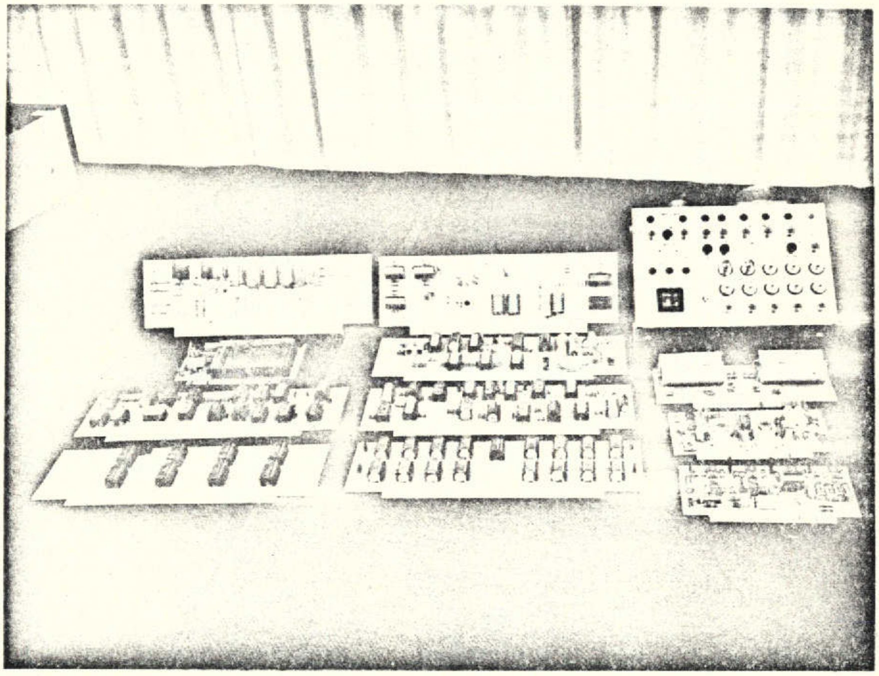


5.16 Electronics Unit Bottom View

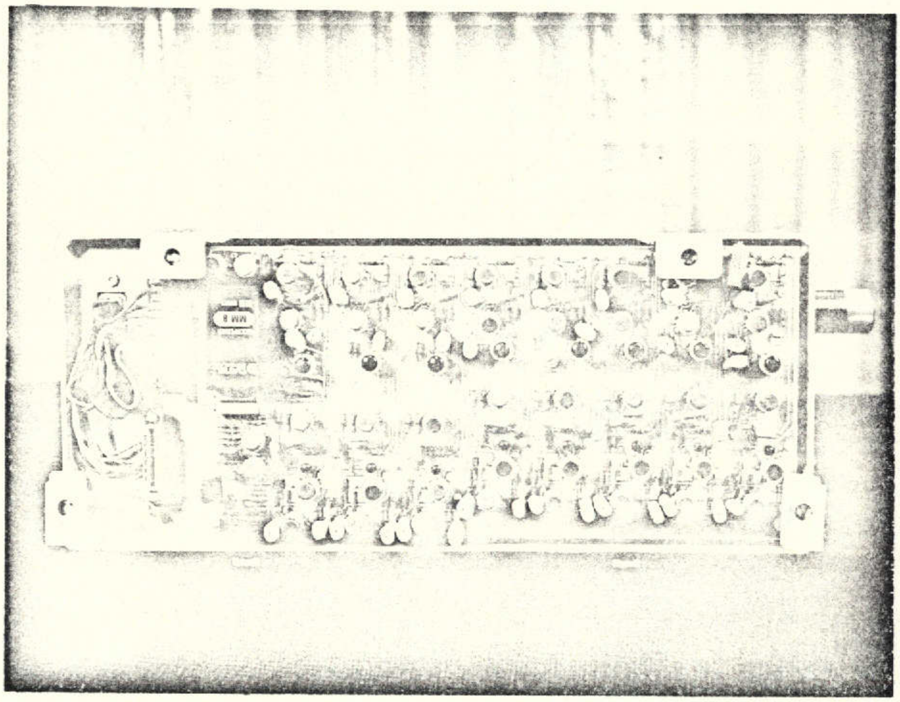


C-2

5.17 Electronics Unit Printed Circuit Boards



5.18 Fluid Transport Unit Printed Circuit Boards



CHAPTER VI

CONTROLLER AND SOFTWARE

6 .1. Definitions:

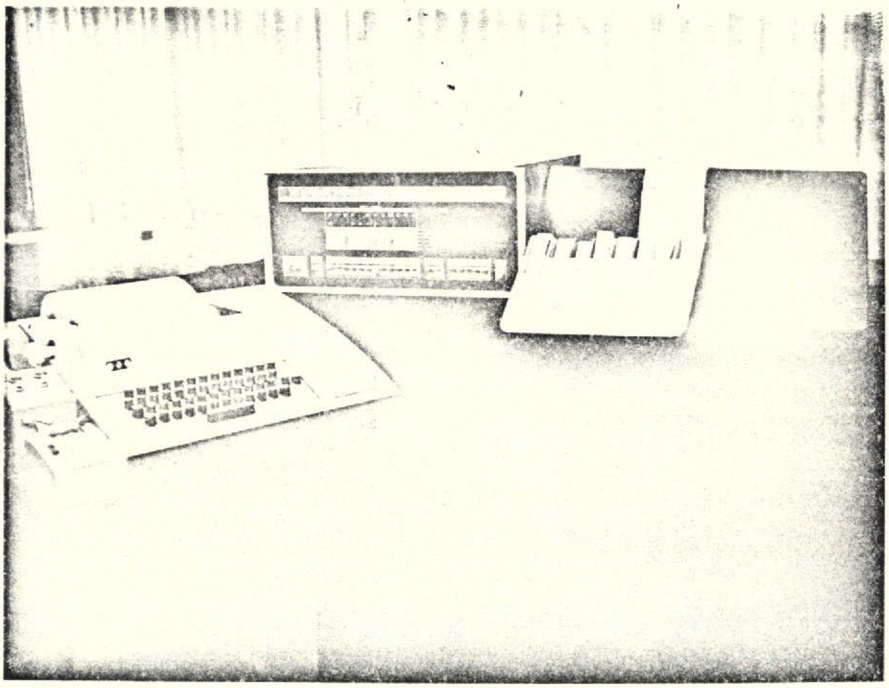
The operating system (O/S) is the hardware and program's (software) necessary to make, support or augment an auto-analysis. Occasionally, O/S represents the executive controller program in situations made clear by the context.

The O/S software is the group of programs and their documentation that controls the operation of the system.

6 .2. Introduction:

The design aims for the (O/S) software for a system which could explore the range of operating conditions useful for an automatic analysis sytem rather than a specific flightworthy system. Therefore, the system would be made as flexible as the resources would reasonably allow. In fact, the need for any ''software'', and ''operating system'', was dictated by the specifications of an adaptable, general-purpose controller instead of a more limited dedicated hardware controller. The configuration operation and

6.1 Operating System Software



timing of the elements of the hardware (F/T and E/U) is determined by the contents of the control processor memory, rather than by the logical and analog functional circuits of a hardwired controller.

6.3. Considerations for implementation of control functions

The capabilities of the smallest control processor are much greater than the capabilities of any hardwired controller built using similar resources. The basic function of the software is to direct the hardware to perform an auto-analysis. The software comprises several programs, which when cast in the proper form, placed in the processor's memory, and the processor started, are ''translated'' into directions to and interrogation of the E/U. The E/U in turn communicates in both directions with the F/T.

This general approach allows for considerable modification of the parameters (in time) for the components (pump, valves, etc.) of the F/T and E/U by simply modifying a small segment of data stored in memory. Even greater modification could be achieved by loading the memory with a different O/S. The accomplishment of any approach to analysis is limited only by the various meaningful combinations of valve conditions, pump-on, pump-off, controllable modes of the ADC, etc. In addition, a GP processor allows many raw data manipulations which can be easily modified and changed to a far greater extent than the most complex hardwired controller. The same is true of the media through which the results are reported, and the format within this media.

6.4. Choice of a general purpose digital control processor:

Although the last year has seen the introduction of several devices that meld the characteristics of the hardwired device controller and a simplified general purpose digital processor, these are, as of yet, infant devices. The performance of the PDP-8, in terms of available services, demonstrable reliability, widespread acceptance, manufacturer's software support, and prior applications make it a good choice for the processor. The PDP-8E used is a small general purpose digital processor with a twelve-bit word and two 4096 word fields (banks) of memory. It communicates with the E/U through the DR-8E, an adaptable interface. which takes care of the dialog between the processor proper and the E/U, allowing the processor to send twelve bits of information to the E/U (most of which the E/U ''remembers''), and to receive as many returning from the E/U.

The processor manufacturer provides an array of software support items. Considered for inclusion in the data manipulation section of the O/S, were their math routines, ''floating point'' arithmetic package, and FOCAL program. Although the FOCAL program occupies the most memory, it offers more alternatives as to method, format and ease of modification, than the others or a program developed in-house. It requires less development time and is probably easier to understand. Other programs, such as the D.E.C. machine code assemblers and text editor were used within the O/S software development loop. The popularity of this processor family makes it more likely that the user is familiar with the manufacturer's software.

6.5. O/S Software Structure:

The core of the O/S is the Executive Controller. It has provisions for formatting information sent to the E/U, interpreting information from the E/U and acting on that and keyboard information. The sequence of an auto-analysis is determined by the contents of the Control Table. The contents of the control table can be changed, if an analysis is not in progress, by using the MODIFY program. Thus a balance is struck between an O/S that has wide latitude of configuration but is difficult to comprehend, and one that is easily understood, but unchangeable. The MODIFY routine only accesses the contents of the control table, and then only in a simple manner. The MODIFY program provides protection because it is impossible to inadvertently modify and possibly destroy the O/S.

Octal Debugging Technique (ODT), a ''trouble-shooting'' program, is included to satisfy any contingency requiring the examination, change or piece-by-piece operation of machine code. Certain basic changes which would be impossible by modification of the control table alone could be effected simply in the O/S by someone familiar with ODT and the O/S. Both MODIFY and ODT are merely utility programs, for convenience, peripheral to both the operations and the purpose of the controller. Analysis is made without their use.

In the O/S, FOCAL is the controller's sub-program, directed by the controller's interpretation of the control table to perform its tasks of manipulating data and printing a report.

6 .6. Hierarchy:

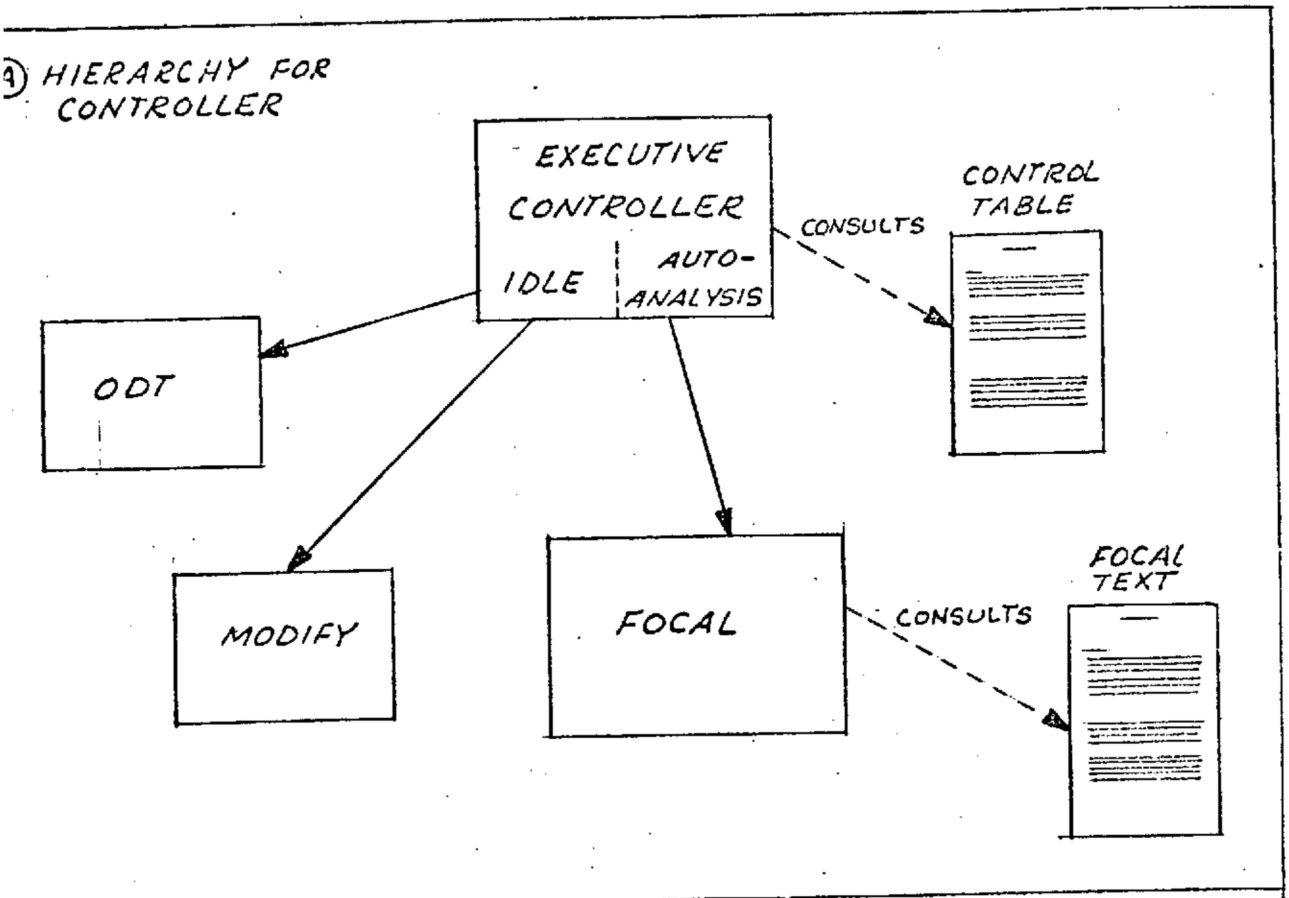
The amount of memory occupied by the major program segments does not show their level of control. The program hierarchy from superior to subordinate is shown in Figure 6.2. Assume that the Executive Controller is running. Part A shows that, besides controlling the hardware, the controller consults the control table and allows FOCAL to run during auto-analysis. During idle, the controller can relinquish its supervision to either of the utility programs, MODIFY or ODT. FOCAL refers to its stored ''text'' when it is allowed to run, returning control to the Controller when it has finished the requested task. Figure 6.2B shows MODIFY, the control table editor, running, as a result of a user request from the keyboard. The user can now edit the control table via the keyboard. When finished, he asks for the controller to take up supervision again. Part ''C'' shows a similar condition for ODT.

6 .7. Normal Operation of the System

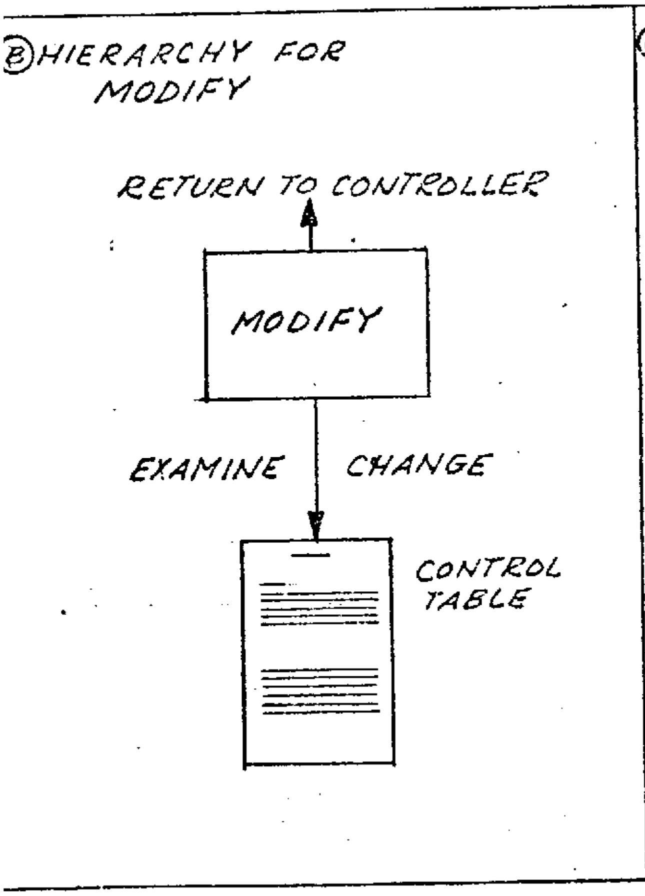
6 .7.1. Executive Controller:

When the user starts the system, the controller initiates the whole system (Fig. 6.3.1.) then enters

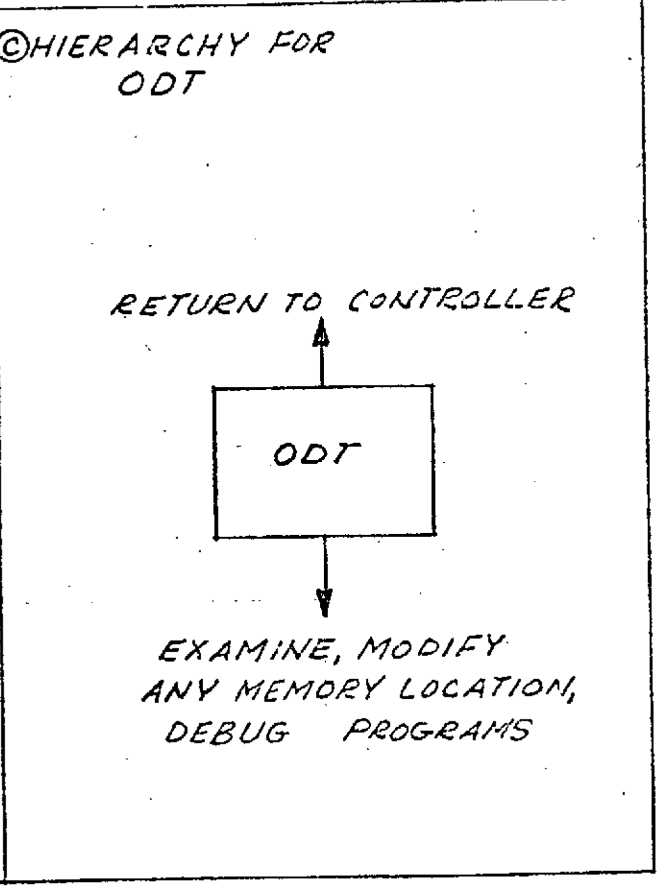
6.2 Program Hierarchy



A) HIERARCHY FOR CONTROLLER

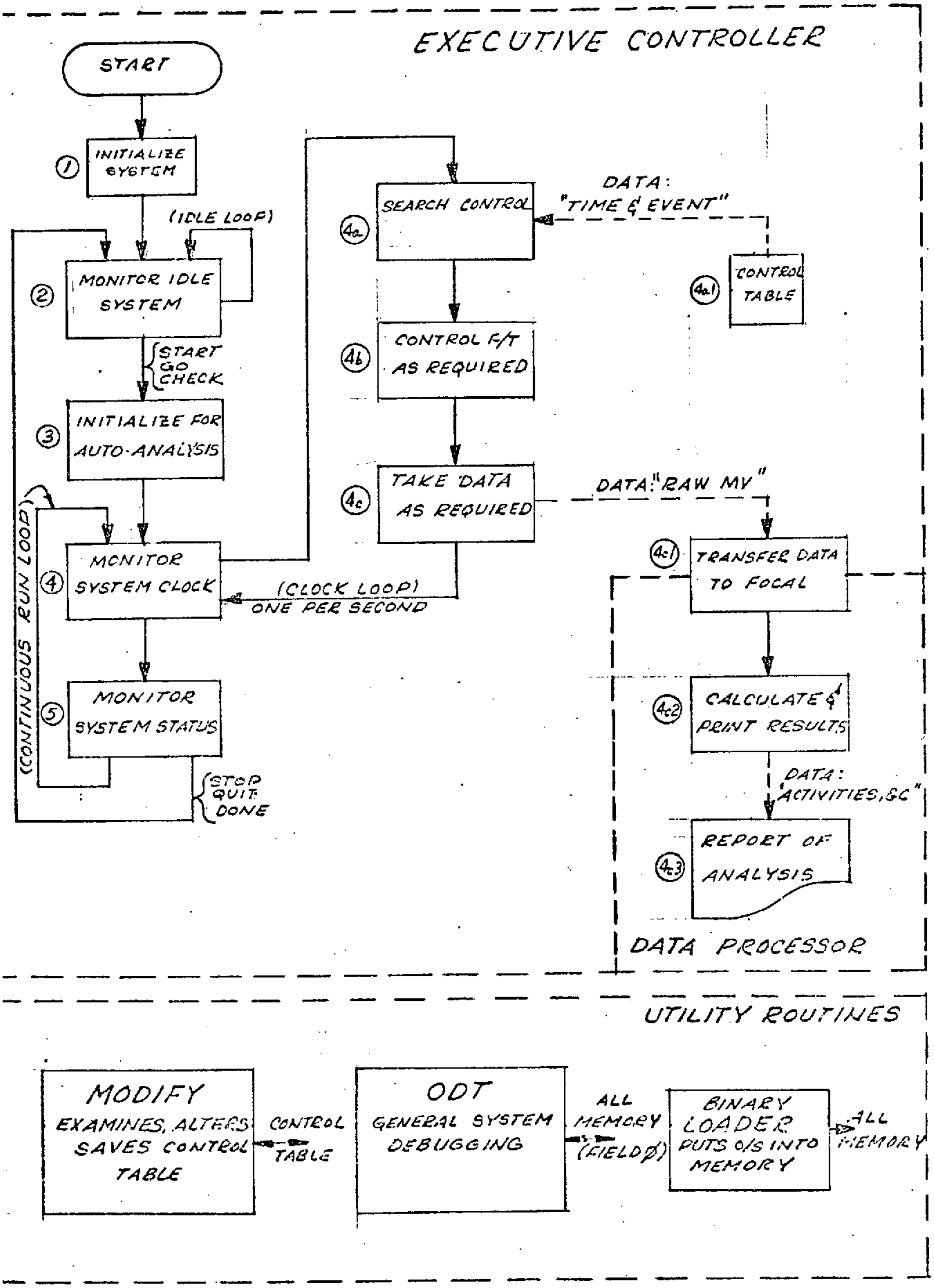


B) HIERARCHY FOR MODIFY



© HIERARCHY FOR ODT

6.3 Normal Operation of the System



the idle condition (2). The controller, while idle, continues to monitor the system. When the user requests an analysis (or check) the controller puts the system in condition for an analysis (3), and normally proceeds to monitor the 1 p.p.s. system clock signal coming from the E/U (4). If the clock pulse has not occured yet, or control just returned from the clock loop, the controller checks the status of the system, taking any appropriate action (5), then loops back (4) to check the clock again. This happens continually until the controller is told to stop [return to idle (2)], or finds the clock ready with a pulse. The accumulated time increases and the controller searches (4a) the control table (4a1) for every ''time/event'' pair whose time value is the same as the time accumulated by the clock loop. All the events for that second round in the table are turned into control information for the hardware (4b) and is sent to the E/U. Refer to the O/S listing and drawings 7862(E board multiplexer) and 7864 (H board, expander) for bit assignments. If a data transfer is required (4c), the raw millivolt data is read from the E/U, and given to the FOCAL program (4C1) via a special function, then the controller instructs FOCAL to perform the necessary data transformations (4c2) and, if appropriate, print the results (4C3). When it has a task, the data processor works independently of the controller while no other task requires attention.

When the last control table entry is found or if the user asks (via the E/U front panel, or the keyboard) to stop the analysis (5), the system returns to the idle condition.

6.7.2. FOCAL:

An adaptation of FOCAL* processes the data derived from the electrodes and temperature sensor, accepts information from the user about the standards used, and prints a report of the analysis in terms understandable to the clinician. The version used will run on all models of the processor, simplifying a possible change of processors.

The standard FOCAL (FOrmula CALculator) is a simple, small-scale, problem-oriented, algebraic programming language interpreter program (the name also applies to the language itself) similar to the FORTRAN, BASIC, or ALGOL languages, but operating in an on-line interactive dialoguing mode. It is easily learned and used by those familiar with any of these languages. It has

---

*trademark D.E.C.

just twelve basic commands, which allow editing, computations in a calculator mode, conservation of generation of programs (all in the ''direct'' or ''edit'' mode), and execution of programs previously defined (''indirect'' or ''run'' mode). Programs are defined in terms of line numbers, constants, variables, the twelve commands and fourteen predefined functions. These functions (which are brought into operation like subroutines) provide circular (trigonometric), logarithmic and exponential, square root, absolute value, sign value, integer value, random number, and other specialized operation.

Of the many modifications, the most apparent to the user is that the O/S calls FOCAL as one of its subroutines. FOCAL never enters the direct mode but stays in the indirect mode, executing a previously defined program stored in the ''text area'' of memory. Thus, in normal system operation, FOCAL is not available to the user, never entering the interactive mode. Other modifications changed details of core location, input and output format, and execution. The circular, random number, and specialized functions were eliminated. O/S functions were substituted, and the initialization interrupt, and error recovery routines were altered to be compatible with the O/S.

Among the many publications D.E.C. has published which describe FOCAL's operation, the most useful for an understanding of this application are:

> <u>Programming Languages 1972</u>. PDP-8 Handbook Series, volume 2.
>
> <u>FOCAL-8 Programming Manual</u>. DEC 08-AJAD-D.
>
> <u>Advanced FOCAL, Technical Specifications</u>. DEC-08-AJBB-DL.

and especially, part II, ''User defined functions for FOCAL-8'' in:

> <u>Change Notice to Programming Languages 1972</u>. DEC-08-LFCNA-C-DN1

which has the clearest explanation of user-functions, and:

> <u>Listing of FOCAL, 1969</u>, etc. DEC-08-AJAE-LA

Specific details can be examined by referring to the documents listed above and the program listing of the modifications.

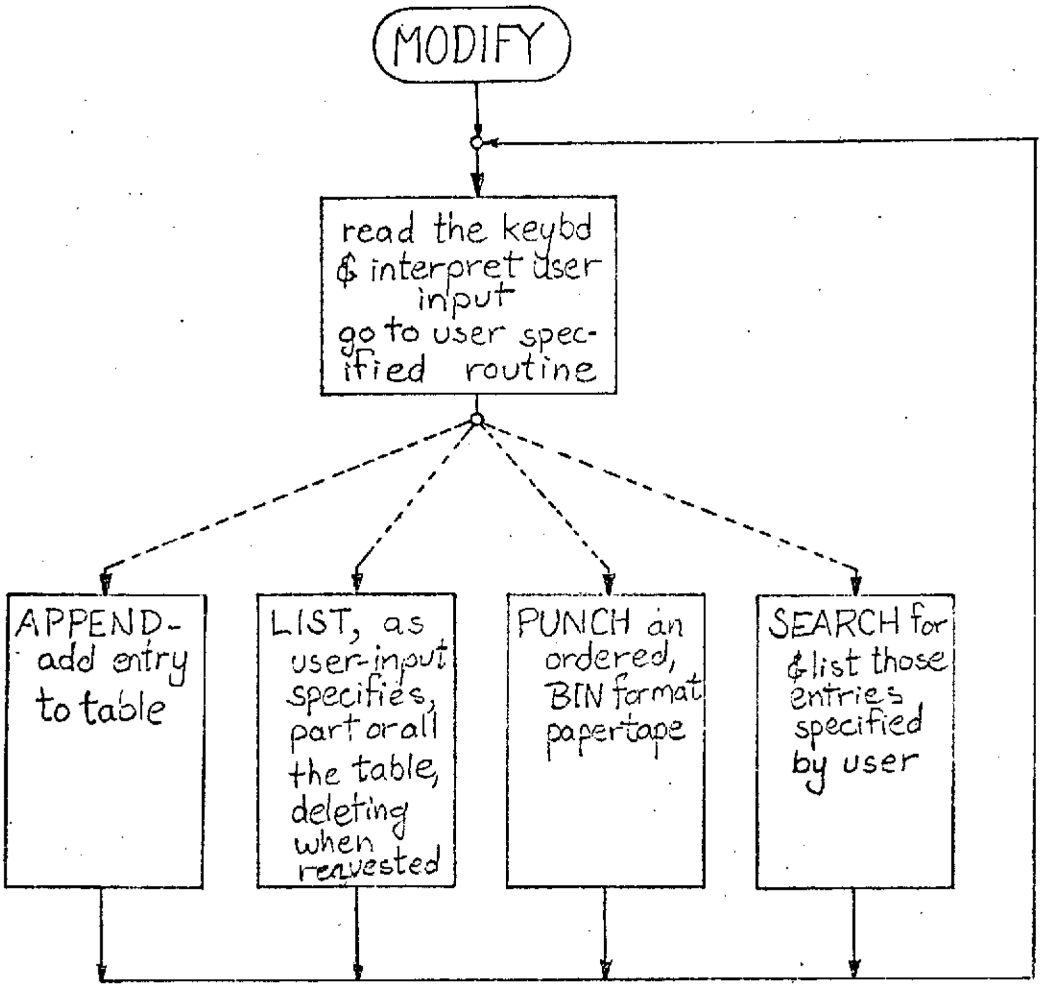
6.7.3. MODIFY:

The MODIFY program is the operating system (O/S) table editor. It is used for adding to, deleting from, reviewing, and punching binary-loader-format tapes of the control table, using decimal time values and symbolic, numeric, or combined octal values for control-codes (c-c's). It is designed similarly to the editing features of ODT (trademark D.E.C.). Refer to the simplified flowchart, Figure 6.4

A review of the format of the control table will help show the need for and use of MODIFY. The O/S controls auto-analysis by consulting a table containing c-c's associated with time. The table is actually a time-table, a schedule of events. Each entry has a time (indicated as a number of seconds after the beginning of the analysis) at which its associated c-c will be decoded in order to initiate, direct, or affect an operation of some component of the system.

The entry is stored in memory as a twelve bit binary value of time in an even numbered memory location, followed by a twelve bit binary c-c in the next higher (odd) numbered location. Manipulation of the contents of the table are facilitated if the time can be expressed in decimal notation (i.e., 129 = the 129th second instead of 0201_8 or 000010000001_2) and the c-c as a letter of the alphabet, as a mnemonic, followed by two octal digits (i.e., J34 = 1234_8). This is particularly appropriate for the c-c, because octal

6.4 A.P.E.A.S. Command Table Editor



notation corresponds closely to the hardware decoding process. Each letter has a value that is an integral multiple of 100_8, starting with A = 0100_8 and ending with Z = 3200_8; thus, J = 1200, J34 = 1234. The table is always ended with two consecutive locations set to zero. The physical order of the time/c-c pairs within the table is unimportant to the controller since it scans the entire table for the current time, entry-by-entry each second. Every entry for thet second is found and decoded when the controller is running an auto-analysis.

6.6.4. ODT

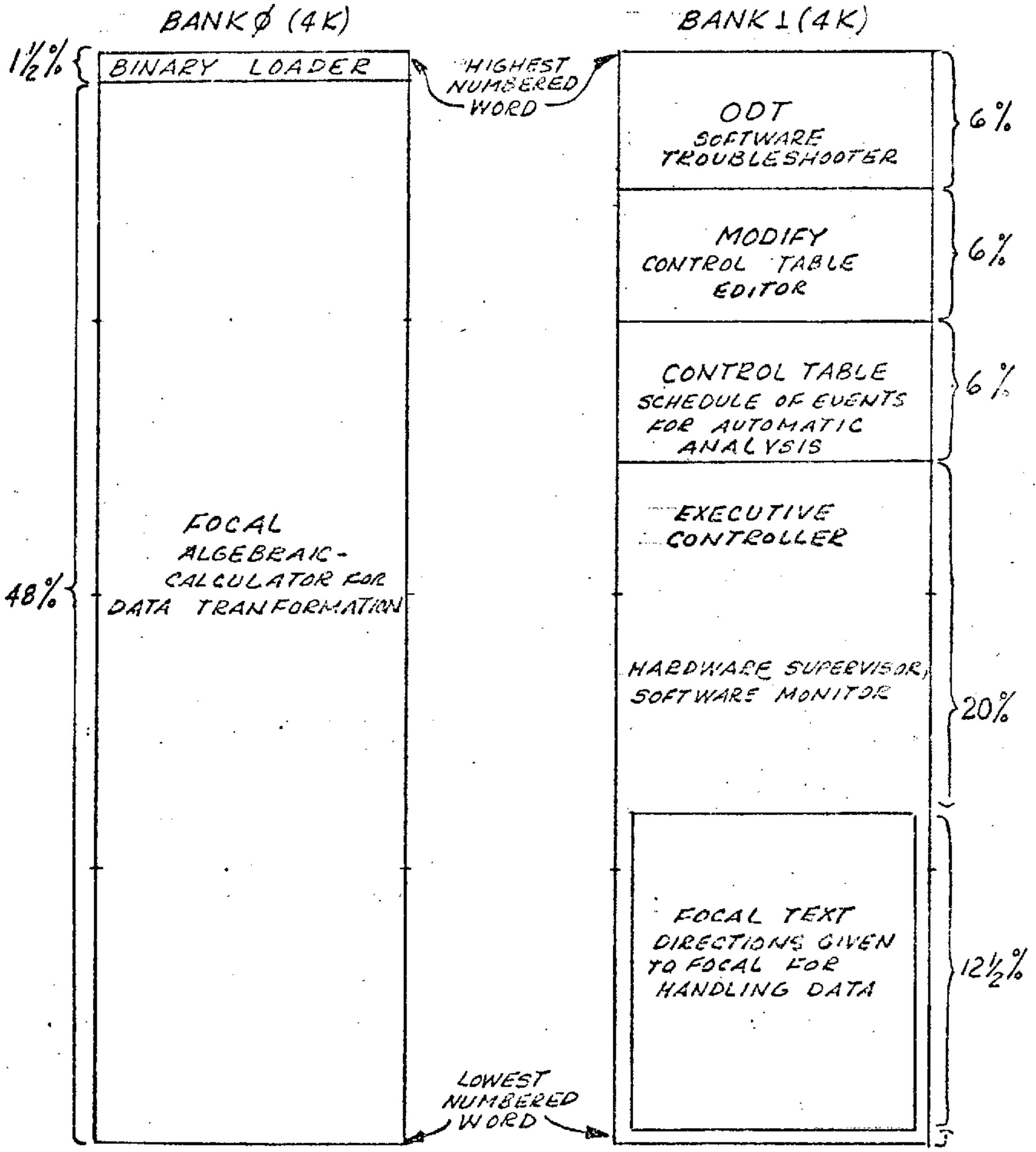
ODT is, as was previously explained, the program through which the user may examine or change any memory location (in field 1 only), trace the progress of another running program, and ascertain the state of the processor. It is short enough so that its operation is best understood by referring directly to the listing:

DEC-ODPA-LA.

6.8. Memory Allocation:

Figure 6.5. shows the amounts of memory that the O/S programs occupy. All memory is used.

6.5. Memory Allocation



Chapter VII

TEST RESULTS

7.1. Calculations

7.1.1. Sodium, Potassium, and Chloride Electrodes:

There are no significant interferences for these electrodes in the anticipated standards and samples for this system. Therefore the concentrations of these ions can be calculated directly from the Nernst equation.

7.1.2. pCO_2 Electrode

The pCO_2 electrode potential varies in a Nernstian manner with the partial pressure of carbon dioxide in the sample. The A.P.E.A.S. standards are independently assayed for pCO_2 at the system temperature. This allows one to substitute partial pressure of CO_2 for activity in the normal Nernst equation.

$$E = \text{Constant} + 2.3\,\frac{RT}{F}\log[pCO_2]$$

7.1.3. Calcium Electrodes:

Calculations for ionized and total calcium use a modified version of the Nernst equation which permits correction for the appreciable sodium error for this electrode.

This equation is:

$$E = \text{constant} + \frac{2.3RT}{2F}\log[Ca^{++} + k(Na^{+})^{2}]$$

where (Ca^{++}) and (Na^{+}) are the activities of calcium and sodium, respectively.

If the H^{+} error is found to be a significant interference for the total calcium electrode, it might be necessary to correct by the following equation:

$$E = \text{constant} + \frac{2.3RT}{2F}\log[(Ca^{++}) + k(Na^{+})^{2} + k(H^{+})^{2}]$$

7.2. Analytical Results:

In order to test system performance, an aqueous test mixture was prepared which contained all of the species in the physiological range. The composition of this test mixture is as follows:

Component	Ml/l
1 M NaCl	117.0
0.1 M KCl	40.0
0.1 M $CaCl_2$	20.0
1 M $NaHCO_3$	16.5
1 M HCl	42.5
1 M Tris	50.0

This mixture was stored in gas tight containers and assayed by the system under computer control. The results are summarized in table 7.1.

Table 7.1. Test Mixture Results (12 Runs)

Species	Expected	Found	Std. Dev.
Na^+	133.5 meq/l	131.5 meq/l	2.6 meq/l
K^+	4.0 meq/l	3.9 meq/l	0.1 meq/l
Ca^{++}	4.0 meq/l	4.0 meq/l	0.2 meq/l
Ca^{++}_T	4.0 meq/l	3.9 meq/l	0.2 meq/l
Cl^-	167.5 meq/l	166.3 meq/l	2.7 meq/l
pH	7.23	7.23	0.01
pCO_2	37.5 mm	37.9 mm Hg	0.9 mm

Although not required by the contract, the system was also tested for analytical performance on serum samples. The results of these tests are summarized in Table 7.2.

Table 7.2. Serum Results (6 runs)

Species	Expected	Found	Std. Dev.
Na^+	136 meq/l	131.2 meq/l	2.4 meq/l
K^+	4.4 meq/l	4.2 meq/l	0.1 meq/l
Cl^-	103 meq/l	104.2 meq/l	2.2 meq/l
$Ca^{++}{}_I$	4.2 meq/l	4.1 meq/l	0.2 meq/l
$Ca^{++}{}_T$	8.9 meq/l	8.7 meq/l	0.2 meq/l
pH	7.38	7.37	0.01
pCO_2	40 mm	40.3 mm	1.0 mm

7.3. Discussion:

The above results are representative of the system's performance as demonstrated to date. Analytical performance limits for the system as previously agreed on, for aqueous standards in the physiological range, are shown in Table 7.3.

Table 7.3.

Parameter	Precision (larger of two valves)
Na^+	±5% or ±1 meq/l
K^+	±5% or ±0.1 meq/l
Cl^-	±5% or ±1 meq/l
Ca^{++}_{Total}	±10% or ±0.1 meq/l
$Ca^{++}_{Ionized}$	±10% or ±0.1 meq/l
pH	±.01 pH
pCO_2	±5% or ±1 mm

The results of the system tests are well within system specifications for both aqueous controls and serum.

It should be emphasized at this point that system analytical performance represents a number of compromises with respect to constraints such as sample size, and fluid flow rates. If improved accuracy or precision is desired in any subsequent development of a similar system, one could expect to decrease the standard deviation of the individual electrode measurements by approximately fifty percent.

CHAPTER VIII

OPERATION AND MAINTENANCE

8.1. System Set-up

8.1.1. Fluid Transport Package:

1. The fluid transport package shown in system photograph (Figure 1.1.) should be removed from its packing crate, along with electrodes in their blue metal packaging boxes.

2. Remove the metal frame bag carriers, interconnection cables and spare hardware, packaged in blue cardboard cartons, from the packing box.

3. Uncrate the electronics unit.

4. Uncrate the D.E.C. PDP/8e computer and its associated teletype along with the electronic/computer interconnection cables (2).

5. Arrange the components on a bench working surface approximately as shown in Figure 1.1.

6. The fluid transport should be at a convenient height

to allow injection of samples into the injection port. Note: the electronics unit should not be placed on top of the fluid transport package.

7. Clean the surfaces of all sub-systems to ensure that all packing debris has been removed.

8. Remove cover from fluid transport.

9. Inside, remove cable ties from electrode connecting wires, and remove cassette tie downs on the pump.

10. Remove bag carriers from the standard bag containers.

11. Visually inspect the interior of the cabinet to assure all components are in place and securely fastened.

12. Open electrode set number 1. Note that each module is mechanically unique, by virtue of mounting pins in its base, and will fit only one position. (see Figure 4.9.

13. Install the pCO_2 electrode by first fastening the electrical connections to the rear of the module, V_R and TEMP CONTROL.

14. Install the electrode into the pin holes on mounting plate.

15. Install Na^+/K^+ module on the mounting plate, and fasten the ''T'' clamps on the module.

16. Install the Ca^{++}/Cl^- module, Ca^{++}/pH module, and fasten remaining ''T'' clamps.

17. Screw the electronic connecting cables into the appropriate connectors on the tops of the electrode modules. Note the alphanumeric code on top of modules and on the connecting cables

18. Install Fluid Ground Wire (black) onto the electrode terminals.

19. The next step is to connect the appropriate fluid lines to each electrode module.

20. These lines are indicated by numbers attached to each line.

21. Reference may also be made to Figure 4.1. Caution: these fittings are of relatively soft material, and care should be exercised not to ''cross-thread'' the fittings. Tighten each fitting finger-tight, then

tighten with 5/16'' open end wrench (supplied with) unit) until moderate resistance is felt. Do not overtighten!

22. After electrode fluid lines are connected, the standard bags should be attached to the bag carriers. The standard bag should be folded along its narrow seal edges , then placed on the carrier. The long seal is then rolled over the flange of the carrier at the connector end. A bag clamp (black plastic) is slid over the folded bag to retain the fold, see Figure 8.1. The same procedure is followed at the opposite end of the bag. Note that the standard bags have numerical labels, one series of (4) numbers makes one set. After all bags are on carriers, install each into its coded compartment.

23. Remove the needle covers from the four standard lines (12, 13, 14, 15). Insert each numbered line into the appropriate bag. Each fitting is a 1/4 turn ''luer-lok''.

24. Attach large silicone tube from manifold to waste bag via the 1/4 turn ''luer-lok'' fitting. Note the waste bag cap can be removed and placed in the waste pan under the waste bag.

25. Check the pump cassettes for tube alignment. The tubes should ride on top of rollers not in the grooves of the roller.

26. Pressing down on the six (6) cassettes, immediately bring saddle bar over the cassettes and position the bar so that each spring pin engages the appropriate cassette. Repeat for remaining four (4) cassettes.

27. Insert the waste pan with waste bag in place into its position, note that the pan will fit only in one direction. Fasten ¼ turn screws.

28. Replace fluid transport cover and fasten ¼ turn screws.

29. Prepare for sample injection by mounting 21 ga. x 1¼ in. ''Huber'' point needle to 2 cc syringe, supplied in parts kit. CAUTION: Do not use other than supplied needles. These needles are non-coring to prevent septum deterioration.

8.1.2. Electronics and Computer Set-up

8.1.2.1. Cable Connections:

Make the cable connections as listed below. Except where indicated, connectors are unique and keyed to prevent incorrect attachment.

1. Connect the large round-connector cable from the electronics unit (E/U) ''M'' to the fluid transport (F/T) ''J1''.

2. Connect the small round-connector cable from the E/U ''N'' to the F/T ''J2''. Check that all connectors in the F/T are securely attached.

3. Remove the cover from the computer (8/E) and attach the flat ''Berg'' connectors as follows. Caution: the D.E.C. connectors are not keyed to prevent incorrect or inverted attachment.
   Connect J1 of the flat cable marked R and J1 to the 8/E board ''M863'', J2 (pin ''A'' must be up).

4. Connect J2 of the flat cable marked S and J2 to the 8/E board ''M863'', J2 (pin ''A'' must be up).

5. Connect the ''Berg'' connector from the teletype to the 8/E board ''M8650'' connector (pin ''A'' must be up).

6. Route the cables along the power supply module to the rear of the 8/E. Check to see that all boards in the 8/E are securely plugged in. Replace the 8/E cover.

7. Plug the flat cable plug marked ''S'' into the E/U connector ''S'' (note which side is marked ''UP''– the connector is keyed to prevent inversion, but this is not obvious until fully inserted.)

8. Plug the remaining flat cable plug ''R'' into the E/U connector ''R'' as in Step 7.

9. Attach the E/U power cable to the E/U ''P''. Plug the other end into a 115 VAC receptacle on the rear of the 8/E.

10. Plug the teletype power cord into the other 115 VAC receptacle on the 8/E.

11. Be certain that the E/U power switch, 8/E key switch, and teletype switch are in the ''OFF'' positions. Connect the 8/E power cord to a suitable grounded 115 v. 60Hz power source, of at least 15 AMP capacity.

8.1.2.2. Initial Turn On

1. Turn the computer on with the front panel keyswitch. The cooling fans should be heard, although no lights will be on. If there is no response, check the circuit breaker on the rear of the 8/E and the power source.

2. Turn the teletype to ''LINE''. The teletype motor should start.

3. Open the control cover on the E/U and set all

switches for automatic operation (the position identified by the green rectangle.)

4. Assuming that the F/T is fully prepared, turn the E/U power switch on. Observe the following indicator states -

    ''Main valve - REV & FWD'' off (''SET'' may be on)

    ''FLUSH'' off

    ''AIR'' off

    ''PUMP-ON'' off

    ''MIXER'' off

    ''THERM-FAIL'' off

    ''THERM-NORM'' on steadily

    ''AUX'' off

    ''LO-TEMP-HI'' both off

    ''CLOCK-1PPS'' flashing (once/sec,)

The valve position should not be changing, the electrode channel should read 8, and the data display will indicate temperature. The temperature should be at ambient (nominally 25,00 - ignore the display decimal point), and rising due to the heater.

If the ''MANUAL MODE'' indicator is on, check the setting of all switches. Sequence status indicators (''STD B'',etc.) will be off.

8.1.2.3. Program Loading

Operation of the PDP-8/E computer is fully covered in the ''Small Computer Handbook'' supplied with the 8/E. The following instructions are intended as a reminder of the necessary steps. It is assumed that the D.E.C. binary loader is in memory field 0 (if not, consult the above handbook).

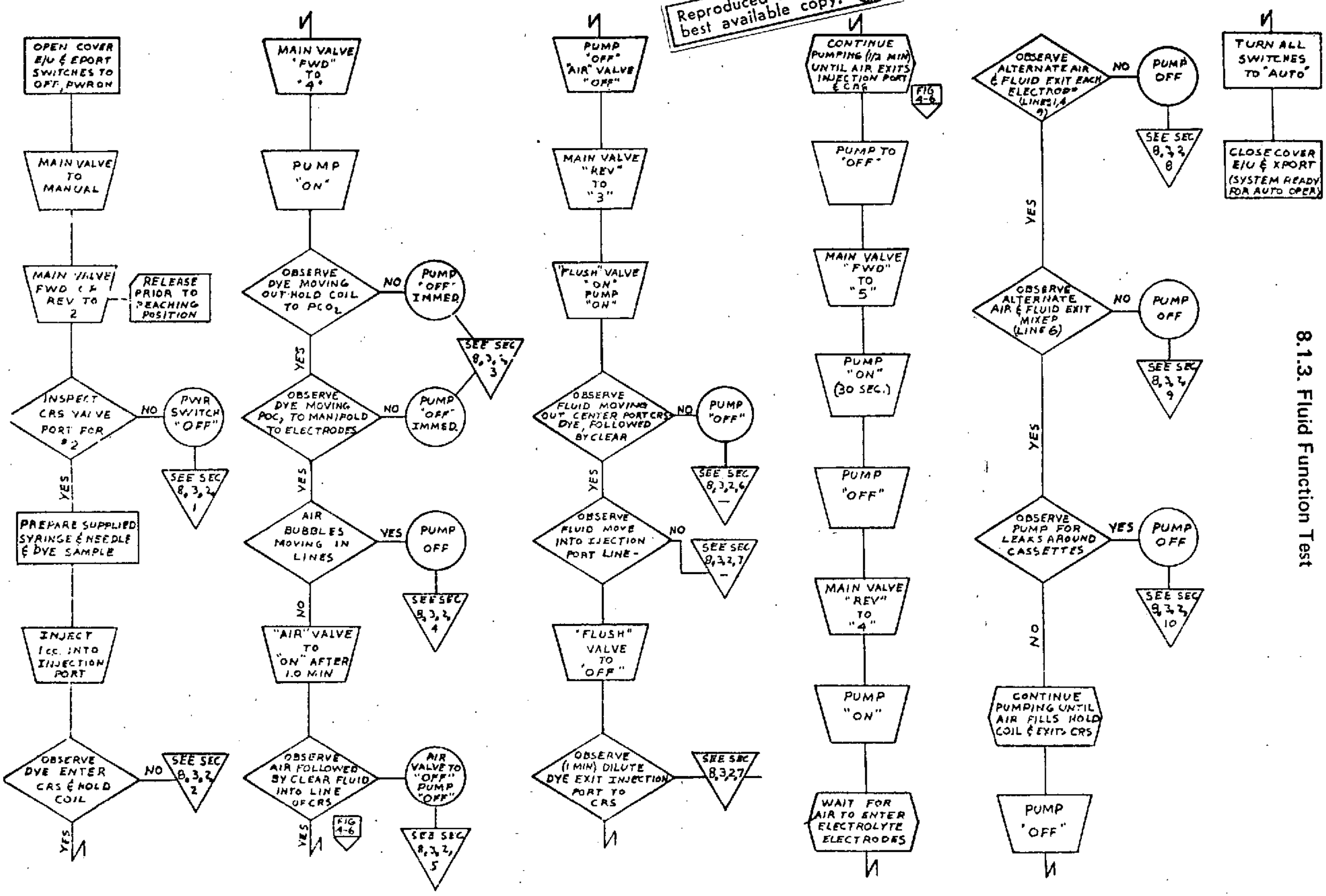
1. Put the A.P.E.A.S. operating system tape in the teletype reader (arrow on top, pointing forward), leader (channel 8 punched) over reading system).

2. Set the 8/E switch register bits 0 thru 11 all up (address 7777 octal).

3. In sequence, push ''ADDR LOAD'', ''CLEAR'', and ''CONT''. The tape should read in.

4. When the reader stops, observe that all lights are out on the 8/E lower display register when set to ''AC'' (Accumulator = 0000). If this display is not zero, the program did not load correctly.

8.1.3. Fluid Function Test



8.2. System Operation

8.2.1. System Starting-

1. Turn system power on in the sequence: PDP-8/E, teletype, and Electronics Unit. (the shut-down procedure is the reverse of this.)

2. Set only bit 4 of the 8/E switch register up (address 0200).

3. In sequence, push ''ADDR LOAD'', ''CLEAR'', and ''CONT''.

4. The teletype will respond by asking if the user wishes to change the standard solution values. The user may type ''NO'', or ''YES'' and enter new values. To allow new values to be entered, the computer will type each parameter and the currently stored value, stopping to permit modification. The user may enter a new value followed by the ''RETURN'' key; or he may press the ''ALT MODE'' key to leave the value unchanged.

At this point the system is completely operational. Observe the same E/U displays as described in the setup section - initial turn on -

Step 4; except as follows:

The main valve must be in position 1

The main valve ''SET'' must be on

Temp ''LO'' indicator should be on (until the system warms up).

5. Wait for system warm up. This requires about one half hour if the system was not recently in use. When the correct temperature is reached, temp ''LO'' will go off and the ''READY'' indicator will come on.

8.2.2. Operating Controls

The only control necessary for normal operation is the ''START'' button on the E/U. This control is pushed to initiate an analysis, and pushed again after sample injection to resume automatic operation Simply:

1. Push ''START''
2. Wait for ''INJECT'' indication
3. Push ''START'' after injecting sample
4. Wait approximately 10 minutes for analysis and typeout
5. The ''READY'' indicator will show when the system is ready to be restarted.

A ''CHECK'' control is provided to allow checking system performance without injecting a sample. The check function is an automatic sequence which types actual electrode potentials and slopes for the ''A'' and ''B'' standards.

Once ''START'' or ''CHECK'' is activated, the other control has no effect. A ''STOP'' control is provided to prematurely terminate either sequence. This action will return the system directly to the ready state, except after a sample injection in the analysis sequence. In this latter case, no analysis will be typed, but the user must wait the balance of the 10 minute period for system cleanout.

Prior to the actual start of either automatic sequence a system status check is performed. If any control is set for manual operation, or if the electrode temperature is incorrect, an appropriate error message is typed. The system will wait indefinitely, giving the user opportunity to correct the condition. However, if the user pushes ''START'' (or ''CHECK'') as the case may be) the sequence will commence, regardless of corrective action.

The teletype keyboard duplicates these controls and provides some additional options. When the system is turned on the teletype is placed in an echo mode, allowing the user to type any general alpha-numeric labels he may desire. By holding the ‘‘CTRL’’ key down and typing ‘‘C’’ (referred to as ‘‘CTRL-C’’), the teletype bell will ring and the keyboard will be shifted to command mode. Typing a key listed below executes the command (typing any other key has no effect.)

‘‘G’’ = GO (same as ‘‘START’’ button)
‘‘C’’ = CHECK (same as ‘‘CHECK’’ button)
‘‘Q’’ = QUIT (same as ‘‘STOP’’ button)
‘‘R’’ = RAW DATA (analysis, but with continuous MV.X2 output)
‘‘M’’ = MODIFY (control table modification routine)
‘‘O’’ = ODT (debugging routine)
‘‘CTRL-F’’ = FOCAL (command mode)
‘‘CTRL-L’’ = Return to Echo Mode

These additional functions are not normally used but are convenient when making changes or performing system tests. The raw data command prepares the analysis sequence to be identical to the normal analysis except raw ADC data will be typed instead of calculated activities, when the sequence is started. Start ans Stop points for this typeout are set by the control table as described later. After sample injection, ''START'' or ''G'' must be used to make this sequence continue. At the end of any automatic sequence the teletype returns to the echo mode.

The modify routine is a service program used to alter the system control table. Its operation is summarized at the end of the section.

ODT is a D.E.C. octal debugging program which is provided to facilitate program changes in memory Field 1. The operation of ODT is fully ocvered in ''Introduction to Programming, 1972'', published by D.E.C.. To return to the main program from ODT control, simply type ''G''.

FOCAL can be used in its command mode only by typing ''CTRL-F'' from the controller's command mode. Consult ''Programming Languages, 1972'', published by D.E.C. for its standard operations. Return from FOCAL to echo-mode by typing ''G 1.2 carriage return'', or simply ''G cariagereturn'', then answering the subsequent request to change activities with ''NO carriagereturn''. The user is warned that the proper operation of the system, is in part, dependent on the interaction of the FOCAL text and initial FOCAL variable values as provided on the system tapes. Modification of the text or variables may prevent subsequent normal system operation.

8.2.3. Special Controls

An auxiliary display and control panel is provided behind a door on the E/U. This panel allows the user to continuously monitor system device operation, and take over manual control, if desired, for system testing. Although safety interlocks prevent system damage if these controls are incorrectly used, automatic analysis data may be meaningless.

8.2.4. System Shutdown

The operator is cautioned not to shut the system down with non-aqueous samples in the electrodes. The system will be properly flushed by all automatic sequence if allowed to go to completion. For manual operation, the responsibility is on the user. Normal shutdown procedure is as follows:

1. Allow analysis check, or stop sequence to be completed. (The ''READY'' light should be on).
2. Push ''HALT'' on the 8/E, and return to the up position.
3. Turn the E/U power off.
4. Turn the computer off with the key switch. The teletype switch may be left on ''LINE''.

8.2.5. Control Table Modification

All system control originates from two control tables. The main table contains all sequencing commands for the sample analysis, normal or raw data operating modes. The second table controls the ''CHECK'' sequence. Commands are discussed in the format:

135 TIME (seconds)
P 1 COMMAND (pump on)

The command code consists of a device (P = pump) and an action (1 = turn on). This event will occur at the 135'th second. The computer software actually stores the above example in the format:

0207 TIME (octal seconds)
2001 COMMAND (control code)

The modify routine allows listing, searching, and changing the table in the first, simpler format. A description follows.

In general, the user input format that MODIFY requires, is a decimal time followed by a command letter followed by an octal c-c expressed symbolically and/or numerically followed by ↳ to indicate the end of input for that line. Since the meaning of the input character is derived according to its context, valid characters, provided they are in the correct position in the line, may include: decimal 0 - 9; commands A (append), L (list), P (punch), S (search); octal A - Z (symbolic) and/or 0 - 7 (numeric). Spaces are not interpreted by MODIFY, but they are echoed, allowing free formatting using them. Leading zeroes, decimals, or octal, are ignored.

Characters that are not valid at the point where they are typed in are echoed, then the error recovery sequence is entered.[3] As there is no provision to ''erase'' a mistyped character, purposely typing an invalid character, such as ''/'' or ''3'' will cancel[3] the line with the mistyped character in it.

Input characters at the beginning of a line are interpreted as a decimal. They represent the second with which the numeric/symbolic octal c-c will be associated. Only the numeric characters 0 - 9, values 1 - 999 are valid at this point. Larger values cause an error.[3] The decimal portion of the input line is always terminated by the command letters A,L,P,or S. The decimal portion may be ''empty'' (none or 0) for L and S, and is treated as empty (i.e. ignored) for P. The actions caused by these codes will be described later. The command letter is always acknowledged by the typeout of its echo followed by a space. The typing of P or L commands automatically terminates the line, no P is needed. In all other cases the input following the command letter will be interpreted as a numeric/symbolic octal c-c. At this point the octal characters 0 - 7 and letters

A - Z are valid.[4] Meaningful formats are up to four octal digits[5] or a letter followed by one or two octal digits[7] B is interpreted as B00, B3 is interpreted as B03 , et cetera. The c-c (and that line) is terminated by ↲.

The command A stands for append or add to the table. The time/c-c pair is placed in the first unused (rubbed out) location in the table. If there are none, it is placed at the end of the table. In this way the length of the modified table is kept to a minimum. A^2 or A followed by a c-c followed by ↲ are errors; the time valve must be greater than zero. 12A would enter the time/c-c pair, 12_{10} 0000_8 into the table, but zero (@00) is an illegal c-c.[4,5] All other valid combinations using A are accepted by MODIFY.[4,5]

The command L stands for list. L is never followed by a c-c because it automatically terminates the line and starts printing out, one entry per line, the entries for the time specified, or the whole table if the time is empty. In the latter case, the entire table is listed without pause, while in the former case, where a time is given the time/c-c pairs are printed one line at a time with a pause at the end of each line. The pause allows the user to type↵, approving and saving that entry, or r.o.[2], deleting that entry from the table (and marking that position in the table ''available''). If there are no entries for a time specified to be listed, there is no printout, only a carriage return followed by two linefeeds. Regardless of how the c-c's are expressed when entered, all entries are printed as an indented decimal time, followed by a space, followed by a letter,[4] followed by two numerals.

The command P stands for punch; it ignores the time, if any, that proceeds it and halts the processor to let the user turn on the teletype[6] punch. The user then depresses the processor '' ''CONTINUE'' switch. The whole table is punched in binary loader format, then the processor is halted to remind the user to turn off the punch. When ''CONTINUE'' is depressed, MODIFY is ready for another line of input. When the O/S software is initially loaded into memory, it includes an original control table. Since the latest table loaded is used for auto-analysis, the user needs a method to save modified and rewritten tables. If the O/S software ever needs tp be reloaded after the user has modified the control table, or if he regularly uses more than one control table, it would be much simpler to load the modified control table ''on top of''(overwriting) the original control table, rather than having to reperform the whole modification procedure. With the use of the P command, control tables can be written and saved. The user should be aware that any major modification to the control table must be co-ordinated with the ''ABORT'' table.

The command S stands for search, a very flexible command. It causes the table to be searched for entries under the time specified and lists all time/c-c pairs that match the specified c-c. If no c-c is given, i.e. 15S all entries at that time will be listed. Note that this is almost the same action as 15L (no ↩ required) but the listing due to ''L'' pauses at the end of each line for an O.K. or VETO(↩or r.o.), whereas, the listing due to ''S'' will run until all entries for that second are printed. For all the conditions above if the S is followed by a single letter (symbol),that character is used as a ''partial mask'', all entries for that second containing that symbol in the c-c will be listed. If the S is followed by a letter and any numerals or only one or more numerals, only those entries exactly corresponding to the input line will be listed.

LISTING 1.

```
L
    1 J34
    2 B00
    3 C00
    3 C77
    3 D45
    4 D01
    4 D03
    4 C77
    8 @45
    9 J34
    9 J36
   10 J34

11A 1↵
11A 102↵
11    A     B     ↵
        0000011        A       000003   12 ↵
   1  1    A       1   2   3   4   ↵
11L
   11  @01↵
   11  A02↵
   11  B00\
   11  C12\
   11  J34↵

11A B09?
↵
11S↵
   11  @01
   11  A02
   11  J34

11S J34↵
   11  J34

S J34↵
    1  J34
    9  J34
   10  J34
   11  J34

S J↵
    1  J34
    9  J34
    9  J36
   10  J34
   11  J34

3S C↵
    3  C00
    3  C77

4S C↵
    4  C77
```

```
L
    1 J34
    2 B00
    3 C00
    3 C77
    3 D45
    4 D01
    4 D03
    4 C77
    8 @45
    9 J34
    9 J36
   10 J34
   11 @01
   11 A02
   11 J34

P
```

↵ =return key

The following example referring to listing 1 illustrates the use of MODIFY. The underlined characters were typed by the user. The rest of the typeout was done by the MODIFY program. First compare those places where the user needs to terminate the line with↵, lines 15 - 19, 29, 34, etc., to those where the termination is automatic, lines 1, 20, 27, 56. Next, examine a typical user session.

While the O/S was running in the ''idle'' (CTRL-C) mode the user first typed M, initializing the MODIFY program, then typed L (line 1) getting a c complete listing of the control table at that time. In lines 15 - 19, he appended some c-c's to the table at second eleven. Compare these to lines 21 - 25. The formatting with spaces and zeroes is completely free. Carried too far, it could even be confusing. Comparing lines 2 - 13 with lines 21 - 25 shows that alone, L lists the whole table, while a time specified before L lists only time/c-c pairs that are the same time as the time specified, and waits at the end of each line listed for the↵ or r.o. Lines 23 and 24 have been deleted. At line 29 the user asks to review all entries for the eleventh second, without having to ''approve'' each line. 11S does this, listing all entries for the eleventh second without pauses. Line 30 corresponds to line 21 (approved) which was entered at line 15. Notice that its octal valve 0001 is listed as @01.[2] The same correspondence holds in lines 31, 22, 16, and lines 32, 25, 19. (A = 0100, C = 0300, J = 1200). Lines 23, entered at 17 and 24, entered at 18, having been ''vetoed'' with the r.o. key, are no longer in the table.

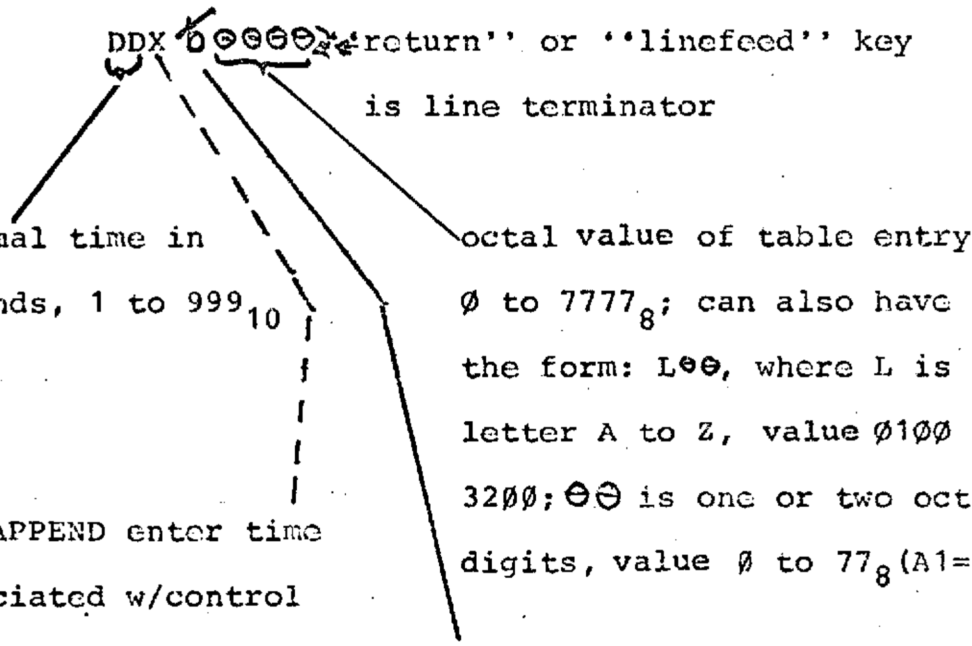
Line 27 is in error because 9 in the c-c position is not a legal octal numeral. The error in the line following is due to the user's typing ↩ which is not valid in this context. We have seen the effect of a time followed by S at line 29. Compare it with line 34, looking for J34 (1234_8) only. Line 37 looks for J34 anywhere in the table. Line 43 looks for ''J'' entries. Line 30 looks for all ''C'' entries at second 3. Line 54 looks for all ''C'' entries at second 4. The user reviewed the whole table at line 56 (S would have exactly the same effect) and punches a binary tape, illustrated on page 2 of listing 1, at line 73. The user may now type control-C to go back to the O/S idle condition or control-L to go to the echo mode for labelling or commenting the listing.

MODIFY

CONCISE COMMAND SUMMARY

TABLEPOINTER: Octal Loc. XXXX

GENERAL FORMAT FOR USER INPUT:



DDX 0⊖⊖⊖⊖↵ ‘‘return’’ or ‘‘linefeed’’ key is line terminator

decimal time in seconds, 1 to 999_{10}

octal value of table entry, 0 to 7777_8; can also have the form: L⊖⊖, where L is a letter A to Z, value 0100 to 3200; ⊖⊖ is one or two octal digits, value 0 to 77_8 (A1=A0101

A = APPEND enter time associated w/control code into table

command typein is always acknowledged by a space typeout

L = LIST (auto ‘‘return’’) prints all control-code entries associated with that time. Waits at end of each line for ‘‘↵’’ meaning ‘‘keep this entry’; or for ‘‘rubout’ (echoed as ‘‘\’’) meaning ‘‘delete this line.’’ ‘‘0L’’ or just ‘‘L’’ lists whole table. P=PUNCH (auto ‘return’) halt processor for punch-turn on. Depressing ‘‘CONTINUE’’ switch starts punching of binary tape of table. At end of punching processor halts to remind user to turn punch off.

S=SEARCH searches the entries for the specified second (or whole table if second is = 0 or blank) for the specified control-code entry. (See MODIFY routine description and example for more detail.)

NOTES

TO SECTION 8.2.5.

1. Trademark of Digital Equipment Corporation.

2. Throughout,↵ means ''return''key or ''linefeed'' key. Their effect is equivalent, either one causing a carriage return and linefeed. The ''rubout'' key is represented by r.o. It is echoed with the backslash character, ''\\''.

3. This action generates the error recovery sequence. The message ''?'', carriage return, linefeed is typed. MODIFY ignores the previous line input and is ready to accept a new line.

4. @, [,\\ ,], ↑ will also be accepted as actual symbols. As with letters their valves are multiples of 100_8, being 0000, 3300, 3400, 3500, and 3600, respectively. Although MODIFY accepts these inputs, the first is superfluous (@23 = 23 = 0023_8, in listings, leading zeroes are printed as @), and the other four are illegal c-c's to the O/S, generating system error message when an auto analysis is run. The O/S only recognizes c-c 0100 - 3200_8, and even within this range some code combinations are not defined.

5. It is possible to enter any value up to 7777_8 using numeric octal input to MODIFY. The same warnings as in note 4 apply.

6. Trademark Teletype Corporation.

7. A peculiarity of the structure of MODIFY is that during c-c input, if only octal numerals have been entered and no symbol has been input previously, inputting a symbol replaces the internal c-c field with its own value. Thus, 12A 7654C33E results in a c-c of u.c. 33, whereas, 12A followed by anything sililar to these: CD or C12D or 7654C33E, et cetera, all cause errors.

ANALYSIS TABLE

```
L
  1 D20     185 R57     335 R57     515 R51
  1 T01     190 R52     340 D21     520 R56
  1 V04     195 R52     355 R00     525 R55
  6 M01     200 R56     370 R55     530 R56
  6 P01     205 R56     375 R55     535 R52
 21 P00     210 R56     380 R56     540 R52
 22 V12     215 P00     385 R56     545 R52
 23 M00     215 R00     390 R56     550 R55
 25 D10     216 V05     395 R51     555 R55
 25 T02     219 P01     400 R51     570 R54
 25 V00     222 J01     405 R54     575 R54
 26 D60     223 P00     409 J02     595 J00
 26 T03     223 V14     410 R54     600 B00
 26 V05     225 P01     415 R52     601 D20
 31 M01     240 R55     420 R53     602 F10
 31 P01     245 R55     425 R52     602 M00
 34 I01     250 R51     460 D22     602 P00
 35 P00     255 R51     470 F01     602 V01
 35 V13     270 R54     475 R00     604 T24
 38 P01     275 R54     490 R57     605 Q00
 40 B01     295 R53     495 R57
 96 I00     300 R53     500 R53
175 F03     320 F02     505 R53
180 R57     330 R57     510 R51
```

CONTROL TABLE – COMMAND SUMMARY

```
B 0    RAW DATA OFF SWITCH
B 1    RAW DATA ON SWITCH
       (RECOGNIZED ONLY IN THE RAW DATA MODE)

D 1    DISPLAY "SAMPLE"
D 2    DISPLAY "STD A"
D 4    DISPLAY "DATA" (VALID)
D 10   DISPLAY "INJECT"
D 20   DISPLAY "RUN"
D 40   DISPLAY "STD B"
       (THESE COMMANDS MAY BE COMBINED BY ADDING CODES.)

F 1    AVERAGE AND STORE "STD A" VALUES (FOCAL COMMAND)
F 2    AVE. AND STORE "SAMPLE" VALUES
F 3    AVE. AND STORE "STD B" VALUES
F 4    RUN TEMP. HI/LO TEST (FOR E/U DISPLAY)
F 5    PRINT ELECTRODE TEMPERATURE
F 6    AVE. TEMP. AND PRINT
F 10   CALCULATE AND PRINT ANALYSIS RESULTS
F 11   CALCULATE ELECTRODE SLOPES AND PRINT (INCL. MV.)

I 0    FLUSH VALVE OFF
I 1    FLUSH VALVE ON

J 0    AIR VALVE OFF
J 1    AIR VALVE ON

M 0    MIXER OFF
M 1    MIXER ON

P 0    PUMP OFF
P 1    PUMP ON

Q      QUIT (END OF SEQUENCE)

R 0    READ ELECTRODE CH. 8 (TRANSFER DATA TO FOCAL)
R 1    READ CH. 1
R 2    READ CH. 2
R 3    READ CH. 3
R 4    READ CH. 4
R 5    READ CH. 5
R 6    READ CH. 6
R 7    READ CH. 7
       (ADD "20" TO ANY CODE TO PRINT MILLIVOLTS DIRECTLY)

T X    (REFER TO PROGRAM LISTING FOR MESSAGE TYPEOUTS)

V 1    RUN MAIN VALVE FORWARD TO POSITION 1
V 2    FWD. TO POS. 2
V 3    FWD. TO POS. 3
V 4    FWD. TO POS. 4
V 5    FWD. TO POS. 6
V 6    FWD. TO POS. 6
       (TO RUN REVERSE, ADD "10" TO ANY CODE.)

W      WAIT (STOPS CLOCK TO ALLOW SAMPLE INJECTION.)
```

8.2.6. Use of Focal

8.2.6.1. Focal Modification -

Changes to the Focal data processing program should seldom be required. If they are note the following:

As Focal never enters its direct (* or command Mode) in normal system operation, except as noted in section 8.2.2, it is unavailable to the system user. However, ans to any questions concerning its standard use can be found

''Programming Languages 1972.'', PDP-8 Handbook Series, Vol.2. available from Digital Equipment Corp., Maynard, Mass.

''Listing of FOCAL, 1969, etc.''
DEC-08-AJAE-LA

'' APEAS Focal Data Processing Package''
part of Orion Research listings

8.3. Maintenance and Troubleshooting

8.3.1. Maintenance

8.3.1.1. Fluid Container Replacement

After approximately every 100 cycles the fluid system (standards, KCl, reagent) must be replenished. The waste bag container must also be replaced at this time. The fluid bags are packaged in sets in the fluids shipping container.

To replace the fluid system:

1. Turn power ''off'' on the electronics unit.

2. Remove the cover of fluid transport package, by turning counterclockwise the six (6) cover fasteners.

3. Remove waste bag line by ¼ turn (CCW) the ''luer-lok'' fitting.

4. Place the waste bag cap on the waste bag fitting and clockwise lock.

5. Remove and dispose of waste bag.

6. Remove waste pan from package by unlocking six (6) fasteners.

7. Remove the four (4) needle connectors.

8. Remove the four standard bags and carriers.

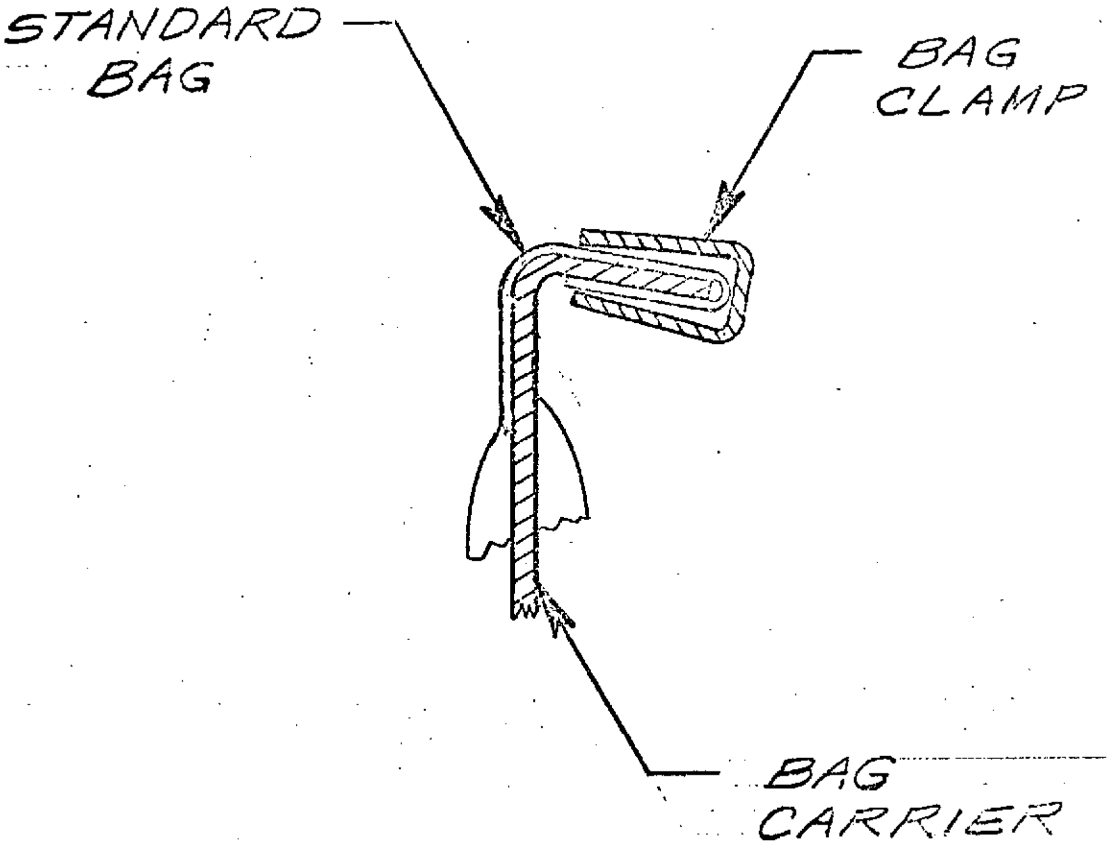
9. Remove the bag clamps from each end of the bag carriers.

10. Remove bags from carriers and dispose of them.

11. To mount new standards bags first fold the bag along the narrow seal edges then place on the carrier. The long seal is then rolled over the flange of the carrier at the connector end. A bag clamp is slid over the folded bag to retain the fold (see Figure 3.1). The same procedure is followed at the opposite end of the bag. Repeat the procedure for each of the remaining three (3) bags.

12. Replace the numbered bags on carriers and into their respective compartments.

8.1. Standard bag assembly



13. Replace needle connectors into the appropriate fluid bag and lock.

14. Replace waste pan into the fluid package.

15. Place a new waste bag into the pan.

16. Remove the waste bag fitting cap and place in the waste pan.

17. Attach the waste outlet line to the waste bag and lock with ¼ turn (C.W.).

18. Replace the fluid package cover and lock in place.

8.3.1.2. Septum Replacement, Injection Port

In conjunction with the fluid system replacement, the septum of the injection port must be replaced.

To remove the septum, unscrew the injection port cap at the front of the fluid transport package. Remove and dispose of the white silicone septum from the injection port. Using a new septum from the spares replacement package, insert a new septum into the injection port.

Replace the injection port cap on the injection port and tighten (CW) the cap until it bottoms on the threads.

8 .3.1.3. Pump Tube Replacement

The pump tubing for the peristaltic pump is a long lasting silicone compound. If proper care is used when the pump tubing is clamped by the cassettes, replacement should be required only after approximately 3000 cycles of operation.

To replace the pump tubing:

1. Turn power off on the electronics unit.

2. Unlock the six (6) fasteners on the fluid transport package cover and remove.

3. Remove the waste pan with waste bag attached.

4. Release the two (2) saddles of the pump.

5. Using socket tool supplied, unscrew each of the six (6) tube fittings going into the waste manifold directly between the pump and the standards container.

14. Spare pump tubes with proper number designation are packaged in the spare parts package.

15. Place the new tubes into the cassettes by snapping the tube holders into the slots on each cassette end.

16. Place waste tubes and cassettes lines number 20, 21, 11,13, 24, and 25 in the pump.

17. Connect the fittings from these lines to the waste manifold and to the components.

18. Install lines 2, 7, 10, and 12 in the cassettes. Re the component end fitting and ferrule.

19. Place the three (3) KCl lines (2, 7, 10) around and under the pump cage.

20. Run the lines under the manifold and to each electrode module.

21. Replace the tube fitting and ferrule using the tool shown in Figure 8.2

22. Screw fittings into appropriate electrode module. Tighten fittings with the 5/16 under open end

wrench supplied. CAUTION: fittings are of soft plastic. Do not cross thread, do not overtighten.

23. To install line 12,remove both end fittings and ferrules. Wrap pump tube around the pump roller cage so that the longer end of the tube comes from the acid reagent bag under the pivot bar to the cassette. The shorter end (pump outlet) goes from the cassette, around the roller cage and under the pivot bar to the mixer.

24. Insert the tube fittings and ferrules.

25. Screw the needle connector for the acid reagent into the inlet tube end.

26. Screw the outlet tube end into the mixer body and tighten the fittings using the 5/16 open end wrench.

27. Check that all connections are made and tightened, check that each cassette and tube are aligned on the pump rollers, and clamp the cassettes with the two (2) saddles.

8.3.1.4. Electrode Replacement

Electrode performance should be tested weekly or after extended periods of shut down. These checks are facilitated by using the ''CHECK'' mode described in section 8.2. In addition, if during fluid function testing an air leak is determined to be in the module, the module should be replaced.

Once the defective module is identified, the electrical and fluid connections must be removed. The ''T'' clamps on the electrode mounting base are released and the module can then be removed.

Spare electrode modules have been supplied in blue metal packing boxes.

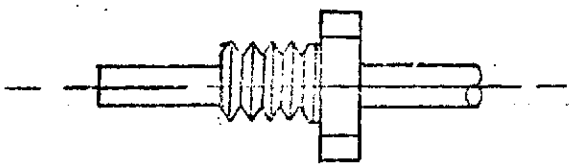
1. Choose the appropriately marked module and remove the fluid plugs.

2. Install the fluid input connectors from the removed module.

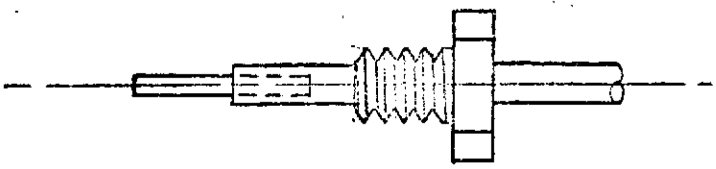
3. Replace the new module and connect its electrical and fluid connectors. Refer to the fluid function test chart (8.1.3.) to debug the fluid system with the new module.

8.2. Fitting Assembly – 1/32 pumpline

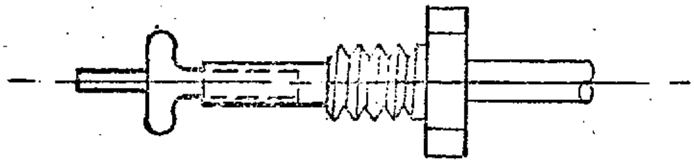
1. SLIP TUBE FITTING ON TUBE.



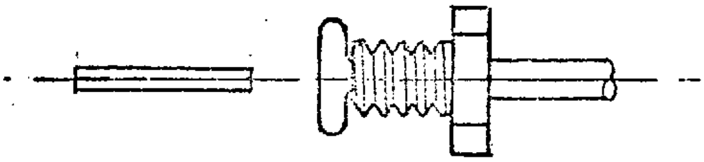
2. INSERT ROD SUPPLIED INTO TUBE.



3. PUSH FERRULE ONTO ROD, AND PUSH TUBING OVER FERRULE.



4. REMOVE ROD AND SLIP FITTING OVER FERRULE & TUBE.



4. Place the fluid plugs from the new module into the defective module. Pack the defective module carefully in a foam lined container and return for failure analysis and repair.

8.3.2. Troubleshooting - Mechanical

The fluid transport system is designed for operation with minimal maintenance. HOWEVER, the following areas are indicators of trouble. They fall into the two (2) main categories of lack of fluid movement, air-fluid leads and malfunction of major subassemblies.

The following sub-paragraphs are complementary to the fluid function test flow chart in 8.1.3. This chart outlines the step-by-step procedure for test and debugging of the fluid transport system.

8.3.2.1. Test of CRS valve to locate proper port.

The chromatographic rotary switching valve is described in 4.4. Failure of this subassembly means that fluids cannot be properly routed through the fluid system. In addition, a greater damage may result to the system if the pump is allowed to aspirate on the electrode modules while the valve creates a dead head (closed volume). Many safety devices have been built into the system to prevent this occurence.

The CRS valve is keyed to the electronics unit and its position can be read directly on the display panel. Also, an observation hole is located beside the valve body on the CRS valve housing. Through this hole the valve position may be read.

8.3.2.2. Test of Fluid to Enter Through the Septum Injection Port

When a sample is injected into the system through the injection port fluid should flow into the holding coil that is wrapped around the body of the CRS valve.

If the fluid sample will not enter and regurgitates through the septum, a fluid blockage is present. The location is either in the CRS valve, the holding coil, lines to the waste manifold, the waste manifold, waste line, or waste bag fitting.

The first of these points, (the CRS valve) is most crucial. No other valve station other than 2 will allow injection. Check the electronics unit display and CRS valve observation hole for No. 2 (see section 8.3.2.1.).

If the CRS value is ascertained to be in proper position, then the blockage is in a tube between the CRS valve and the waste bag. Each of the lines described above have fitting connections that can be broken and the downstream side tested by inserting a syringe and needle with test dye solution (supplied) and flushing the line.

8.3.2.3. Fluid Movement Test

If fluids do not move while the pump is activated, then the pump must be turned off immediately. This step is necessary to prevent electrode damage due to line dead-heading. Check to ensure the valve is in proper position, (CRS valve position 4 in the fluid function test sequence). If the valve is not in position, see section 8.3.2.1. Otherwise there are two (2) possible reasons for lack of movement:

1. Line blockage or air leaks. The pump may be turned on for a brief period (10 sec.) to see if air is leaking into the system at some point. This can be checked by watching for extraneous air bubbles downstream on the leak between

fluid segments

Line blockages may be located by removing the line fittings between components and injecting dye solution (supplied). Line blockage should be rare. Therefore, this technique should be last in the test sequence. If a tube is damaged, spare fluid lines are located in the system spares kit.

8.3.2.4. Test for Spurious Air Bubbles

The primary cause for extraneous air bubbles moving in the lines is improperly tightened or threaded fittings. There are many fluid line fittings in the fluid transport package. As a result, care must be exercised on set-up and during component replacement to properly thread and tighten each fitting. These fittings are inert plastic materials that are soft and can be easily cross threaded, or stripped. A cross threaded fitting will leak air.

A second source for air leaks is around the lines entering the CRS valve. A special technique was utilized to form these joints. This technique requires that the CRS valve be disassembled to repair a joint failure because of the valve construction. Care must be used not to abuse the joints at the top of the CRS valve. If it is determined that the air leak is in a valve joint, then the CRS valve assembly must be removed from the fluid transport package to be disassembled and repaired.

Air may leak into the system within an electrode module. If it is determined that an electrode module is leaking air and that the fittings are properly seated into the module, then the electrode module should be replaced. (See section 8.3.1.4.)

8.3.2.5. ''A'' Standardizing Sequence Test

The ''A'' standard cycle is controlled by a three (3) way solenoid activated diaphragm valve. During the fluid test cycle (CRS valve position 4) air is drawn into the holding coil as dyed sample is being drawn out. When the ''AIR'' valve is turned to ''ON'' the valve switches ''A'' standard into the holding coil. ''A'' standard is a clear fluid so that the fluid boundary must be seen moving through the CRS line into the holding coil.

If the fluid cannot be seen moving into the holding coil then a failure of the diaphragm valve or a leaking fitting is indicated. The fluid connections should be checked for tightness. If a valve failure is suspected, then the valve must be replaced.

inal point at which ''A'' standard can be restricted
oving into the system is the fluid bag container. The
y concern at this connection is that the connector needle
e flowing. The needle connector may be removed from its
tor union and air passed through to insure free flow.
r blockage may occur inside the bag fitting. The septum
e may be extruded to a degree that the needle will not
ate it. In this case, the bag must be replaced. The
bag failure could occur if the siphon tube within the
llapses or breaks its joint with the bag fitting. In
case, the bag will need replacement.

6. ''B'' Standardizing Sequence Test
standard is a clear fluid that is always present at
RS valve for switching to the electrodes.

'' standard does not move into the CRS valve, a line
ge or fluid container bag blockage has

occurred. Line blockage can be tested as previously described (section 8.3.2.3.) using the test dye solution.

A fluid container bag can be blocked at the needle, in the fitting or in the bag. The needle connector can be removed. If the needle orifice is clear, a bag blockage has occurred and the standard bag must be replaced. The replacement procedure is found in section 8.3.1.1.

8.3.2.7. Test of Septum Injection Port Clean-out Sequence

The second function of ''B'' standard in the fluid transport system is to clean the injection port of samples inserted into the system. This procedure ensures that sample cross contamination does not occur in the injection line.

During the fluid function check ''B'' standard should move from the ''B'' fluid container bag, through the ''B'' manifold, through the ''FLUSH'' valve, through the inlet check valve, and into the injection port. The fluid moves through the injection port and exits through the sample inlet line to the CRS valve, through the CRS valve to a multi-outlet manifold, and through the pump to the waste bag.

Failure of the fluid to move in the line could be the result of blockage in any of the above components. The most critical of these is the CRS valve. If the valve is shown to be properly positioned it can be eliminated from concern. The diaphragm valve is generally not a source of failure.

Check the septum injection port cap to ensure that the cap is tightened.

A less probable cause for no fluid flow could be failure of the inlet check valve. The check valve is simply designed and highly reliable. Should replacement be necessary the septum injection port will have to be removed from the fluid package.

Lack of fluid movement in other components is most often caused by line blockage. The dye sample injection procedure described previously should be used to locate these line blockages.

8.3.2.8. Test of Reagent Addition Line

Acid reagent is added to the sample stream of the Ca^{++}/Cl^{-} electrode module in the mixer assembly. Test for fluid flow in this line can be accomplished by injecting an air slug into the sample holding coil and running a normal sequence. In this test, the observer should see alternate air and fluid slugs exiting the top of the mixer assembly on the way to the Ca^{++}/Cl^{-} electrode module.

If no fluid is seen in this test a line blockage has occured either in the mixer or in the reagent container bag.

8.3.2.9. Pump Tubing Failure

The pump tubing should have a life in excess of 3000 system cycles. If a line is seen to be leaking around its cassette or onto the pump base, the pump should be turned off. Replacement of the ten (10) pump lines has been described in detail in section 8.3.1.3., ''Pump Tube Replacement.''. Refer to this section for proper routing of the pump tubes.

8.3.3. Electronics Servicing

Testing and troubleshooting of the A.P.E.A.S. electronics are facilitated by special test hardware and software provided. A test box which may be substituted for the fluid transport unit will speed E/U output circuit testing and fault isolation. Manual function switches on the E/U allow positive control when troubleshooting in the F/T. A software system controller, which operates from the 8/E switch register, permits manual testing of the computer interface and related circuitry.

Due to the complexity of this system, troubleshooting must be done by fault localization using the above facilities. No attempt is made in this section to diagnose specific malfunctions. As a servicing aid, all schematic diagrams are fully annotated with descriptions of circuit functions, voltages, waveforms, test points, component layouts, and calibration procedures. Virtually all printed circuit boards and integrated circuits are plug in replaceable. P.C. extender boards are provided for circuit measurements.

8.3.3.1 Areas of Malfunction - the following guide will help in localizing system problems:

Nature of Problem	Probable Causes
1. No system response when turned on	No line power, 8/E circuit breaker off, blown fuse(E/U, 8/E, or teletype)
2. Program will not load	Loader not in core, loader not started, teletype or reader off, incorrect procedure, computer malfunction
3. Program loads but will not run (no initial dialogue)	Teletype off, Incorrect procedure, program destroyed by improper starting address.
4. E/U not initialized as specified--program running (see operator)	Incorrect switch settings, incorrect cable conn.,E/U or interface fault, system clock not operating.
5. System runs but not correctly.	Damaged program from incorrect loading or modification, general fault(requires more testing).

Once it is certain a hardware problem exists, it must be localized to one unit. Begin by disconnecting the computer cables to ''R'' and ''S'' at the E/U. Connect the cables together using the D.E.C. jumper block provided. Load and run the DRB-E/A interface diagnostic (MAINDEC - 08 - DHDRA - A -PB) using the D. E. C. instructions provided. If this test fails, contact Digital Equipment Corporation field service. If the diagnostic runs properly, the trouble is most likely in the E/U of F/T.

The next step is to check all power supply voltages in the E/U. Observe the 115 volt cautions on the power supply schematics! If the ± 15 or +5 VDC supplies are in error by more than 5% they should be completely checked. The allowed limits for the + 24 VDC are +20 to +26 V.; for +10 VDC, -8 to -12 v. (remember that the -10 v. is TRIAC bias, and is connected to the low side of the AC line.) Disconnect F/T and remove P.C. boards B thru H when servicing the supplies. Test loads may be applied via the E/U test box except for the ADC ± 15 v.

Note: If a malfunction is observed that appears related to a small circuit area, the technician may elect to skip the above steps. If the fault is not subsequently located, they must be performed.

Using the E/U manual control switches, operate each device in the F/T. If incorrect response is observed, substitute the E/U test box for the F/T. Checking the amplifiers and ADC requires a precision voltage source (such as an analogic AN3100). When applying potentials to the amplifiers, observe the following precautions:

a. Do not exceed 5 v. input

b. Do not connect guards (shields) together

c. Provide a connection between either input and analog ground to prevent excessive common mode voltage.

If a malfunction appears to be located in the temperature control circuitry, proceed cautiously. Check the measurement circuit first, and avoid making adjustments to the calibration controls until the fault is located. (Note: the temperature measuring circuit works only with the No.8 amplifier.)

8.3.3.2. Electronics Unit Servicing

Once the problem is localized to the E/U, a special software controller should be employed. Assuming that the computer, computer interface, and E/U power supplies are functioning properly; load and start the Orion Switch Register Controller (see the end of this section for operating details). Refering to the control tables on the multiplexer and expander board schematics, operate all functions of the system from the computer. (All E/U control switches should be set for automatic operation.) Check I.C. logic levels and control voltages as required to locate the bad components.

8.3.3.3. Computer Software Problems

Every attempt has been made to fully test software systems supplied by Orion. If a program bug is suspected, please contact the Orion Engineering Department for assistance.

8.3.3.4. Switch Register Controller

This test software allows complete manual control of the E/U and F/T from the computer switch register. All data returned to the computer is displayed in the 8/E accumulator.

8.3.5. Operation of the Switch Register Controller

8.3.5.1. Preliminary

1. Load this program in either memory field

2. Load the appropriate memory field.

3. Load address 200, clear switch register, and start program.

8.3.5.2. Output to E/U - (see expander BD. schematic-
No. 700864)

1. Select the desired output byte using bits 0,1,2.
2. Set the expanded data desired using bits 8,9,10,11.
3. Momentarily raise bit 3 to strobe output to the E/U expander buffer.

   NOTE: The strobe (bit 3) may be left up for continuous update but any changes to the byte control will instantly update all addressed bytes with the same data.
4. Direct bits 4,5,6,7, may be operated at any time, without regard to byte code or the strobe.

8.3.5.3. Input to E/U - (see multiplex BD. schematic-
No. 700862)

1. Be certain the 8/E display is set for ''AC''
2. The display normally shows input bits. It may be altered by typing a control letter as follows:

   ''O'' = display output

   ''P'' = display interrupt accumulator

   ''I'' = return to input display

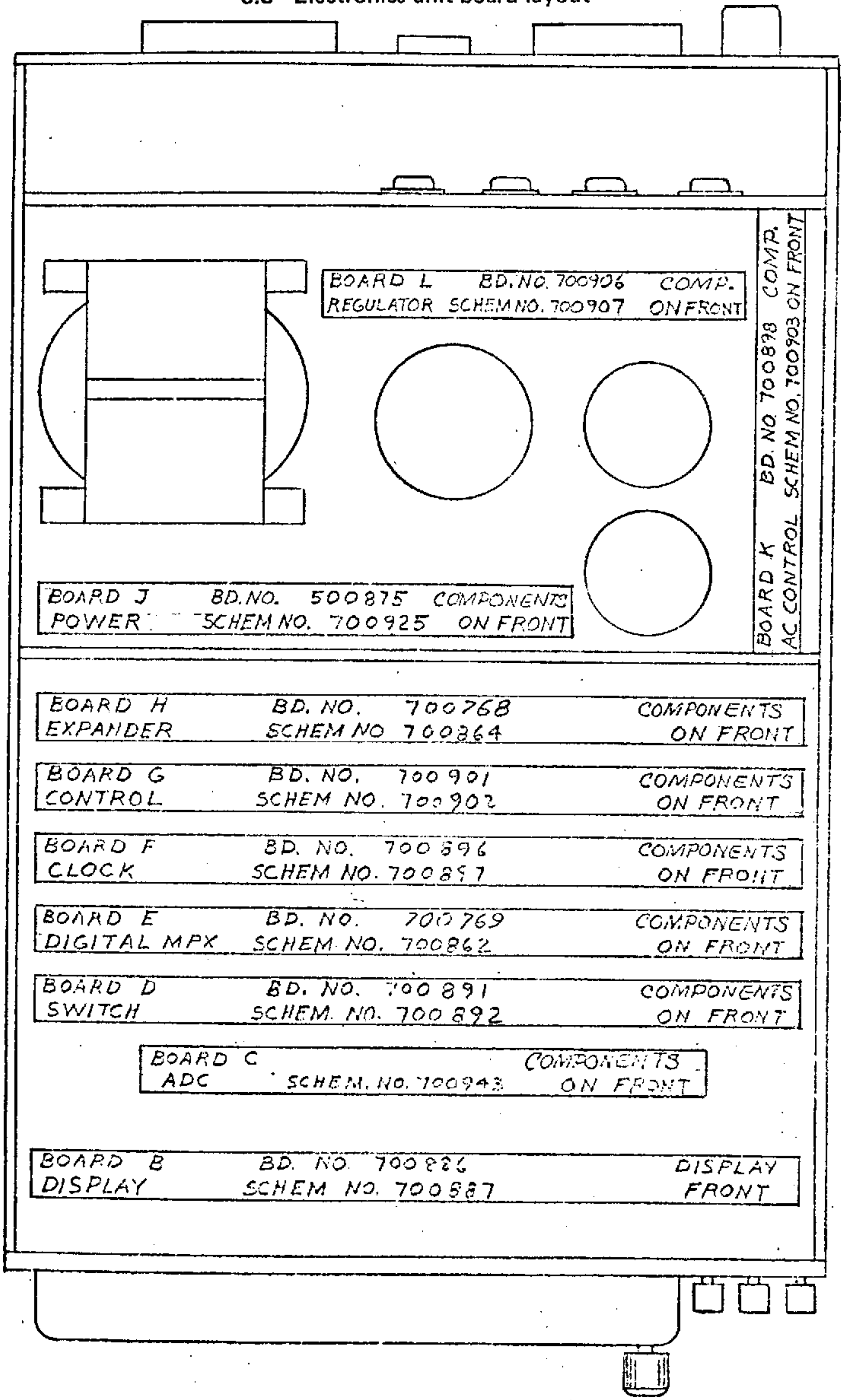
(For most testing the input mode is used.)

3. Select the desired byte, using bits 0,1,2,and observe the inputs on the 8/E.

   NOTE: Pulse inputs are processed by a ''software one-shot'' in order to be visible. The bit 3 switch must be down to avoid altering the output.

4. Display bits 0,1,2,3 are direct, and independent of byte code.

8.3 Electronics unit board layout



CHAPTER IX

SUMMARY AND SUGGESTIONS

9 .1 Summary:

It should be emphasized that the system described in this report represents a hardware demonstration of the feasibility of employing chemical sensing electrode technology for the determination of various clinical parameters under weightless conditions.

A flight-hardened version of the system described by this report would appear to be well suited for operation under space flight conditions. Some of the major advantages of this approach over previously available instrumentation for the determination fo blood gases and electrolytes are:

1 . Compactness - provisions for analysis of as many as 8 parameters can be included in as little as 1 cubic foot of space.

2 . Ease of operation - the system restandardizes automatically on every sample cycle, eliminating the necessity for constant operator manipulation of sensitivity and slope controls. Under normal operating

conditions, the operator is only required to inject the sample and to push the ''START'' button to complete an analysis cycle.

3 . Self-contained - all reagents and waste containers are incorporated into the system, eliminating the need for external plumbing.

4 . Reagent requirements - in the current system, only two reagent and two standard containers are required for the determination of 7 parameters. Also, no flammable gases are needed for the electrolyte determinations.

5 . Ruggedness - sensors are incorporated into epoxy blocks to provide the necessary mechanical support and to minimize plumbing connections.

6 . Serviceability - expendable items, such as liquid membrane electrode internals and fluids containers employ snap-in modules with leak-free connectors and solid internal references to prevent fluid leaks.

7. Flexibility - the utility fo this approach is not limited to the parameters selected for inclusion in

the existing system (i.e., pH, pCO_2, Cl^-, Na^+, K^+, $Ca^{++}_{Ionized}$, and Ca^{++}_{Total}.)

For example, one could measure urea with an ammonia electrode and an enzyme cartridge of immobilized urease. Other important parameters, such as glucose and oxygen, could be included in a similar manner. These and other options would allow tailoring a system to NASA's anticipated requirements.

9.2. Suggestions:

The purpose of this section is to point out some of the modifications that we feel would be necessary to fabricate a flight-approved version of the existing hardware.

9.2.1. Electrode and Chemistry Modifications:

Neither the chemical approaches nor the basic electrolyte designs would require more than minor modifications for flight hardware. One possible exception to this is the pCO_2 electrode which employs a rather fragile pH sensor. There are several viable approaches to this problem, but time limitations did not allow evaluation and incorporation of any of these into the current system.

9.2.2. Mechanical and Materials Modifications:

The primary materials employed for fabrication of the existing system are aluminum, stainless steel, silicone, rubber, teflon, epoxy, and flame retardent urethane. The system neither evolves flammable gases or uses corrosive reagents.

Some possible modifications are listed below:

1. Both internal and external structural design should be evaluated with respect to launch and recovery stresses.

2. Fluidic sensors for aqueous vapor or fluid loss within the unit could be incorporated for leak detection.

3. All electromechanical components should be optimized for minimum power consumption.

4. The fluid unit could be redesigned for single plane access to all electrical and mechanical components.

5. All plumbing, with the exception of pump tubes, could be accomplished by teflon I.D. coated stainless steel tubing.

6. The unit can be readily shielded from electromagnetic interference.

9.3.3. Electronics Modifications:

Major electronic design changes would be necessary for space flight operation of the system. The current system employs a dedicated controller and teletypewriter for system operation. This is not the most efficient flight configuration for the system, but it is the most flexible system for ground evaluation and testing. Specific suggestions for each electronics section follow.

9.3.3.1. Fluid Transport Electronics Modifications

1. Convert fan, pump, and main valve motors to suitable frequency (presumably 400 Hz).

2. Evaluate the mixer for 400 Hz operation.

3. Reduce amplifier performance for lower impedance electrodes, to simplify circuitry.

4. Consider multiplexing with reed or F.E.T. switches prior to amplification, to reduce the number of amplifiers.

5. Modify heater control based on available voltage and power.

6. Modify the physical configuration to withstand appropriate shock and vibration.

7. Make all electrical connections waterproof.

9.3.3.2. Electronics Unit Modifications:

1. Complete redesign to provide the appropriate interface with a telemetery link or on-board computer.

2. Design a fixed program dedicated hardware controller to relieve data processor of control functions. In emergency situations, this allow the system to be operated without interface to any other equipment.

3. Remove all manual controls and other functions used for system servicing. These should be packaged separately for use by ground-based technicians as required. The service module is envisioned as a plug-in test device.

4. Review all circuitry for space flight suitability. This will include: power requirements, RFI and EMI,

thermal dissipation, ambient temperature, packaging limitations, shock and vibration, serviceability, and operating modes.

9.3.3.4. Controller Modifications

1. Interface modification will be required for the on-board computer to be used. A serial data transfer approach will probably be more suitable.

9.3.3.5 Controller Software Modifications

1. Software sould be simplified to a data reduction routine only. All system sequencing would be done by a dedicated hardware controller.

2. System status and output data checks should be added to certify validity of analysis results.