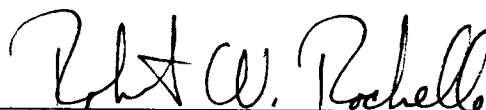


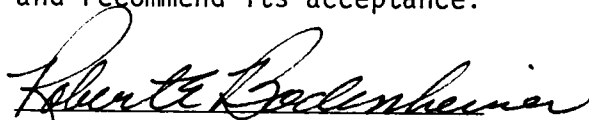
To the Graduate Council:

I am submitting herewith a thesis written by Arville McKinley Billings entitled "Automation of an On-Line Infrared Spectrometer for Gas Analysis." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.



Dr. Robert W. Rochelle, Major Professor

We have read this thesis
and recommend its acceptance:



Donald W. Bouldin

Accepted for the Council:



Vice Chancellor
Graduate Studies and Research

AUTOMATION OF AN ON-LINE
INFRARED SPECTROMETER
FOR GAS ANALYSIS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Arville McKinley Billings

June 1981

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Greatest thanks of all is due my wife, Genois, without whose encouragement and patience I could never have completed this thesis.

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ABSTRACT

A low-cost controller is required for automation of an existing infrared spectrometer used for gas analysis. The controller must also perform limited data reduction on the spectrometer output and present the results in printed form.

The existing hardware to be used, and the design criteria for the controller are presented to provide the information upon which the design was based. Operational and hardware considerations are discussed and justified in the design of the controller. An example of the implemented design is given which fulfills the original goal of performing limited automation of the spectrometer.

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1.0 INTRODUCTION

The primary purpose of the Oak Ridge Gaseous Diffusion Plant (ORGDP) is the enrichment of uranium hexafluoride (UF_6) in the U^{235} isotope. The element uranium, in its naturally occurring state, is about 0.7% U^{235} and 99.3% U^{238} by weight. By combining this element with the element fluorine and maintaining a sufficient temperature, UF_6 gas is created. The UF_6 is then forced past a series of porous barriers which allow the gas molecules of U^{235} content to pass through more often than the slightly heavier U^{238} gas molecules. Eventually, the U^{235} isotopic content of the UF_6 reaches a level (about 3%, or higher) acceptable for use as reactor fuel, in weapons, etc. Impurities in the form of lighter gases pass through the succession of barriers quite readily and must be purged from the process stream and discharged to atmosphere after removing nearly all traces of UF_6 from them. Diligent monitoring of the enrichment and purging processes is required due to the complications introduced by certain of those impurities in the process, and to the corrosiveness and radioactivity of UF_6 .

Infrared spectrometry is the preferred method of gas analysis for several applications within the enrichment and purge processes, as well as in some other gaseous processes which are associated with plant operations. One spectrometer in particular, the Beckman Acculab, has received wide acceptance within the ORGDP due to its low cost, reliability, and measurement range. Unfortunately, there are several disadvantages to using this spectrometer.

Both operational and safety problems are frequently encountered due to the requirement that an operator must be present to perform and evaluate an analysis. Specific inadequacies resulting from this requirement are:

1. The operator performs the analysis as an aside to his other duties, and may not be present at the spectrometer site at the scheduled analysis time.

2. The percentage of the gas sample attributable to the constituent(s) of interest is not readily available from the graphical output of the spectrometer, which is plotted as percent light transmittance versus light wavelength.

3. Due to the possibly overlapping absorption frequencies of two constituents, a peak on the graph at a wavelength of interest may actually be the sum of two peaks.

Unfortunately, a spectrometer with the required wavelength range which will perform automatic analysis and data reduction is not available off-the-shelf. The currently available instrument which comes closest to satisfying these requirements costs in excess of \$17,000, as opposed to the cost of the presently used instrument at approximately \$9,000. Spectrometers capable of only single-wavelength analysis might be cheaper, but not interchangeable, and would require special design and the stocking of spare parts and/or spectrometers for each of the five different applications of the twelve spectrometer installations within the ORGDP.

The goal of this thesis is to demonstrate the design of an instrument to be used in conjunction with an existing Beckman Acculab infrared spectrometer which will provide:

1. Initiation of analyses at preprogrammed time intervals.
2. Automatic interpretation of the output, with a paper-tape log of the derived mole percent of the constituent(s) of interest and the time the analysis was made.
3. Control of valves, when required, for multi-stream analysis by a single spectrometer.
4. Adaptability to several applications through changes only in software.
5. All of the above at a hardware cost not exceeding \$1,300.

2.0 GAS ANALYSIS BY INFRARED ABSORPTION SPECTRA

When a gas is exposed to electromagnetic radiation whose wavelength is appropriate to cause some quantum change in the energy levels of the gas molecules, that radiation will be absorbed to some extent. The particular quantum change may be the result of an inner or outer electron being shifted into a higher energy level, or it may be the result of vibration and rotation of the gas molecules. Absorption of the lesser energies required to cause vibration-rotation of gas molecules is the result of radiation in the infrared portion of the electromagnetic spectrum.

In the electromagnetic spectrum, which is depicted in Figure 2.1, the infrared region is adjacent to the visible light region, and is generally considered to include radiation wavelengths between roughly $0.8\text{ }\mu\text{M}$ and $900\text{ }\mu\text{M}$.¹ Radiation of varying wavelength within a portion of this region may be passed through a gas. A graph of absorbency versus wavelength can then be created for a particular range of wavelengths, and this graph is known as a spectrum.² Spectra for two common gases are shown in Figure 2.2. All common gases have a singular absorption spectrum within the one-to $23\text{-}\mu\text{M}$ portion of the infrared region, with the exception of those whose molecules are nonpolar and diatomic, such as O_2 , N_2 , Cl_2 , and F_2 .² The absorption spectrum of a mixture of gases will always be the sum of the absorption spectra of the individual gases in the mixture. The amount of energy absorbed by a gas will depend upon only the partial pressure, or concentration, of the gas and the length of the path taken by the radiated energy through the gas.

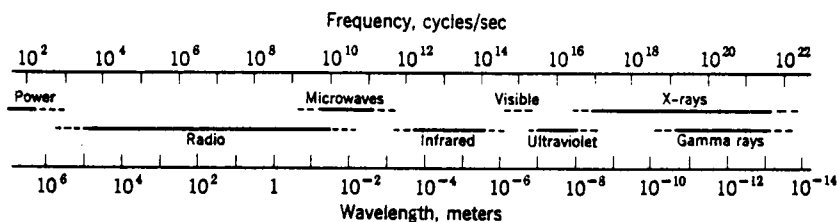
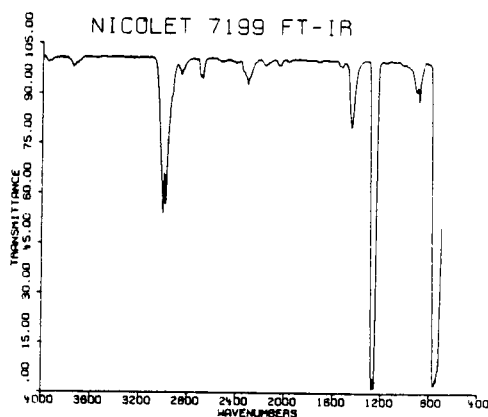


Figure 2.1 The Electromagnetic Spectrum

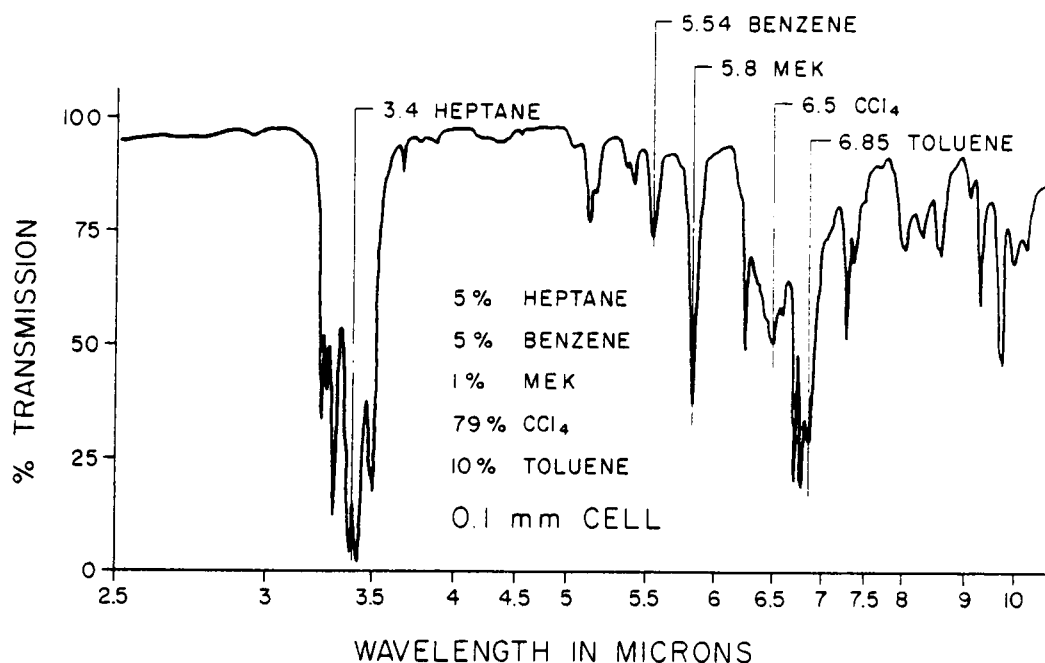
Source: Halliday, David and Resnick, Robert, Fundamentals of Physics. First Edition. New York: John Wiley and Sons, Inc., 1970.

2.1 INFRARED SPECTROMETRY

The basic components of any infrared spectrometer are the infrared source, the chambers through which the infrared radiation is passed and which contain the subject and reference gases, and an infrared detector. Sources are generally constructed of Nichrome which is heated to provide sufficient infrared radiation. Some spectrometers use two sources, one for the reference chamber and one for the sample chamber. Other instruments make use of one source by placing mirrors in such a way that the light beam is split before passing through the two gas chambers. These chambers, or cells as they are commonly called, contain the reference gas and the gas to be analyzed. The reference gas is normally a gas which is inert within the spectral region of interest in order to provide a zero-absorbency reference point. Windows in the cells through which the infrared beams enter and exit may be made of any of several spectrally inert materials, such as CaF_2 , BaF_2 , AgCl , and others. Spectrometer detectors are generally thermocouples or other similar, temperature sensing devices. A rotating chopper wheel causes the two radiation beams passing through the gas cells to strike the detector



(a) Methylene chloride.



(b) Hydrocarbon mixture.

Figure 2.2. Spectra of some common gases. The spectrum in (a) was determined on a highly sophisticated (and expensive) Nicolet 7199 instrument. A much less costly Wilks Model 80 analyzer was used to produce the spectrum in (b).

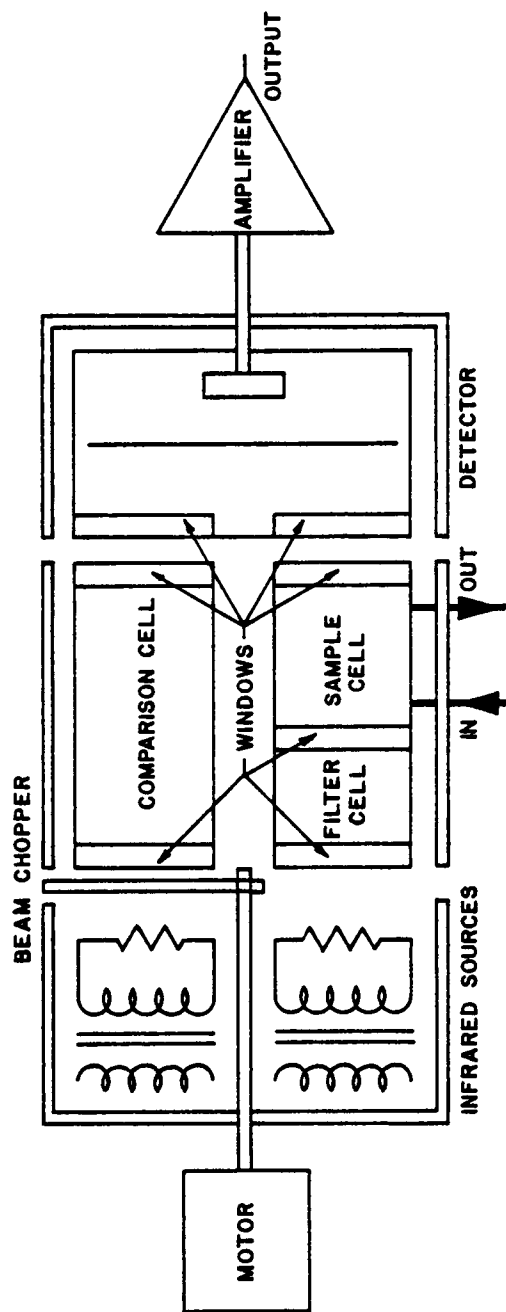
Sources: The Nicolet GC7000. Madison, Wisconsin: Nicolet Instrument Corporation; and Wilks Model 80 Computing Infrared Analyzer. Bulletin L-11-15M-8/76. South Norwalk, Connecticut. Wilks Scientific, Inc. (1976).

alternately. The detector senses any changes in absorbency through changes in the radiant energy reaching it, and translates this signal to an electrical one.

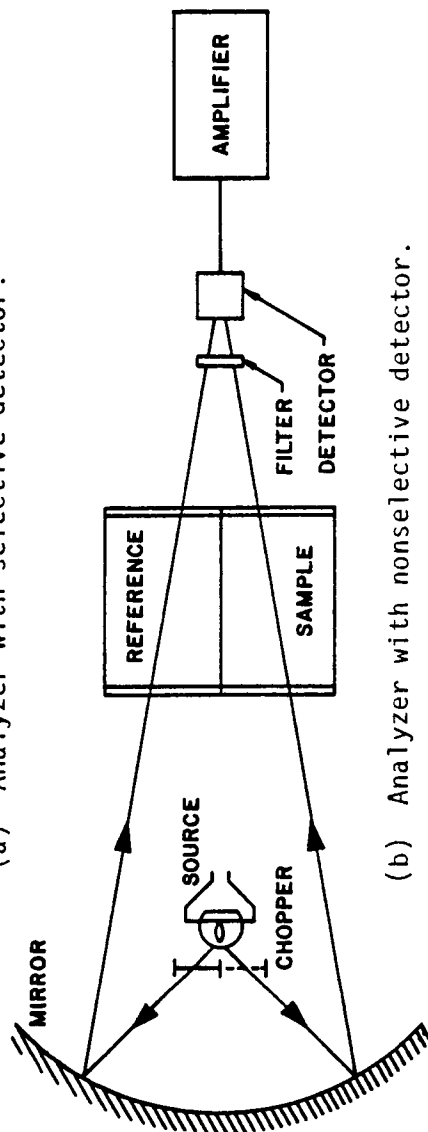
Spectrometers may be categorized as either dispersive or nondispersive. The dispersive infrared instrument incorporates a prism or grating to disperse the energy from the source into some of its component wavelengths, two of which are utilized in the instrument. By design, one of these wavelengths will be unaffected by the gas component of interest, and the other will be absorbed by that component. A comparison of the absorptions of the two wavelengths will then yield a measure of the concentration of the gas component of interest.

Nondispersive infrared (NDIR) spectrometers used an unfiltered source. This leads to greater simplicity and reliability, since source filtering requires two adjustable monochromators if the instrument is to be useful in a variety of applications. The most common NDIR spectrometer in use is the double-beam variety, so-called because infrared light from the source(s) is propagated along two separate paths through the reference and sample cells. Two examples of double-beam NDIR analyzers are illustrated in Figure 2.3.

Notice that these analyzers are differentiated by the type of detector each incorporates. The analyzer in Figure 2.3(a) incorporates a detector consisting of a chamber filled with the gas component of interest. As the chopper causes infrared radiation to alternately pass through the two cells, the amount of energy absorbed by the gas in the detector will fluctuate in proportion to the difference in the concentration of the component gas of interest in the sample and reference cells. One wall of the detector is a diaphragm which flexes in proportion



(a) Analyzer with selective detector.



(b) Analyzer with nonselective detector.

Figure 2.3. Double-beam NDIR analyzers.

to the amount of energy absorbed by the gas within, and the detector consequently becomes a variable capacitor. An alternating output signal may be thereby derived whose frequency is proportional to the chopper speed and whose amplitude is proportional to the difference of gas component concentration in the two cells. A filter cell may be incorporated in case there are other component gases in the sample whose spectra overlap that of the component of interest. In that event, the filter cell would be filled with a gas which absorbs all energy within the overlapping spectral region, thus eliminating the effects of the interfering component(s). A simple, nonselective detector, double-beam NDIR analyzer is depicted in Figure 2.3(b). The wavelength selectivity of this instrument is accomplished by using a variable optical filter in front of the heat-sensitive detector. With the filter adjusted to allow a particular wavelength to pass through, the difference in absorbency between the reference and sample cells at that frequency results in a varying electrical signal from the detector. A filter cell may also be incorporated if required.

After an infrared analysis is completed on a sample, and the absorbency at frequencies of interest is known, the molar concentration of the constituent(s) must be determined mathematically. The relationship between absorbency and molar concentration originates from Beer's Law, which states that

$$\frac{I}{I_0} = e^{-abc} ,$$

where

I = signal intensity through the cell containing the sample gas

I_0 = signal intensity with no sample in the cell

a = absorbcency constant unique to the gas component at a particular wavelength

b = path length of the infrared signal through the cell

c = molar concentration.^{3,4}

For convenience, the equation may be developed as follows:

$$\frac{I}{I_0} = e^{-abc}$$

$$\ln \left(\frac{I}{I_0} \right) = -abc$$

$$\ln \left(\frac{I_0}{I} \right) = abc$$

$$\log_{10} \left(\frac{I_0}{I} \right) = \frac{abc}{\ln 10}$$

$$\log_{10} \left(\frac{I_0}{I} \right) = Kbc \quad , \text{ where } K = \frac{a}{\ln 10}$$

$$c = \frac{1}{Kb} \log_{10} \left(\frac{I_0}{I} \right) = K_1 \log_{10} \left(\frac{I_0}{I} \right) ,$$

where K_1 is a function of wavelength, molecular composition, and path length. The terms I_0 and I will be represented herein by the terms $\%T_0$ and $\%T$, since the output of most infrared analyzers is presented as "percent transmittance." The reader should note that since transmittance is defined as I/I_0 , analyzer output cannot be a truly accurate transmittance unless $T_0 = 1$. This cannot be assumed to be the case, since short-term temperature fluctuations and internal analyzer noise may cause T_0 to drift. Consequently, there is a need to scan the wavelength(s) of interest with a sample of zero absorbcency at periodic intervals to determine the true value of $\%T_0$. K_1 has been calculated

for all sets of operating conditions in the plant, and a list of these factors is readily available.

2.2 THE BECKMAN ACCULAB-6 SPECTROMETER

The infrared analyzer which is of particular interest in this thesis is the Beckman Instrument Company's Acculab-6 model, shown in Figure 2.4 with operator interface features identified. From the diagram of the Acculab-6 optical system in Figure 2.5, the spectrometer is seen to be a double-beam, nonselective detector, NDIR analyzer. The chopper wheel causes the reference and sample beams to alternately strike the filter, after which the combination of the filter and gratings allows only very narrow bands of infrared energy to strike the thermocouple.

Being temperature-sensitive, the thermocouple generates an a.c. signal whose amplitude is directly proportional to the difference in the incident light energy of the two beams. This a.c. signal is used as an error signal input to the Acculab circuitry, which amplifies the signal and synchronizes it with the rotation of the chopper wheel. Through a servomotor, the attenuator in the reference beam is adjusted by the electronics to maintain equality in the transmittance of the two beams. The chart pen is mechanically coupled to the reference beam attenuator and; therefore, records the transmittance signal which is actually a feedback signal as far as the analyzer is concerned.

The most important aspects of this instrument regarding its automation are the characteristics of the signals required to operate it, and of the data which it produces. The mechanics of operation of the analyzer are fairly simple:⁵

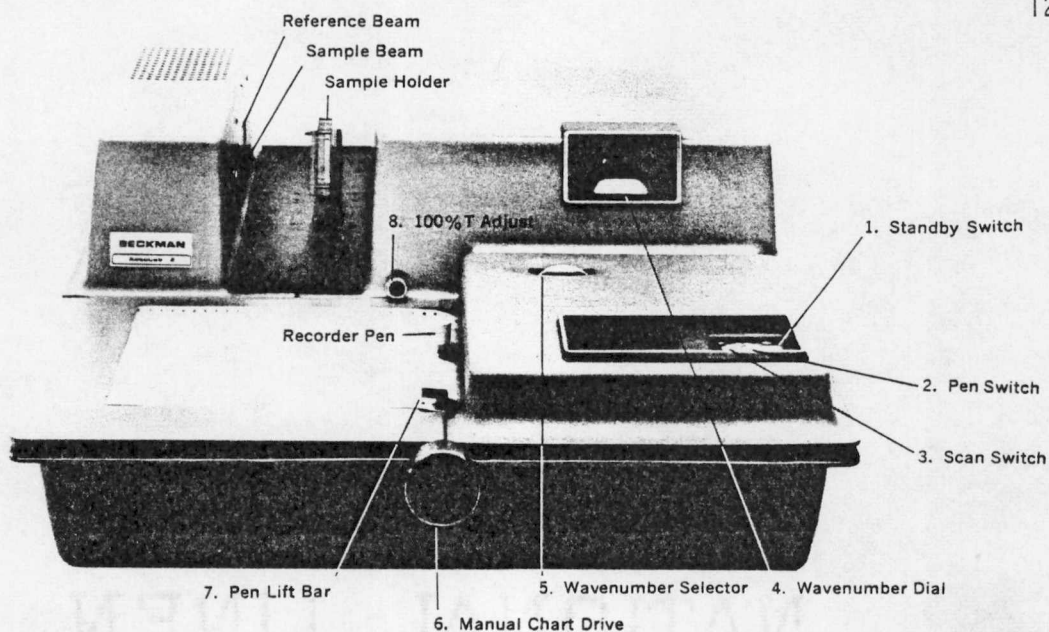


Figure 2.4. Beckman Acculab-6 infrared analyzer. (Overall dimensions: 11" H x 25" W x 24" D).

Source: Acculab Infrared Spectrophotometers Operating Instructions. Fullerton, California: Beckman Instruments Company (1975).

S-SOURCE A1-ATTENUATOR
M-MIRROR S1-ENTRANCE SLIT
C-CHOPPER S2-EXIT SLIT
F-FILTER WHEEL TC-THERMOCOUPLE
G-GRATINGS A2-100% 'T' ADJUST

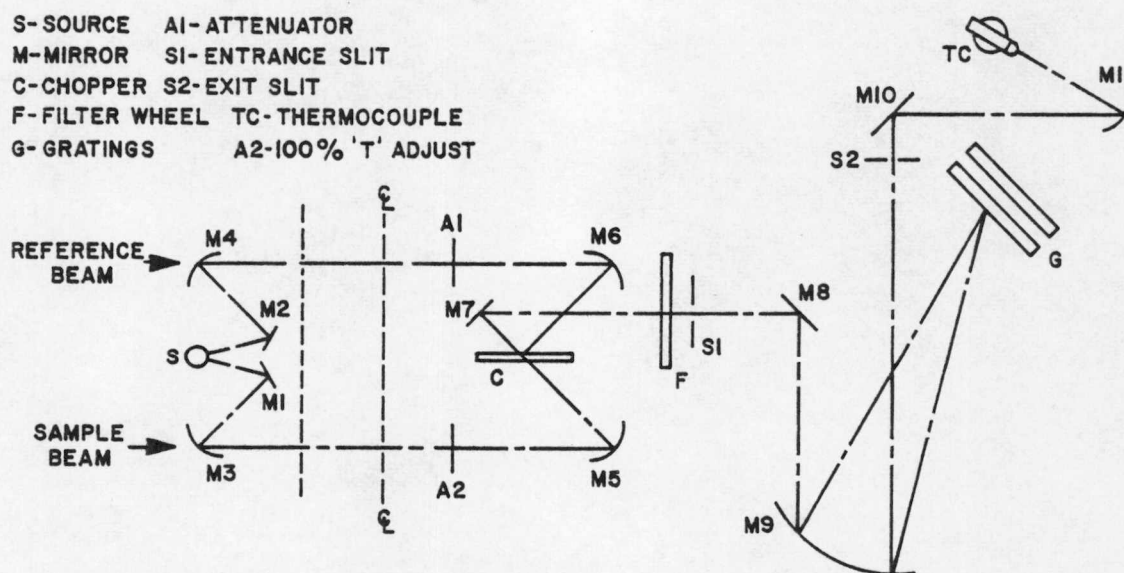


Figure 2.5. Optical system of the Acculab-6.

Source: Acculab Infrared Spectrophotometers Operating Instructions. Fullerton, California: Beckman Instruments Company (1975).

1. Pull Wavenumber Selector toward front of instrument.
2. Slowly rotate Wavenumber Selector in DIRECTION OF DECREASING WAVENUMBERS until Wavenumber Dial reads exactly 4000 cm^{-1} .
3. Push Wavenumber Selector and "feel" that it meshes drive gears, and thus engages the monochromator drive system.
4. Slowly rotate Manual Chart Drive in DIRECTION OF INCREASING WAVENUMBERS until pen is directly over 4000 cm^{-1} coordinate on chart.
5. Verify that both Wavenumber Dial and recorder pen read exactly 4000 cm^{-1} . Initial correct registry is essential for Wavenumber accuracy in the resulting spectrum recording.
6. Place sample in sample holder. Depress Pen Pushbutton and then Scan Pushbutton. Immediately lower pen to chart paper. The scan will begin and recorder pen will trace the sample structure.
7. When scan reaches low-wavenumber end of spectral range, pen will lift automatically; however, chart and scan-drive motor will continue to run for a brief interval until stopped automatically by a limit switch. After scan-drive motor stops, depression of Pen Pushbutton will re-energize the motor, causing it to return to the scan start position, i.e., $4000\text{ cm}^{-1} \pm 1$ chart division.

Operations 1 through 5 need be performed only occasionally, provided the wavenumber selector has not been manually disengaged for "dialing in" a wavenumber of interest. In repetitive scanning, then, all that is required for control of the instrument is to alternately repeat Steps 6 and 7. In these particular applications, new samples will be circulated through a fixed cell and the manual changing of the sample in Step 6 may be omitted. The lowering of the pen to the chart paper as described in Step 6 may be also be omitted since points of interest on the output will be examined by the controller and the result presented in numerical format. The requirements of a controller are now established to be the simulation of the alternating operation of the Pen and Scan Pushbuttons at timed intervals.

The most convenient point in the analyzer at which the output is available is the auxiliary recorder jack. Adjustment capability is provided on the Acculab-6 for setting the range of the auxiliary output

to 0-1.0 volts, corresponding to a transmittance of 0-100%. This signal will be an analog representation of transmittance versus wavenumber, and will vary as the instrument scans the spectrum of wavenumbers from 4000 cm^{-1} to 250 cm^{-1} . The rate of change of transmittance with respect to time is of particular interest, and is examined in greater detail later.

3.0 DESIGN CONSIDERATIONS

Many requirements must be considered during the design of any instrument. The requirements of an infrared analyzer controller which were considered most important in this design were operability, maintainability, flexibility, technical adequacy, and cost. This section is a discussion of the design of the controller hardware and the influence of the above requirements on that design.

3.1 A/D CONVERSION

Of all factors affecting the choice of an A/D converter for the controller, technical adequacy was most important. No other quality would atone for a converter which would not sample accurately and rapidly.

The Acculab-6 was capable of scanning a wavenumber range of 4000 cm^{-1} to 250 cm^{-1} within three different time periods selected by the operator. These time periods were 3.2 min., 9.5 min., and 28 min. The 9.5-min. scan was most useful, since it presented results which were a balanced compromise between the speed of the 3.2-min. scan and the resolution of the 28-min. scan. The rate at which the analog transmittance value was generated was then:

$$\frac{3750\text{ wavenumbers}}{9.5\text{ minutes}} \text{ or } 6.579\text{ wavenumbers/sec.}$$

Next was considered the operator-imposed constraint that the final result of the analysis have an accuracy of 1.5% of the actual signal value. If the %T of a sample was 100, then the controller indication was to be acceptable anywhere within the range of 98.5 to 101.5. Unfortunately, the desired accuracy was a relative quantity and for a

sample with a %T of 10, the controller would have to indicate 10 $\pm 1.5\%$, or 9.85 to 10.15. This absolute accuracy of $\pm 0.15\%T$ was the best that would ever be required of the controller, since results less than 10%T were not considered to be accurate enough for analytical work at this installation.

Based on visual examination of several Acculab 6 chart recordings, the analog T-value had a maximum slope of 100%T/wavenumber at a chart speed of 9.5 min/scan. Reserving some of the allowable error for other A/D inaccuracies, it was decided to allow most of that error, or $\pm 0.1\%T$, to be due to sampling frequency. The required sample interval was then 100/0.2, or 500 samples/wavenumber. Combining this with the previous determination, a minimum sampling rate was found:

$$\left(\frac{500 \text{ samples}}{1 \text{ wavenumber}} \right) \left(\frac{6.579 \text{ wavenumbers}}{1 \text{ second}} \right) = 3,290 \frac{\text{samples}}{\text{second}}$$

The A/D converter was therefore required to sample the Acculab 6 output every 1/3290 seconds, or every 304 μsec . This period of time was all that was available for the controller to initiate a conversion, obtain the digital value and perform storage and/or mathematical operations on the result before beginning the cycle over again.

The remaining allowable controller inaccuracy at this time was 0.05%. Allocating all of this error to converter resolution would have resulted in a converter specification of 10 bits, minimum. The numerical weight of the least significant bit (LSB) would be $1/2^{10}$, or 0.00097656, and the usual $\pm 1/2$ LSB error would be ± 0.0004883 . This was within the maximum allowable resolution error of $\pm 0.05\%$. Not yet considered, however, was the error which would be introduced by converter nonlinearity and sample-hold acquisition time. By using a 12-bit converter, the $\pm 1/2$

LSB error would be reduced to $\pm 1/2^{12}$, or $\pm 0.0122\%$. This would allow $0.05\% - 0.0122\% = 0.0378\%$ error from the other sources just mentioned. Error due to converter nonlinearity can be expected to be ± 1 LSB, at worst, for a converter of mediocre quality; therefore, it was decided to allow $\pm 0.0244\%$ error for nonlinearity. The remaining 0.0134% error was allocated to sample-hold acquisition time and a determination of that time was made next.

If, as assumed earlier, the maximum slope of the signal to be sampled was $100\%T/\text{wavenumber}$, the maximum signal slew rate in volts was:

$$\frac{100\%T}{\text{Wavenumber}} \frac{6.58 \text{ wavenumbers}}{\text{second}} \frac{1 \text{ volt}}{100\%T} = 6.58 \text{ volts/sec.}$$

This value was then used to determine the maximum frequency of the sampled signal, $e(t)$.

$$e(t) = E \sin(\omega t)$$

$$\frac{d e(t)}{dt} = E \omega \cos(\omega t)$$

$$\frac{d e(t)}{dt}_{\max} = E \omega_{\max} = 2\pi f_{\max} E \quad (1)$$

Since the maximum value of $e(t)$ was to be 1 volt, $E = 1$. Substituting the previously determined maximum slew rate,

$$6.58 = 2\pi f_{\max}$$

$$f_{\max} = 1.047 \text{ Hz}$$

Because an accuracy of 0.0134% was desired, $e(t)$ could not change in amplitude by more than 0.000134 volt during the total acquisition time window (Δt). From (1),

$$\Delta e_{\max} = 2\pi f_{\max} E \Delta t$$

$$0.000134 = 2\pi(1.047)(1)(\Delta t)$$

$$\Delta t = 20 \times 10^{-6} \text{ seconds.}$$

A search was then made of various manufacturer's literature for a 12-bit A/D converter with nonlinearity error $\leq \pm 0.0244\%$, total acquisition time of ≤ 20 μ seconds, and an input range of 0-1.0 volts. The sample-hold could have been dispensed with if such a converter existed. The most reasonable device which was found to meet the criteria was an Analog Devices DAS1150. This device contained a sample-hold amplifier with a 3- μ sec acquisition time and total overall error (including nonlinearity) of ± 1 LSB when the resistor-programmable gain was kept low. A few peripheral circuit components were required for zeroing offset and gain errors, and for setting the gain of the input stage so that the converter stage would receive a standard input range of 0-5.0 V. The circuit arrangement is illustrated in Figure 3.1.

Cost of the DAS1150 was \$200 — not cheap by any means — but this was considered money well-spent since this portion of the controller was considered to be the most probable cause of inaccurate results.

Maintainability of this device was expected to be simple, but expensive. If the module didn't work, it could have been unplugged from its sockets and replaced. The peripheral components (resistors, capacitors, potentiometers) were readily available at the work location, should any one of them fail.

3.2 PROCESS INTERFACE

Besides the analyzer output which was just discussed in Sect. 3.1, there were other interfaces between the controller and the sampling process. These consisted of open/close signals to the valves and control signals to the analyzer for initiating an analysis at the proper time.

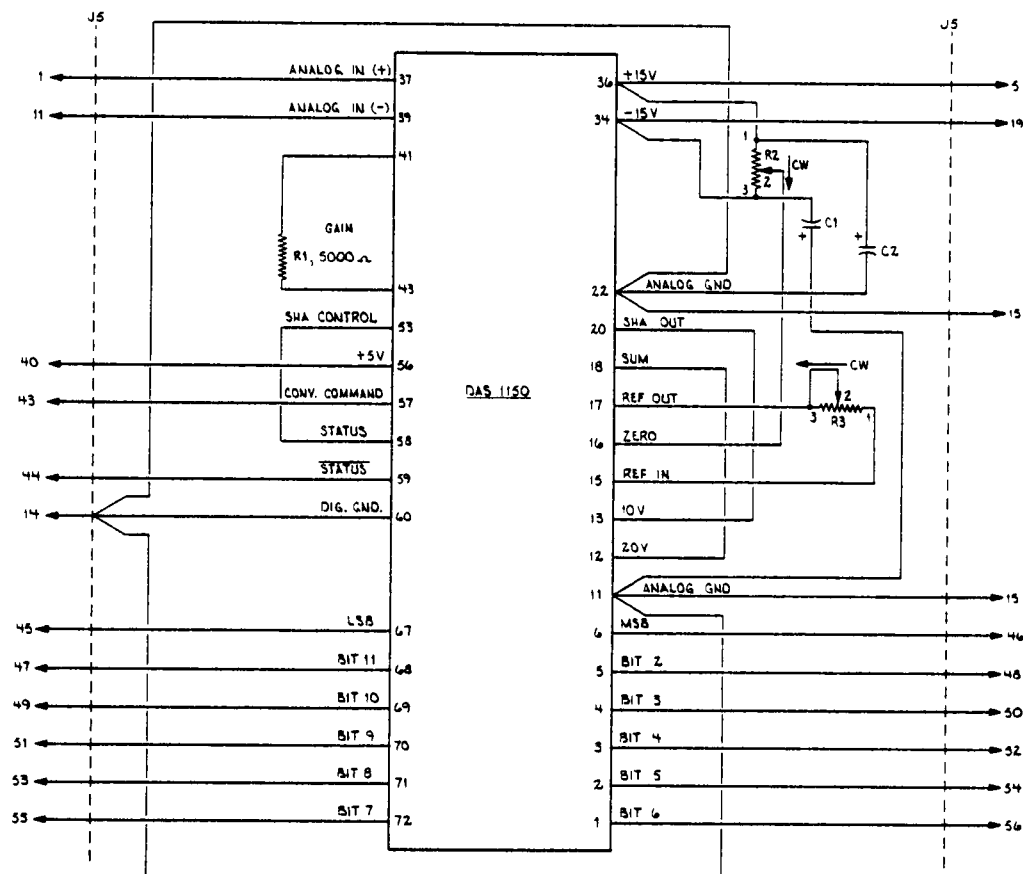
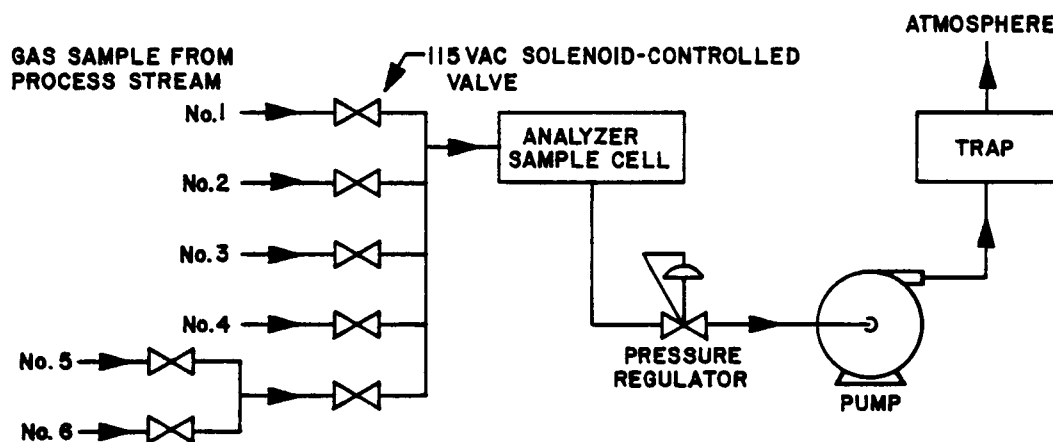


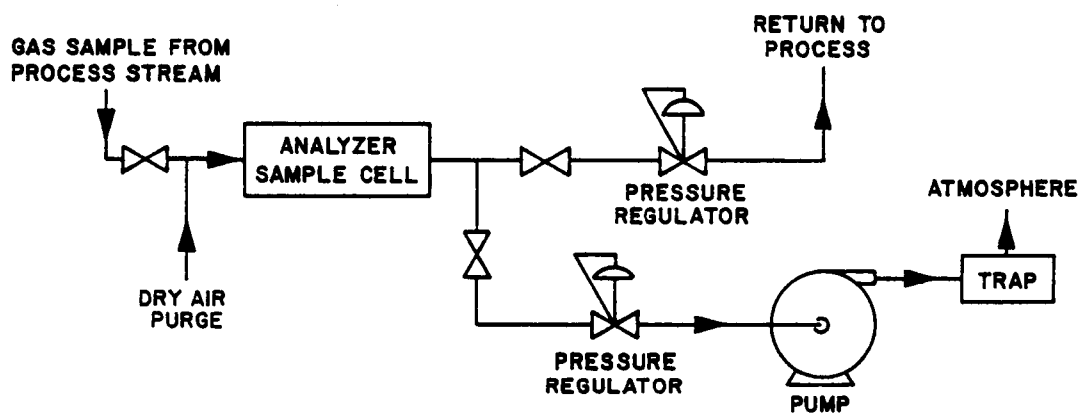
Figure 3.1. A/D converter connections.

Some flexibility had to be incorporated regarding the number of valves to be operated since some applications of the Acculab-6 involve multiple stream analysis, and nearly all applications require periodic pumpdown of the sample cell for the purpose of determining the background level at particular wavenumbers. A canvass of potential applications for the controller showed that the maximum number of valves to be manipulated in any application would be seven. Figure 3.2(a) shows a simplified representation of that application. Another typical application is shown in Figure 3.2(b) where three valves require control signals. At least seven relays would be required to manipulate the maximum number of valves in existing applications. To prevent noise within the controller, minimize hardware, provide somewhat increased reliability, and particularly to save space, solid-state relays (SSRs) were chosen instead of the standard electromechanical components. A convenient, labor-saving circuit board with sockets for 16 SSRs was purchased from Opto-22. The SSRs are driveable with 5 VDC and are optically coupled, unlike electromechanical models which require larger voltages, which in turn requires more hardware for interfacing and isolating 5-VDC logic circuitry. Another feature of the SSRs was the zero-switching capability for longer life and noise reduction. Eight of the Opto-22 SSRs in the AC OUT version were purchased to provide valve switching capability. One of these was included for further expansion convenience.

Two SSRs were used for simulating the operation of the PEN and SCAN pushbuttons. These two control relays were wired to the analyzer circuitry as shown in Figure 3.3. When the PEN button is depressed,



(a) Valves are opened one at a time for analysis of any particular stream. All valves are closed periodically to allow the pump to create a vacuum in the sample cell, at which time a background analysis is made.



(b) Valves in the sample supply and return lines are normally open. Periodically, they are closed and the pumping line valves are opened for making a background analysis.

Figure 3.2. Two typical analysis systems. The purpose of the traps is to block passage of hazardous materials. Pressure regulating devices may be used upstream and/or downstream of the sample cell, depending upon the application.

115 VAC is applied to the SCAN CHART DRIVE motor through S11, S2, and S3. The analyzer mechanism advances to the start position (wavenumber 4000), where the cam causes S11 to open, stopping the drive motor. Depression of the SCAN button causes the PEN button to release, and also restarts the SCAN CHART DRIVE motor by routing the 115VAC on S11 through the SCAN switch contacts. The motor runs until the cam causes the S11 contact to transfer back to the original position. Depression of the PEN button at this time begins the sequence again. At the controller end of the field-installed wiring, the output of the SSR simulating the PEN pushbutton was connected between C and D, and the output of the SSR used for remote SCAN operation was connected between E and F. One additional SSR was purchased and installed in the controller in the event additional control would ever be required.

The relays are very simple to maintain, as an LED indicator turns on when the relay is energized. Correct relay operation can therefore be visually determined with a 5-VDC power supply, and a defective relay may be easily unplugged from its socket and a new one inserted. A single hold-down screw on each relay provides assurance that the SSRs will not fall out of their sockets from vibrations or jostling.

At the expected operating temperature of 100°F, the SSRs would have an expected load capability of 2.4 amps — more than enough for the small solenoids commonly found in sampling systems in the facility.

Cost of the relays was \$10.50 each, and the printed circuit board price was \$40.

3.3 OPERATOR INTERFACE

During the life of any controlling device in the plant environment, there will normally occur instances which require certain forms of communication between the instrument and the operator. These forms may range from simply an on-off switch to a sophisticated CRT network where the operator can review and modify any number of processes within the plant. There are always design decisions to be made regarding just what the operator should and should not be allowed to do to the equipment, and how much the design should expect of the operator (and vice versa). The foregoing is stated to point out that there is practically no limit to the amount of interaction possibilities that could be designed into an infrared analyzer controller, but the design described in this thesis was intended to be a relatively simple one which was adequate for its intended use.

If, on his appointed rounds, an operator examined the past several analysis results and found that the proportion of a particular substance in a particular process stream was either increasing or abnormally high, he would then desire to temporarily abandon the analysis of other streams and dedicate the analyzer to monitoring the troublesome one. This need dictated that the operator be capable of stopping the scanning of other streams by the controller. Depending upon the degree of urgency for further analyses of the stream of interest, the operator might then be content with allowing the automatic analysis to continue, but on the single stream only, or conditions might have required an immediate effort to obtain an analysis of the particular stream by the return of full control of both analyzer and valves to the operator.

These two sets of conditions suggested the existence of two modes (manual and semiautomatic) of operation which would be operator-selectable, and alternative to having the controller periodically both sequence through the valves and operate the analyzer. The first interface requirement was therefore determined to be selection of operating mode. Since, as a result of operating in the semi-automatic mode, valve selection was to be made available to an operator, then that selection also became an interface requirement. Toggle switches, at a cost of only a few dollars each, were purchased for mounting on the front panel of the controller package where they would be accessible to any operator. Two switches were allocated for use in mode selection and eight (one for each SSR) for valve selection. One more switch was to be used for power-on-off.

The remaining operator interface had already been designated as an original requirement of the design, referring to the need of a paper copy of each analysis and the time each had been performed. It was also desirable to indicate the stream upon which each analysis had been performed. Because of monetary constraints, the printer to be used was, of necessity, to be limited in capability. Myriad small printers with 20- to 30-column formats were discovered for sale in various states of assembly. Some manufacturers supply the bare, mechanical chassis and the user must make the additional purchase of a power supply, communications hardware, and control logic, and then package the components himself. In other instances these small printers can be found with graphics capability, multi-color print capability, and fancy vertical mounting panels. Prices ranged from about \$80 to \$900, with the \$80 model requiring the additional hardware mentioned.

There were no other particular requirements for the printer. The standard ASCII character format would have been adequate. There were no data transmission speeds or printing speeds required, since there would have been plenty of time to print the intended information between controller-busy times. The printer chosen was a Digitec-6420, 20-column model. The 6420 prints in a 5x7 dot matrix on electrosensitive paper. Though relatively expensive, this paper is not susceptible to damage from heat exposure as are some of the heat-sensitive papers. The 6420 is complete with internal power supply, and a microprocessor for receiving ASCII codes through an 8-bit, serial character/parallel bit, TTL interface. If operation is desired in a synchronous mode, the printer provides a busy signal which indicates it is not ready to receive the next transmission. A useful "printer test" input is provided which, when grounded, causes the printer to print the entire ASCII set of characters — some in bold-face type. The printer cost \$400 and paper costs approximately \$2 per roll. One roll will contain about 6500 lines of print.

3.4 THE COMPUTER

Had price been no object in this endeavor, a Hewlett-Packard 9825 computer would have suited all other requirements nicely. A much smaller computer could meet the control needs, though with considerably more programming effort. Considerable effort was expended in determining the lowest-cost computer available with the following specifications:

1. At least 37 I/O lines (8 for valves, 3 for analyzer control, 14 for A/D control and data, 10 for printer control and data, and 2 for operator-manipulated switches.)

2. Power requirements of +5 VDC, +15 VDC, or -15 VDC, as these voltages were already required by the A/D converter and it was desired not to add to the number of power supplies needed.

3. Compatibility with 2708- or 2716-EPROM chips, since the capability to program other EPROMS did not exist at this facility. A minimum EPROM capacity of 3K was desired (1K for operating program, 2K for tables, if needed.)

4. Integral keyboard and monitor program to eliminate the need for a teletype in program development and for convenience.

5. Dependable hardware availability, including second sourcing.

6. At least 4K of RAM for data storage in the event the signal peak could not be located by executing the required software within sampling intervals.

7. Integral timing and interrupt capability.

Out of the 86 discovered candidates for a control computer, the lowest-priced computer found which met all the above specifications was the SYM-1 single-board microcomputer manufactured by Synertek Systems, Inc. The essential characteristics of the SYM-1 are:

1. 41-I/O line capability, individually programmable for either input or output.

2. Single +5-VDC power requirement.

3. Compatibility with 2716 EPROMs (up to 6K).

4. Integral keyboard with 4K monitor.

5. Incorporated the popular 6502 microcomputer and standard support chips, second-sourced by Rockwell.

6. 4K RAM capability (on-board sockets).

7. Seven on-board timers and two interrupts.

Cost of the computer and extra components required to obtain the capabilities listed above is itemized below:

1 - SYM-1	\$240
6 - 2114 RAM Chips	60
1 - 6522 Interface Chip	20
2 - 2716 EPROM Chips	<u>80</u>
TOTAL	\$400

3.5 DC POWER

Major considerations for DC power requirements were the load, regulation, and protection of the power source(s) and the controller. Parts of the controller requiring +5 VDC were the SSRs, the SYM-1, and the A/D converter. The total of the currents needed for the SYM-1 and the A/D converter was 1.63 A. Current drawn by the SSRs was considered negligible since, at most, only two or three of these would be energized simultaneously. The A/D converter required ± 15 VDC at 30 mA.

Regulation for the SYM-1 and the A/D converter supply voltages was not specified, so care was taken merely to ensure the supply purchased had less than 1% regulation.

A power supply was chosen with which this author had had previous successful experience in a microcomputer application. The supply was an Acopian 51515T6 with outputs of +5 VDC at 3.0 A, and ± 15 VDC at 500 mA. Regulation was $\pm 0.15\%$, and overvoltage and overcurrent protection were included. The AC line input is fused, as well. Remote sensing is an option, but was not required in this application. The unit cost \$180.

3.6 ODDS AND ENDS

At this time, total costs had reached \$1335, but packaging was still to be accomplished. A rather large, but portable, cabinet which was on hand was utilized. A check with the operator indicated space would be no problem for the 20" W. x 18" D. x 8" H. cabinet. Although it was a bit roomier inside than required, the extra space would make assembly and maintenance easier. Standard Amphenol connectors were used for controller I/O, and one terminal strip was added for dc-voltage distribution. Not a particularly pleasing arrangement was made for affixing the printer, as it sits atop the cabinet with the power and signal cables exposed and plugged into receptacles at the rear. A better arrangement would be to have recessed the printer flush with the cabinet top, and this will be done in the future. Figures 3.4 and 3.5 are photographs showing the exterior and interior of the prototype instrument. Wiring of the assembly is shown in Figure 3.6.

The cost of this particular cabinet was \$100, with another \$100 for connectors, switches, terminals, resistors, etc. Grand total of hardware costs for this design was \$1,535, \$235 more than the original target cost, but still significantly less than the cost of a commercial version. Several computer-controlled infrared analyzers were available, but prices ran from \$17K to \$30K and much of this cost would have been wasted on features not required.

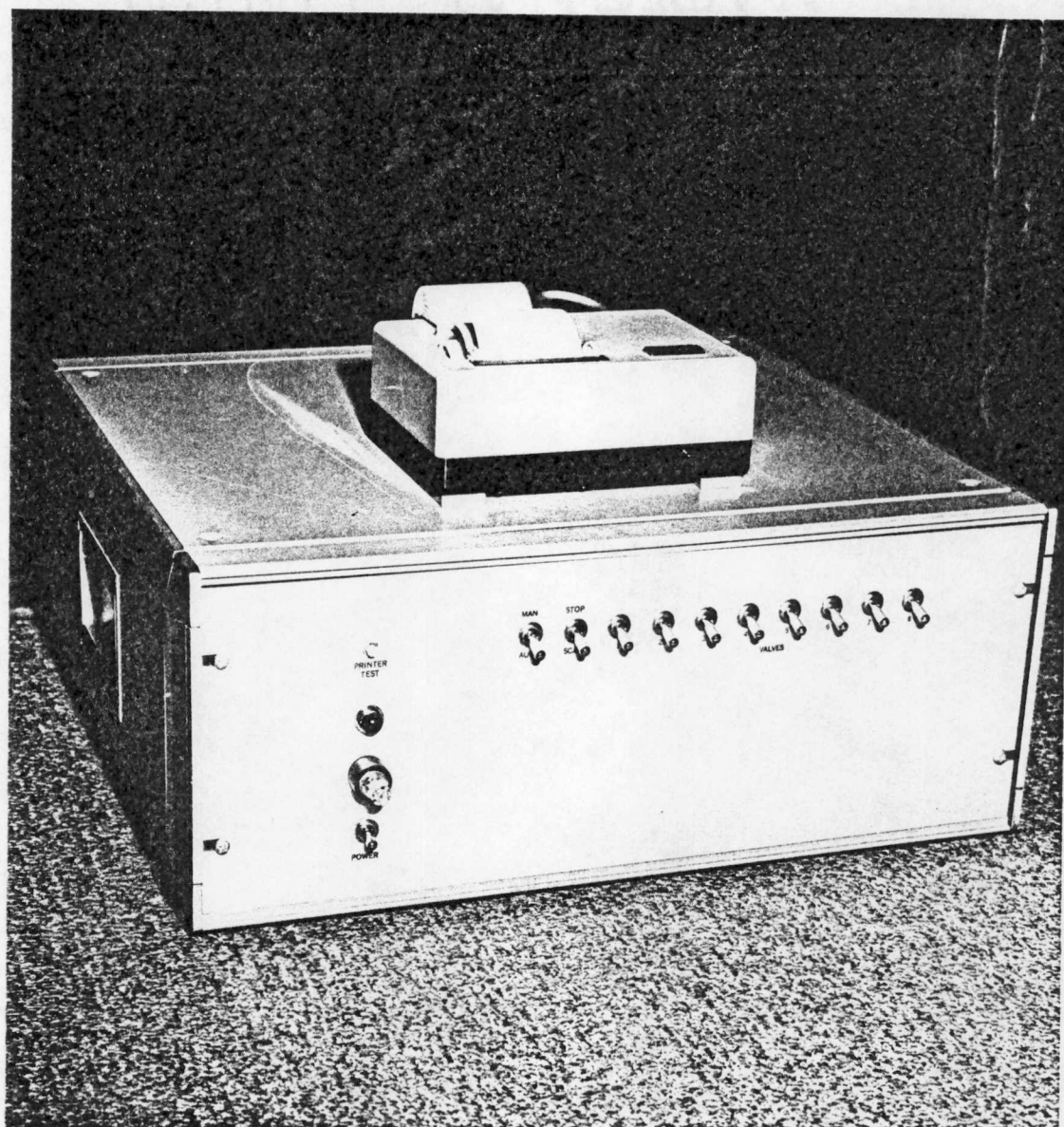


Figure 3.4. Prototype controller. Prominent features are the printer mounted atop the cabinet, row of control switches on the front panel, and the "printer test" pushbutton which makes use of the printer's built-in self-test program.

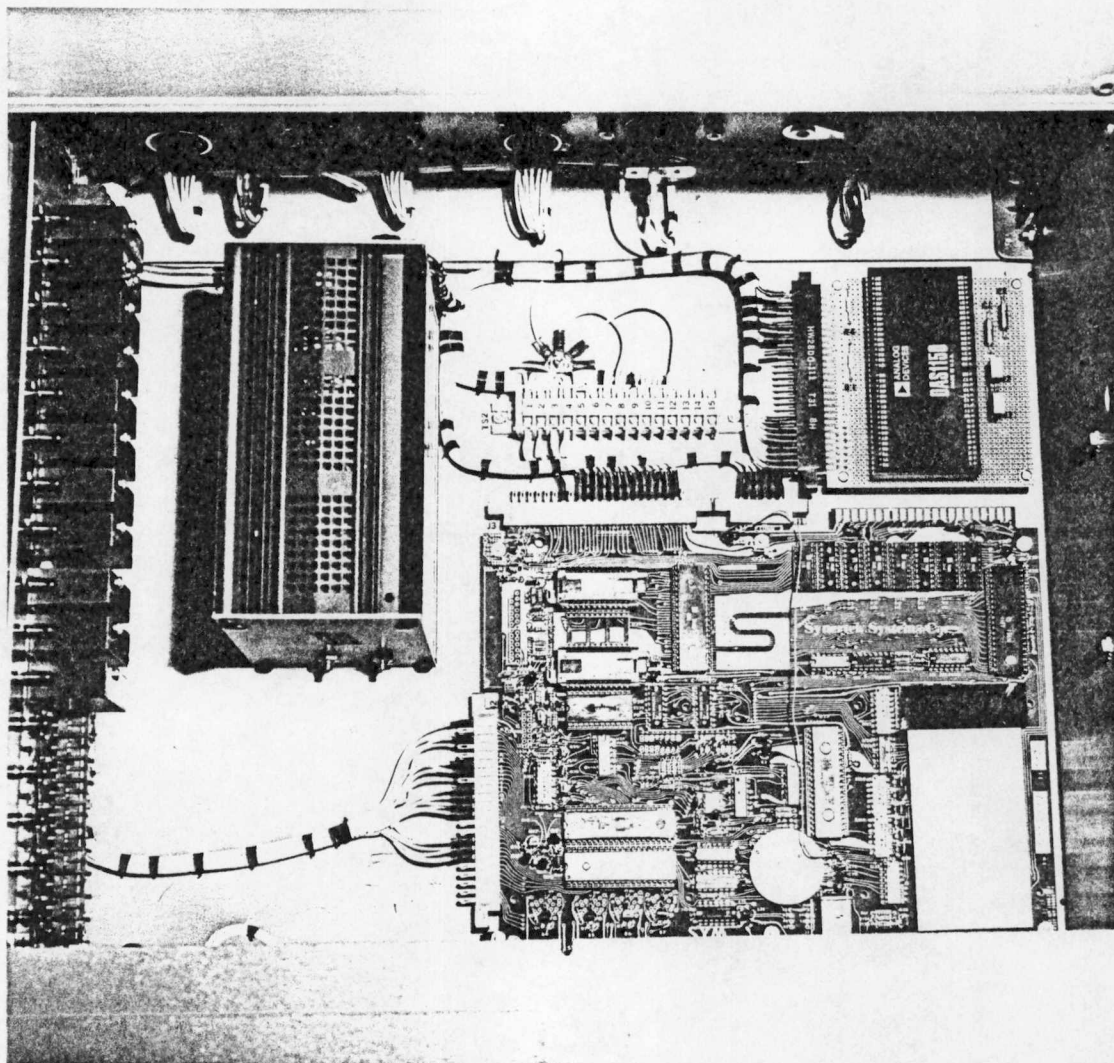


Figure 3.5. Prototype controller — top view with cover removed. At far left is the SSR mounting board with relays installed. To the right of the SSRs is the power supply. At bottom right is the SYM-1 computer. The A/D conversion system is at upper right. Power and signal distribution is accomplished through the central terminal strip and the connectors at the rear of the cabinet.

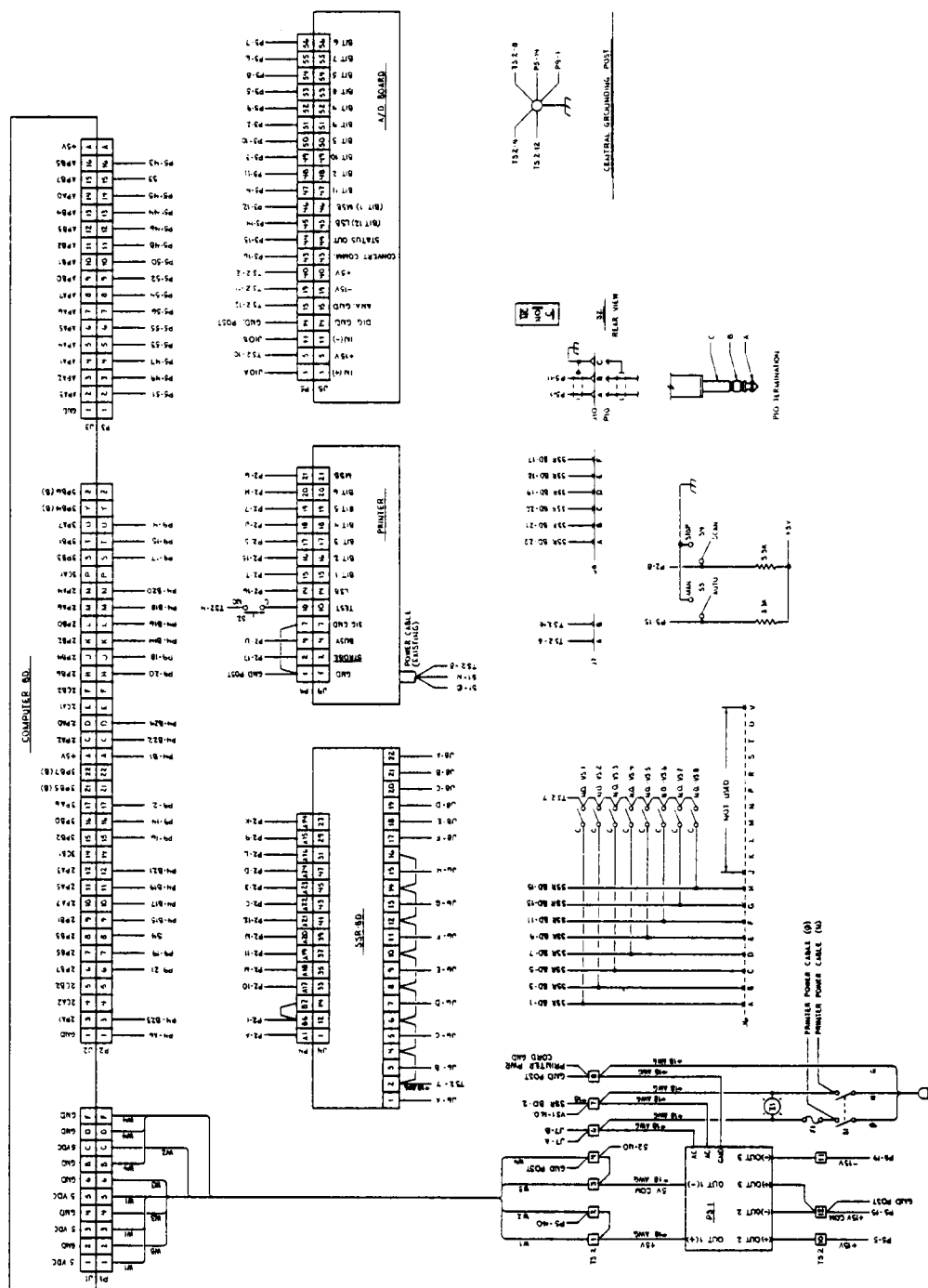


Figure 3.6. Controller wiring diagram. Analyzer analog output is received through J10. Valves are collectively supplied power through J7, and their individual return lines are received through J6.

4.0 THE SOFTWARE

The software used in the prototype instrument was created in six functional divisions:

1. Control program
2. Real-time clock interrupt routine
3. Logarithm subroutine
4. Multiply routine
5. Print subroutine
6. Manual operation routines

The control program initiates analyzer operation at appropriate intervals, detects the value of the %T at some particular wavenumber, performs valve sequencing, monitors front panel switches, and performs general housekeeping chores. By definition, the real-time clock runs continuously and was implemented using the hardware timer T1 on one of the 6522-chips on the SYM-1 board. Through the logarithm/multiply subroutine, the control program establishes the mole % of the component of interest in the sample gas, and places the BCD value in the printer buffer locations. The print subroutine then provides a paper copy of the time, the result, and the number of the stream analyzed. The SYM-1 waits for the appropriate time to begin the next analysis, then checks the front panel switches labeled MAN/AUTO and STOP/SCAN. A separate alternate mode of operation is initiated by the control program in response to the setting of each of these switches.

Since the documenting of computer software is not governed by any widely-recognized standard, and is a difficult task to perform adequately, flowcharts are not provided with the exception of the general flowchart

for the entire controller operation. This is shown in Figure 4.1. Descriptions for the software in each division are included. A commented listing of the program is included as Appendix A.

As many application-dependent parameters as possible have been kept in separate memory locations instead of being incorporated into the program statements as constants. This was to allow maximum flexibility of application of the instrument.

4.1 CONTROL PROGRAM

Upon starting the controller, the control program immediately initializes the on-board timer used in the real-time clock. Next performed is the initialization of the data direction registers, the I/O registers, and the RAM portion of the printer buffer.

An investigation is then made of the two alternate-mode switches, and one of the alternate operation routines is entered if either of the switches is activated. The stream number last sampled is checked against ASCII "X", if neither of the alternate modes has been chosen by the operator. If the last stream was "X", then the controller was in the MAN mode and resumes normal operation with stream number zero, or background. If the last stream sampled was not "X", then the next stream in sequence is sampled unless all of the streams in the system have been analyzed. In that event, stream number zero is set up for the next analysis. The I/O register controlling the valves and the ASCII stream number in the printer buffer are set to correspond to the stream number.

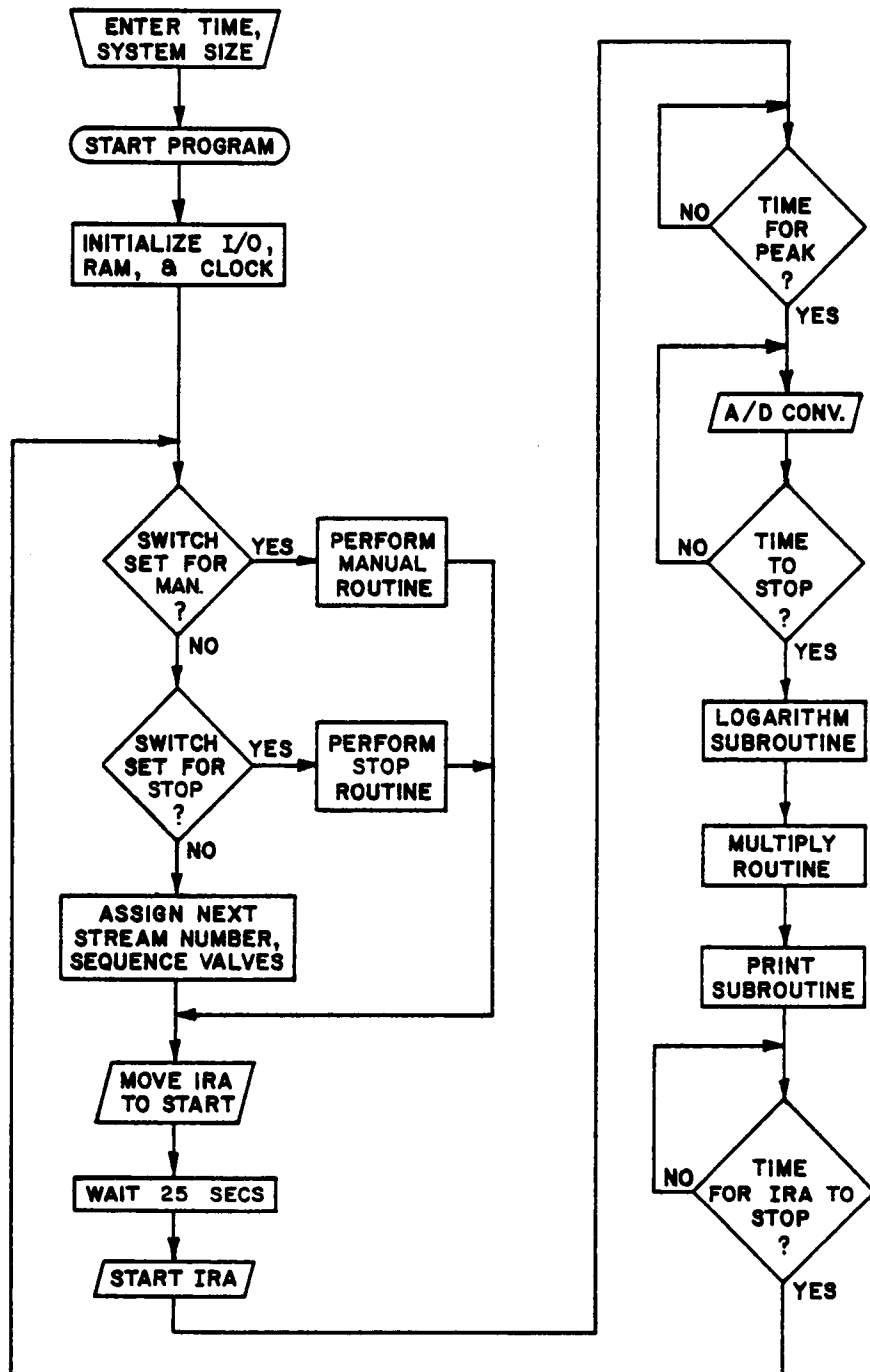


Figure 4.1. General flowchart of controller software.

The analyzer is set to the start position by simulating the operation of the analyzer PEN pushbutton with one of the SSRs in the controller. Approximately 25 seconds are required for this operation, and the controller must wait this length of time before causing an analysis to begin.

The analysis is then begun by simulating the depression of the SCAN switch on the analyzer with a second SSR. The elapsed time RAM locations are next zeroed. When these locations reach time value T1, A/D conversions are begun and are performed until time value T2 is reached. T1 and T2 must be predetermined and set in ROM, and should ideally represent as large a time window as possible to allow for any imprecision in the analyzer mechanical system. Of course, the time between T1 and T2 must not encompass any wavenumbers of gas compounds which might have a value of $\%T$ less than the compound of interest.

With the value of the peak of interest now obtained, the analyzer continues its spectrum scan and the controller tends to the matter of the logarithm and multiply routines, and the printing of the results. When the time elapsed since beginning the analysis has reached the preset value T3, a return is made to the start of the control program. The value T3 determines how often an analysis is made, and must be greater than the 9.5 minutes required for a complete spectrum scan by the analyzer.

4.2 REAL-TIME CLOCK INTERRUPT ROUTINE

A routine for initializing and servicing one of the SYM-1 on-board timers was adapted from Bach's clock program.⁶ For this application,

the display routine was discarded as unnecessary, and a binary elapsed-time clock was added, using one byte for seconds and one byte for minutes.

Whenever the hardware timer causes an interrupt, the SYM-1 goes to a RAM interrupt vector, which contains the address of the next instruction to be executed. This next instruction causes a jump to the clock servicing routine. The first instruction in this routine is a jump to a subroutine (SAVER) in the SYM-1 monitor program which saves all registers. Control is then returned to the clock servicing routine, which reloads the timer index and modifies the real-time hours/minutes/seconds, and the elapsed time minutes/seconds, if required. The time base for the clock is the 1-MHz clock cycle of the crystal on the SYM-1 board. One of the on-board timers is first loaded with the value $C350_{16}$. The timer decrements to zero at a rate of 1 count/cycle and causes an interrupt at that time. Since $C350_{16} = 50 \times 10^3_{10}$, then the countdown will be completed each $(1 \mu\text{sec}) \times (50 \times 10^{-3}) = 50 \text{ msec}$. The number of 50 msec countdowns is totaled in the index TIME, a RAM location, and when twenty of these have occurred, the clock is updated. The time required to service the clock is not consequential, because the timer reloads the C350 value automatically and begins decrementing again.

After the timer/clock is serviced as necessary, the clock routine restores all registers which were originally saved by SAVER, and executes a return-from-interrupt.

Since the real-time values of hours and minutes are stored in BCD form, these values have to be converted to ASCII before storing

them in the printer buffer. The subroutine "ASCII" was written to perform this function, and must be called before attempting to print the current time.

4.3 LOGARITHM SUBROUTINE

In order to solve the prescribed equation

$$\text{mole } \%_X = \left[\log_{10} \left(\frac{\%T_o}{\%T} \right) \right] \left[K(X, \text{cm}^{-1}) \right],$$

a logarithm-finding routine was required. A particularly useful one was found for calculating $\log_b x$, where $1 \leq x < 2$ and b is any number.⁷ To apply this algorithm, the A/D converter output and the peculiarities of the signal scale had to be examined in detail.

The 12-bit converter output corresponding to $\%T$ is always a number between 0 and 4095, inclusive. This number may be expressed as a product of $(2^n)(1.X)$ where $0 \leq n \leq 11$ and X is composed of twelve binary digits. This is illustrated by the following example:

n	11	10	9	8	7	6	5	4	3	2	1	0
12-bit binary number	0	0	1	0	1	1	1	0	0	0	1	1
1.X	1. 0 1 1 1 0 0 0 1 1 0 0 0											

Notice that this follows since n is the number of one-digit shifts to the left required to make the binary $1.X$ equal to the 12-bit binary whole number result. The logarithm of the A/D converter output to the base ten can be calculated as $\log_{10} [(2^n)(1.X)] = \log_{10}(2^n) + \log_{10}(1.X) = n \log_{10}(2) + \log_{10}(1.X)$. By shifting the converter output to the left until a logic 1 appears in the 13th-bit position, n will have been determined as 12- (no. of shifts required).

This procedure was implemented in the logarithm routine by setting an index register to 12 and decrementing the register each time the converter output was shifted left one digit. This operation was performed until the leading one was in the thirteenth bit position. The value remaining in the index register was then multiplied by $\log_{10} 2$. The quantity $\log_{10} 1.X$ was then found by implementing the routine described by Knuth.⁷ The entire logarithmic portion of the equation was evaluated as follows:

$$\begin{aligned}
 \log_{10} \left(\frac{\%T_o}{\%T} \right) &= \log_{10} \left(\%T_o \right) - \log_{10} \left(\%T \right) \\
 &= \log_{10} \left(\frac{\text{A/D value}_o}{4096} \times 100 \right) \\
 &\quad - \log_{10} \left(\frac{\text{A/D value}}{4096} \times 100 \right) \\
 &= \log_{10} \left(\text{A/D value}_o \right) - \log_{10} 4096 + \log_{10} 100 \\
 &\quad - \log_{10} (\text{A/D value}) + \log_{10} 4096 - \log_{10} 100 \\
 &= \log_{10} \left(\text{A/D value}_o \right) - \log_{10} (\text{A/D value})
 \end{aligned}$$

where all quantities subscripted o are background signal values.

4.4 MULTIPLY ROUTINE

A routine was required to multiply $K(x, \text{cm}^{-1})$ by $\log_{10} \left(\frac{\%T_o}{\%T} \right)$. The latter expression would always be a number between 0 and 1, and would be available in the double-precision format $0.NNN_{16}$, where N is any hexadecimal integer. For the variety of applications found in this plant, K

was to be assigned one of hundreds of values ranging from roughly 1 to 1000 depending upon the application. In general, then, the multiplication of these two quantities involved the operation

$$(0.NNN_{16}) (NNN.NN_{16}) = NNN.NNNNN_{16} \quad (2)$$

A general procedure for performing an 8 x 8-bit multiply was listed by Leventhal.⁸ This procedure was utilized in the form of a subroutine in order to perform the more extensive operation given in (2), as illustrated in Figure 4.2. Leading zeros have been added to achieve a convenient 8-bit format for each term. Once this was performed, the product had to be converted first to a BCD form and then to ASCII. The hexadecimal-to-BCD subroutine used was found in Weller.⁹ The assembly language in which this conversion was presented was for an 8080 microprocessor, but translation was not difficult. Since the code conversion routine was valid only for whole numbers, a second conversion routine had to be created for finding the BCD representation of a binary fraction. Once the two routines were established, the useful integer and fractional portions of the 40-bit product were separated by the use of shift and logical OR commands, converted first to BCD, and then ASCII. These operations were performed as shown in Figure 4.3. Note that before these operations were performed, the three most significant, and the three least significant hexadecimal digits were dropped from the 40-bit product. This was justified since the most significant digits would never occur in actual application, and the three least significant digits represent, at most, a decimal fraction less than 0.004. Note also that, once the BCD representation was obtained, the least significant decimal digit was dropped due to its small value of ≤ 0.009 . The

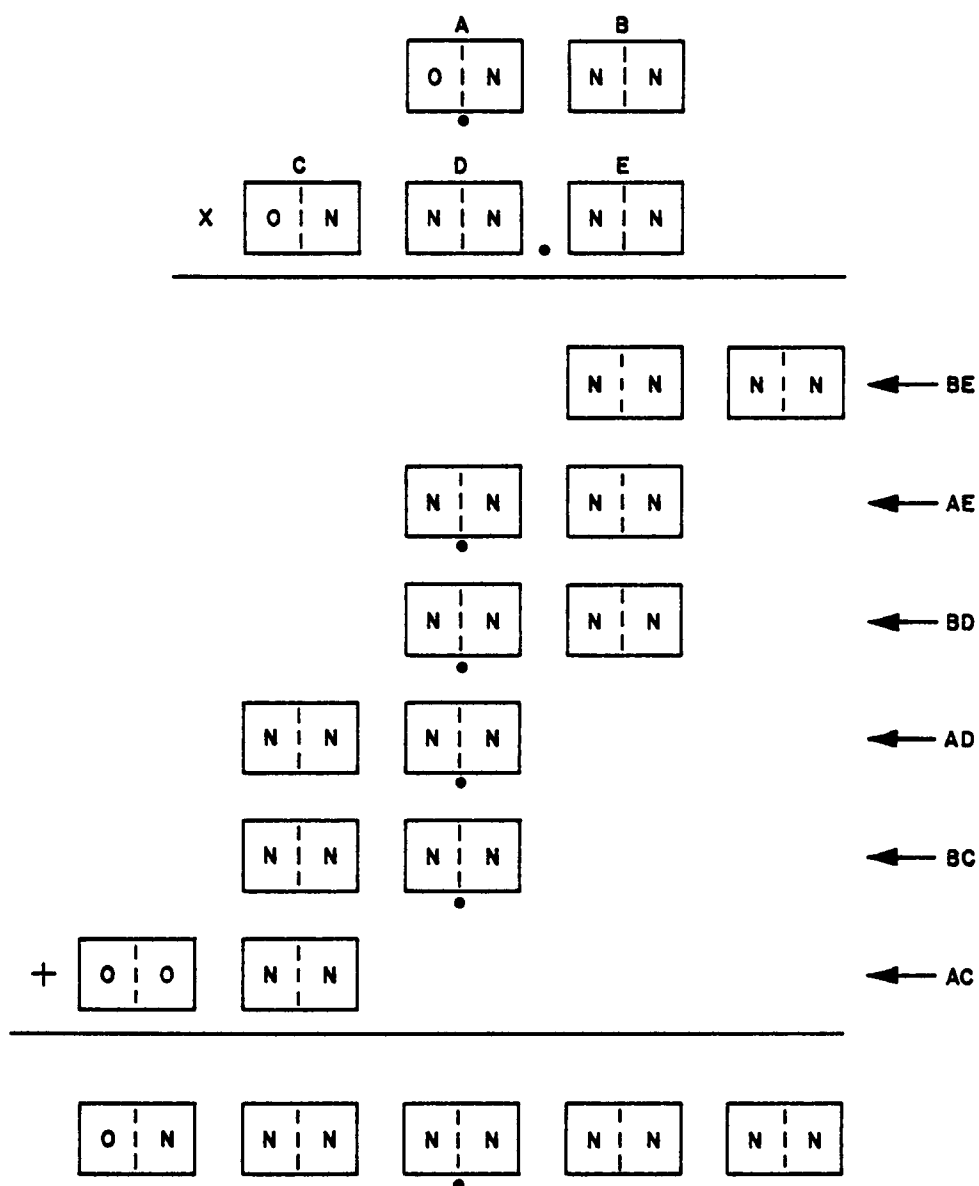


Figure 4.2. Method of combining 8 x 8-bit products to obtain a 16 x 24-bit multiply. N represents any hexadecimal integer. Leading zeros are shown to fulfill 8-bit format requirements.

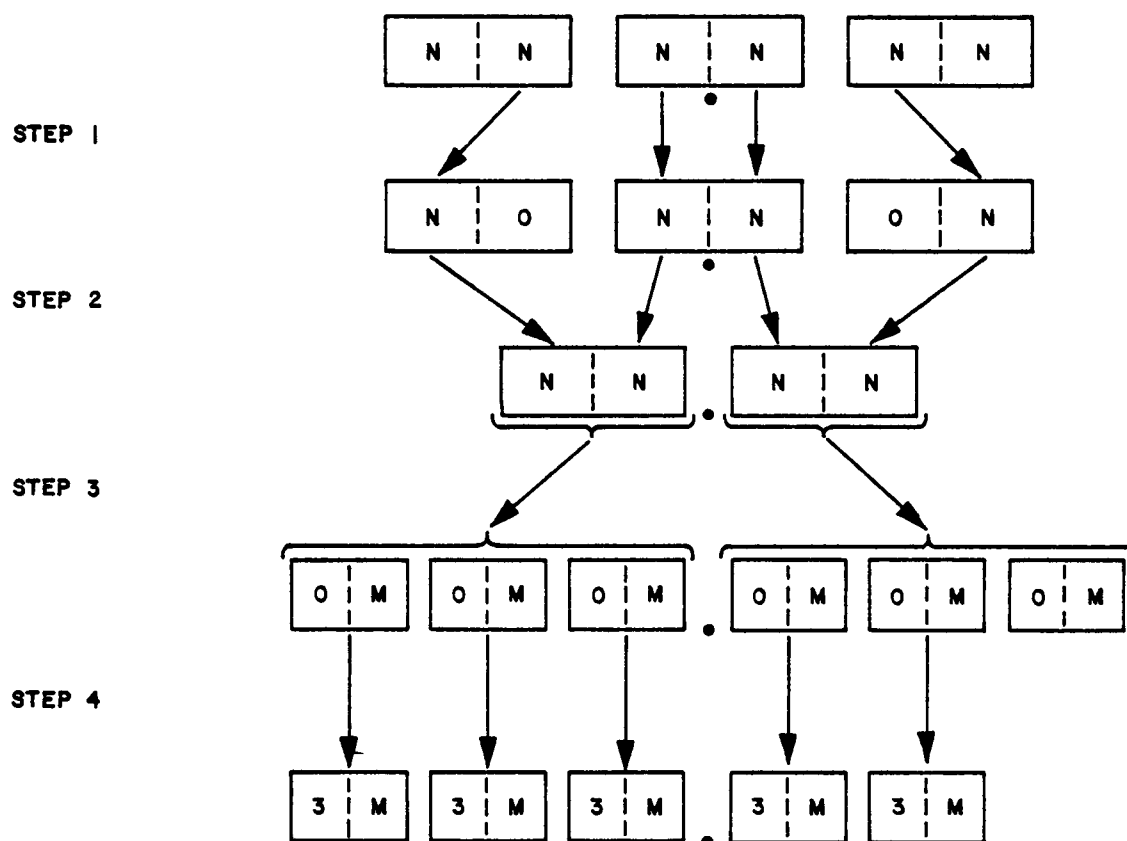


Figure 4.3. Binary to ASCII decimal conversion. Steps 1 and 2 arrange the 16 useful bits into convenient relationship with the decimal point. Step 3 converts the 8-bit words to three BCD digits each (six locations). Step 4 places a "3" in the most significant four bits of each location. M represents the presence of a decimal number.

designer felt that the total error (≤ 0.013) introduced in both the above cases was justified, since this error was likely to be introduced anyway, when the math was performed manually.

4.5 PRINT ROUTINE

Since only a limited number of messages were intended to be printed on the prototype controller, these messages were stored in ASCII format in ROM. Messages, or parts of messages, which would require change during program execution were moved to RAM in the initialization portion of the control routine. Each message was divided into lines, which became the basic unit of print. The print routine must, therefore; be called each time a printed line is required. The calling program places the starting address of the line to be printed into a particular pair of RAM locations before calling this routine. Post-indexed indirect addressing is used to print the proper line of text, which is terminated with a null character.

4.6 ALTERNATE MODE ROUTINES

These two routines are actually part of the control program. The first action taken in each routine is to determine if the rest of the routine should be executed or skipped.

Should the SYM-1 find the AUTO/MAN switch in the MAN position, the controller closes all valves but continues to cause infrared analyses to be made on schedule. The stream selection must be made by the operator, using the front panel switches. The word "MANUAL" and the time are printed, and an ASCII "X" is loaded into the printer buffer so that at

the end of the next analysis, the printed record will reflect an operator-selected stream. The portion of the control program is skipped which opens the proper valve and puts the corresponding new stream number into the printer buffer.

If the SCAN/STOP switch is found in the STOP position, all valves are then closed, the words "ALL STOP" and the time are printed, and all operation ceases, except for the real-time clock and the continuing examination of this switch by the SYM-1. Full control of both the analyzer and valves is given to the operator. As soon as this switch is returned to the SCAN position, full control is returned to the instrument and the printer writes the word "AUTO" and the time.

5.0 TRIAL RUN AND EVALUATION

After a considerable amount of both hardware and software debugging, a proof-of-principle experiment was performed with a sample, at 100 torr absolute pressure, of approximately 10% $C_2Cl_2F_4$ (Freon 114) by molar concentration in dry air. The operations necessary to perform the experiment, and which are described here, are typical of those required to use the controller-analyzer combination in an application where one simple peak is detected and analyzed. An application requiring interpretation of interfering peaks would require software modification, as would a different sample pressure.

During setup of the analyzer, the discovery was made that the auxiliary output to be used was not capable of adjustment over the range of 0.0-1.0 volts, as was previously calculated. An operable range of 0.0-0.9 volts was used, and the gain resistor on the controller A/D converter was accordingly changed to 4400 ohms. The sample cell containing the Freon 114 was placed into the analyzer and a normal manual scan of the gas was made for timing purposes. The time required for the analyzer to advance to the Freon 114 peak at 1270 cm^{-1} was ≈ 5 min, 45 sec, and an estimate was made that the leading and trailing edges of the peak base were at 5:40 and 5:47, respectively. These were converted to $01:54_{16}$ and $01:5B_{16}$ and programmed into the 2716 PROM at locations C7C0 thru C7C3. The reader must note that 1 minute = 256 seconds for these locations. The time elapsed when the analyzer finished the scan and shut off was found to be just under 11 minutes, 20 seconds. A value of $02:B7_{16}$ was programmed into the PROM at locations C7C4-C5. This value allowed 11 minutes, 35 seconds for a complete scan, not including

the 25 seconds required to move from the standby to the start position. An analysis would, therefore, be available every 12 minutes.

The K-factor for Freon 114 at its peak at 1270 cm^{-1} and with a 6-cm path length was 21.5. This value was stored in the PROM at locations C792-94 as the hexadecimal value 0015.10_{16} . The desired extent of the experimental system was two gas streams plus the usual background reading, for a total system of three. This number was stored in RAM location 0016.

The two cables were connected between the analyzer and the controller, and the analyzer pushbuttons were all set to the release position.

The real-time clock datum was entered into RAM at 0000-02, and the SYM-1 was instructed to begin execution at C000.

The results of 2 cycles through the simulated system are shown in Table 5.1. The sample cell was only placed into the analyzer when stream 1 was undergoing analysis. A power supply was used to simulate a background scan when streams 0 and 2 were being analyzed. The power supply was set to give the A/D converter the voltage corresponding to a background scan which had been made a few days before with the same sample cell. This allowed the analyzer to compare two different scans of the same composition. Additional tests of the controller were performed with only a power supply used as an input. The voltage input to the A/D converter was decreased at intervals to simulate an infrared scan with various background and peak values. The results of this simulation are also presented in Table 5.1.

As the results of the preliminary tests indicate, the performance principle of this design appears successful. Further testing with better test equipment than was available to the author will be necessary to determine exact performance.

Table 5.1. Preliminary Test Results

A/D Input		Controller Result	Actual Result
Background	Power supply = 0.850V		
Stream #1	Analyzer	10.86% Freon	9.54%
Stream #2	Power supply = 0.850V	00.00%	00.00%
Background	Power supply = 0.850V		
Stream #1	Analyzer	10.80%	9.81%
Stream #2	Power supply = 0.850V	00.00%	00.00%
Background	Power supply = 0.897		
Stream #1	Power supply = 0.897	00.00%	00.00%
Stream #2	Power supply = 0.875	00.22%	00.23%
Background	Power supply = 0.846		
Stream #1	Power supply = 0.779	00.74%	00.77%
Stream #2	Power supply = 0.778	00.74%	00.78%
Background	Power supply = 0.578		
Stream #1	Power supply = 0.558	00.31%	00.33%
Stream #2	Power supply = 0.544	00.54%	00.57%
Background	Power supply = 0.543		
Stream #1	Power supply = 0.343	04.17%	04.29%
Stream #2	Power supply = 0.071	<10%T	NA
Background	Power supply = 0.851		
Stream #1	Power supply = 0.097	19.88%	20.28%
Stream #2	Power supply = 0.228	12.05%	12.29%

The approximate final cost of the analyzer is itemized in Table 5.2. The extra 2114-RAM chips and one of the 2716-EPROM chips which were originally purchased are not included in the total cost, since they are not required for normal operation. Hardware costs could be further reduced by spending more time on the design of the converter and printer circuitry, and constructing these from discrete components. A cheaper cabinet could also be used.

Table 5.2. Final Hardware Cost

Quantity	Item	Cost
1	A/D converter	\$ 200
11	SSRs	115
1	SSR PC board	40
1	Printer	400
1	Power supply	180
1	SYM-1 microcomputer	240
1	6522 Interface chip	20
1	2716 EPROM chip	40
1	Cabinet	100
	Miscellaneous hardware	<u>100</u>
	TOTAL	\$1435

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APPENDIXES

APPENDIX A

CONTROL PROGRAM

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C000	EA	DAY1:	NOP	BEGIN INITIALIZATION.
01	A9 00		LDA #00	I/O REGISTERS AND
03	8D 03 A0		STA A003	DATA DIRECTION REGISTERS.
06	8D 00 A0		STA A000	
09	A9 FF		LDA #FF	
0B	8D 00 A8		STA A800	
0E	8D 03 A8		STA A803	
11	8D 01 AC		STA AC01	
14	8D 02 AC		STA AC02	
17	A9 FE		LDA #FE	
19	8D 01 A8		STA A801	
1C	A9 20		LDA #20	
1E	8D 02 A0		STA A002	
21	A9 F7		LDA #F7	
23	8D 02 A8		STA A802	
26	AD 03 AC		LDA AC03	
29	09 40		ORA #40	
2B	29 40		AND #40	
2D	8D 03 AC		STA AC03	
30	A2 00		LDX #00	RAM PORTION OF PRINTER
32	BD C6 C7	BUFF:	LDA C7C6,X	BUFFER.
35	9D 27 00		STA 0027,X	
38	E8		INX	
39	8A		TXA	
3A	C9 22		CMP #22	
3C	D0 F4		BNE BUFF	
3E	A9 58		LDA #58	STREAM NUMBER.
40	85 2E		STA STREAM	
42	20 86 8B		JSR ACCESS	CLOCK.
45	A9 95		LDA #INTL	
47	8D 78 A6		STA IRQVEC	
4A	A9 C7		LDA #INTH	
4C	8D 79 A6		STA IRQVEC+1	
4F	A9 C0		LDA #C0	
51	8D 0E A0		STA IER	
54	A9 40		LDA #40	
56	8D 0B A0		STA ACR	
59	A9 40		LDA #40	
5B	8D 06 A0		STA T1LL	
5E	A9 C3		LDA #C3	
60	8D 05 A0		STA T1CH	
63	A9 EC		LDA #EC	
65	85 23		STA TIME	
C067	58		CLI	END INITIALIZATION.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C068	A9 08	MANUAL:	LDA #08	BEGIN MANUAL ROUTINE.
6A	2D 00 A8		AND A800	IF AUTO/MAN SWITCH = MAN,
6D	D0 2B		BNE STOP	CONTINUE ANALYZER OPERATION
				WITHOUT SEQUENCING VALVES.
6F	A5 2E		LDA STREAM	OTHERWISE, RETURN.
71	49 58		EOR #58	IF STREAM# IS ALREADY "X",
73	F0 22		BEQ STOP-3	DO NOT PERFORM THIS
75	A9 FF		LDA #FF	ROUTINE AGAIN.
77	8D 01 A8		STA A801	CLOSE ALL VALVES.
7A	A9 58		LDA #58	
7C	85 2E		STA STREAM	SET STREAM# IN PRINTER
7E	A9 98		LDA #98	BUFFER TO ASCII "X".
80	85 21		STA LINUML	PRINT "MANUAL" AND TIME.
82	A9 C7		LDA #C7	
84	85 22		STA LINUMH	
86	20 00 C4		JSR PRINT	
89	A9 31		LDA #31	
8B	85 21		STA LINUML	
8D	A9 00		LDA #00	
8F	85 22		STA LINUMH	
91	20 5F C5		JSR ASCII	
94	20 00 C4		JSR PRINT	END MAN ROUTINE.
97	4C 0D C1		JMP IRAGO	
9A	A9 80	STOP:	LDA #80	BEGIN STOP ROUTINE. IF
9C	2D 00 A0		AND A000	SCAN/STOP SWITCH = STOP,
9F	D0 44		BNE BACK	STOP ALL OPERATION,
A1	A9 FF		LDA #FF	OTHERWISE, RETURN.
A3	8D 01 A8		STA A801	CLOSE ALL VALVES
A6	8D 00 A8		STA A800	
A9	A9 A6		LDA #A6	PRINT "ALL STOP" BY LOADING
AB	85 21		STA LINUML	START ADDRESS OF LINE 6
AD	A9 C7		LDA #C7	INTO 0021,0022, AND JUMP
AF	85 22		STA LINUMH	TO PRINT.
B1	20 00 C4		JSR PRINT	
B4	A9 31		LDA #31	PRINT TIME.
B6	85 21		STA LINUML	
B8	A9 00		LDA #00	
BA	85 22		STA LINUMH	
BC	20 5F C5		JSR ASCII	
BF	20 00 C4		JSR PRINT	
C2	A9 80	CHSW:	LDA #80	CHECK FOR SWITCH
C4	2D 00 A0		AND A000	RETURNED TO SCAN.
C7	F0 F9		BEQ CHSW	
C9	A9 A0		LDA #A0	PRINT "AUTO" AND TIME.
CB	85 21		STA LINUML	
CD	A9 C7		LDA #C7	
CF	85 22		STA LINUMH	
C0D1	20 00 C4		JSR PRINT	

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
COD4	A9 31		LDA #31	
D6	85 21		STA LINUML	
D8	A9 00		LDA #00	
DA	85 22		STA LINUMH	
DC	20 5F C5		JSR ASCII	
DF	20 00 C4		JSR PRINT	END STOP ROUTINE.
E2	4C FD C0		JMP AROUND	
E5	EA	BACK:	NOP	
E6	A9 58		LDA #58	IF STREAM = X, RESET TO 0
E8	C5 2E		CMP STREAM	FOR RETURN TO NORMAL
EA	F0 11		BEQ AROUND	OPERATION.
EC	0E 01 A8		ASL DR	VALVE OUTPUT REGISTER
				SEQUENCE.
EF	EE 01 A8		INC DR	
F2	A5 2E		LDA STREAM	
F4	29 0F		AND #0F	
F6	18		CLC	
F7	69 01		ADC #01	
F9	C5 16		CMP SYSTEM	TIME FOR BACKGROUND CHECK
FB	D0 0C		BNE VALVE	IF STREAM #># OF SAMPLE
FD	A9 30	AROUND:	LDA #30	LINES.
FF	85 2E		STA STREAM	
01	A9 FE		LDA #FE	
03	8D 01 A8		STA DR	
06	4C 0D C1		JMP IRAGO	
09	09 30	VALVE:	ORA #30	
0B	85 2E		STA STREAM	
0D	A9 F5	IRAGO:	LDA #F5	MOVE ANALYZER TO
0F	8D 00 A8		STA A800	START POSITION.
				WAIT UNTIL THERE.
12	A2 01		LDX #01	
14	A0 01		LDY #01	
16	A9 4D		LDA #4D	
18	85 26		STA Z	
1A	20 50 C4		JSR DELAY	
1D	A9 F6		LDA #F6	ANALYZER READY, GIVE
1F	8D 00 A8		STA A800	START SIGNAL.
22	A9 00		LDA #00	INITIALIZE ELAPSED TIMER
24	85 24		STA ETMIN	LOCATIONS
26	85 25		STA ETSEC	
28	78	PEAK:	SEI	WAIT UNTIL TIME FOR PEAK.
29	A5 24		LDA ETMIN	CHECK MINUTES.
2B	CD C0 C7		CMP TIMIN	
2E	F0 04		BEQ SCNDS	
30	58		CLI	
31	4C 28 C1		JMP PEAK	
34	78	SCNDS:	SEI	
35	A5 25		LDA ETSEC	CHECK SECONDS.
37	CD C1 C7		CMP T1SEC	
3A	58		CLI	
C13B	F0 03		BEQ CONV1	

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C13D	4C 34 C1		JMP SCNDS	
40	A9 0F	CONV1:	LDA #0F	
42	85 0D		STA MEM+1	
44	A9 FF		LDA #FF	
46	85 0C		STA MEM	
48	78	CONV2:	SEI	
49	A9 20		LDA #20	RESET A/D.
4B	8D 00 A0		STA A000	
4E	A9 00		LDA #00	CONVERT COMMAND
50	8D 00 A0		STA A000	
53	AD 00 A0	STATUS:	LDA A000	CHECK A/D STATUS
56	29 10		AND #10	UNTIL NOT BUSY.
58	F0 F9		BEQ STATUS	
5A	AD 00 A0		LDA A000	GET A/D RESULT.
5D	29 0F		AND #0F	
5F	85 0F		STA MEM+3	HIGH-ORDER 4 BITS.
61	AD 01 A0		LDA A001	
64	85 0E		STA MEM+2	LOW-ORDER BYTE.
66	38		SEC	COMPARE HIGH-ORDER BITS.
67	A5 0F		LDA MEM+3	
69	C5 0D		CMP MEM+1	
6B	90 0B		BCC SWITCH	IF NEW RESULT IS LESS,
6D	D0 11		BNE NSWITCH	SAVE NEW RESULT
6F	A5 0E		LDA MEM+2	
71	C5 0C		CMP MEM	
73	90 03		BCC SWITCH	
75	4C 80 C1		JMP NSWITCH	
78	A5 0E	SWITCH:	LDA MEM+2	
7A	85 0C		STA MEM	
7C	A5 0F		LDA MEM+3	
7E	85 0D		STA MEM+1	
80	A5 24	NSWITCH:	LDA ETMIN	CHECK FOR TIME TO STOP
82	CD C2 C7		CMP T2MIN	TAKING DATA.
85	F0 04		BEQ CKSEC	
87	58		CLI	
88	4C 48 C1		JMP CONV2	
8B	A5 25	CKSEC:	LDA ETSEC	
8D	CD C3 C7		CMP T2SEC	
90	F0 04		BEQ MATH	
92	58		CLI	
93	4C 48 C1		JMP CONV2	
96	58	MATH:	CLI	
97	20 20 C2		JSR LOG	
9A	A9 27		LDA #27	STARTING ADDRESS OF LINE 1.
9C	85 21		STA LINUML	
9E	A9 00		LDA #00	
A0	85 22		STA LINUMH	
A2	20 00 C4		JSR PRINT	
A5	A9 31		LDA #31	STARTING ADDRESS OF LINE 2.
C1A7	85 21		STA LINUML	

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C1A9	20 5F C5		JSR ASCII	
AC	20 00 C4		JSR PRINT	
AF	A9 38		LDA #38	STARTING ADDRESS OF LINE 3.
B1	85 21		STA LINUML	
B3	20 00 C4		JSR PRINT	
B6	A5 24	TMSTOP:	LDA ETMIN	CHECK FOR TIME FOR IRA TO
B8	CD C4 C7		CMP T3MIN	STOP.
BB	D0 F9		BNE TMSTOP	
BD	A5 25	SPEC:	LDA ETSEC	
BF	CD C5 C7		CMP T3SEC	
C2	D0 F9		BNE SPEC	
C1C4	4C 68 C0		JMP MANUAL	TIME TO START OVER AGAIN.

REAL-TIME CLOCK ROUTINE

Entered through an interrupt vector when the on-board counter decrements to zero every 50 msec.

Returns with clock locations for real-time HR/MIN/SEC and elapsed time MIN/SEC updated. Saves all registers.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C1D0	20 88 81	CLOCK:	JSR SAVER	
D3	E6 23		INC TIME	COUNT # OF 50 msec INTERVALS.
D5	D0 38		BNE DONE	
D7	E6 25		INC ETSEC	# OF INTERVALS=20, SO UPDATE ELAPSED- AND REAL-TIME CLOCKS.
D9	D0 02		BNE NOMIN	IF 256 SECONDS HAVE ELAPSED,
DB	E6 24		INC ETMIN	INCREMENT ELAPSED-TIME MINUTES.
DD	F8	NOMIN:	SED	
DE	18		CLC	
DF	A5 02		LDA RTSEC	
E1	69 01		ADC #01	
E3	85 02		STA RTSEC	
E5	C9 60		CMP #60	IF SECONDS=60, LET SECONDS=0
E7	90 22		BCC COUNT	AND ADD 1 TO MINUTES.
E9	A9 00		LDA #00	
EB	85 02		STA RTSEC	
ED	18		CLC	
EE	A5 01		LDA RTMIN	
FO	69 01		ADC #01	
F2	85 01		STA RTMIN	
F4	C9 60		CMP #60	IF MINUTES=60, LET MINUTES=0
F6	90 13		BCC COUNT	AND ADD 1 TO HOURS.
F8	A9 00		LDA #00	
FA	85 01		STA RTMIN	
FC	18		CLC	
FD	A5 00		LDA RTHR	
FF	69 01		ADC #01	
01	85 00		STA RTHR	
03	C9 24		CMP #24	IF HOURS=24, LET HOURS=0.
05	90 04		BCC COUNT	
07	A9 00		LDA #00	
09	85 00		STA RTHR	
0B	A9 EC	COUNT:	LDA #EC	
0D	85 23		STA TIME	"TIME"=0 EVERY 1 SECOND.
0F	AD 04 A0	DONE:	LDA TILL2	
12	D8		CLD	
13	68		PLA	RETRIEVE REGISTERS FROM STACK.
C214	A8		TAY	

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C215	68		PLA	
16	AA		TAX	
17	68		PLA	
18	28		PLP	
C219	40		RTI	

LOGARITHM SUBROUTINE

Enter with low-order byte of A/D output in MEM, and high-order byte in MEM+1.

Exit with $\log_{10}$ (A/D output) in NUM2+1, NUM2, and proceed directly to Multiply routine. Destroys X, Y, A.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C220	A5 0D	LOG:	LDA MEM+1	CHECK TO FIND IF A/D OUTPUT IS LESS THAN 10% OF FULL SCALE. IF SO, GO TO TLOW ROUTINE.
22	38		SEC	
23	E9 01		SBC #01	
25	90 08		BCC JUMP	
27	D0 09		BNE CNTNU	
29	A5 0C		LDA MEM	NUMBER OF LEFT SHIFTS (12-N) IS KEPT IN Y.
2B	E9 9A		SBC #9A	
2D	B0 03		BCS CNTNU	
2F	4C 06xC3	JUMP:	JMP TLOW	
32	A0 0C	CNTNU:	LDY #0C	
34	A5 0D		LDA MEM+1	SHIFT 12-BIT NUMBER LEFT.
36	88		DEY	
37	0A		ASL A	
38	06 0D		ASL MEM+1	
3A	06 0C		ASL MEM	
3C	90 02		BCC CCLR	CHECK IF BIT #13 = 1. IF $\neq$ 1, GO BACK AND SHIFT AGAIN.
3E	E6 0D		INC MEM+1	
40	29 10	CCLR:	AND #10	
42	F0 F0		BEQ CNTNU+2	
44	84 1F	MPYLSB:	STY MTPLN	
46	AD E8 C7		LDA LOGTAB	BIT #13 = 1, SO MULTIPLY NUMBER OF SHIFTS TAKEN BY $\log_{10} 2$. STORE RESULT IN OFFSET+1, OFFSET. SHIFTS X LOGTAB+OFFSET+1, OFFSET.
49	85 20		STA MTPLR	
4B	20 D0 C4		JSR MPY	
4E	85 10		STA OFFSET	
50	A5 04		LDA PROD+1	
52	85 11		STA OFFSET+1	MOST SIGNIFICANT BYTE CAN'T OCCUR, SO SHIFTS X LOGTAB+1 $\rightarrow$ OFFSET+1.
54	AD E9 C7		LDA LOGTAB+1	
57	85 20		STA MTPLR	
59	20 D0 C4		JSR MPY	
5C	18		CLC	
5D	65 11		ADC OFFSET+1	FIND $\log_{10} 1.X$: NUM2+1, NUM2= $\log_{10}$ (MEM+1, MEM). SET NUM2+1, NUM2=0.
5F	85 11		STA OFFSET+1	
61	A9 00	STEP1:	LDA #00	
63	85 05		STA NUM2	
65	85 06		STA NUM2+1	
C267	18		CLC	SET NUM3+1, NUM3= (MEM+1, MEM)/2.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C268	A5 0D		LDA MEM+1	
64	6A		ROR A	
6B	85 08		STA NUM3+1	
6D	90 08		BCC THERE	
6F	A5 0C		LDA MEM	
71	6A		ROR A	
72	09 80		ORA #80	
74	4C 7A C2		JMP SOME	
77	A5 0C	THERE:	LDA MEM	
79	6A		ROR A	
7A	85 07	SOME:	STA NUM3	
7C	A2 01		LDX #01	SET K=1.
7E	A5 0C	STEP2:	LDA MEM	STOP IF MEM+1, MEM=0100.
80	D0 09		BNE STEP3	
82	A5 0D		LDA MEM+1	
84	49 10		EOR #10	
86	D0 03		BNE STEP3	
88	4C EE C2		JMP LOGDUN+2	
8B	38	STEP3:	SEC	IF (MEM+1, MEM)-(NUM3+1,
8C	A5 0C		LDA MEM	NUM3)<1, GO TO STEP5.
8E	E5 07		SBC NUM3	
90	85 0A		STA TEST	
92	A5 0D		LDA MEM+1	
94	E5 08		SBC NUM3+1	
96	85 0B		STA TEST+1	
98	A9 10		LDA #10	
9A	25 0B		AND TEST+1	
9C	F0 40		BEQ STEP5	
9E	A5 0A	STEP4:	LDA TEST	LET MEM+1, MEM=(MEM+1, MEM)
				-(NUM3+1, NUM3).
A0	85 0C		STA MEM	
A2	85 07		STA NUM3	
A4	A5 0B		LDA TEST+1	
A6	85 0D		STA MEM+1	
A8	85 08		STA NUM3+1	
AA	86 09		STX KTEMP	
AC	18	STEP4A:	CLC	LET (NUM3+1, NUM3)=
AD	A5 08		LDA NUM3+1	(MEM+1, MEM)/2 KTEMP.
AF	6A		ROR A	
B0	85 08		STA NUM3+1	
B2	90 08		BCC CRYCR	
B4	A5 07		LDA NUM3	
B6	6A		ROR A	
B7	09 80		ORA #80	
B9	4C BF C2		JMP FROG	
BC	A5 07	CRYCR:	LDA NUM3	
BE	6A		ROR A	
BF	85 07	FROG:	STA NUM3	
C1	C6 09		DEC KTEMP	
C3	D0 E7		BNE STEP4A	
C2C5	8A		TXA	

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C2C6	18		CLC	
C7	0A		ASL A	
C8	38		SEC	
C9	E9 02		SBC #02	
CB	A8		TAY	
CC	18	STEP4B:	CLC	LET (NUM2+1, NUM2)=(NUM2+1,
CD	A5 05		LDA NUM2	NUM2)+LOG ₁₀ (2 ^K /(2 ^K -1))
CF	79 E8 C7		ADC LOGTAB, Y	AND RETURN TO STEP2.
D2	85 05		STA NUM2	
D4	A5 06		LDA NUM2+1	
D6	79 E9 C7		ADC LOGTAB+1, Y	
D9	85 06		STA NUM2+1	
DB	4C 7E C2		JMP STEP2	
DE	A5 08	STEP5:	LDA NUM3+1	
EO	18		CLC	LET (NUM3+1, NUM3)=(NUM3+1,
				NUM3)/2.
E1	6A		ROR A	
E2	85 08		STA NUM3+1	
E4	A5 07		LDA NUM3	
E6	6A		ROR A	
E7	85 07		STA NUM3	
E9	E8		INX	LET K=K+1 AND RETURN
				TO STEP2 UNLESS K=12.
EA	E0 0C		CPX #0C	STOP IF K=12.
EC	D0 90	LOGDUN:	BNE STEP2	
EE	18		CLC	ADD N(LOG ₁₀ 2) + LOG ₁₀ (1.X)
EF	A5 10		LDA OFFSET	TO GET FINAL LOG ₁₀ (A/D
F1	65 05		ADC NUM2	OUTPUT) AND STORE IN
				NUM2+1, NUM2.
F3	85 05		STA NUM2	
F5	A5 11		LDA OFFSET+1	
F7	65 06		ADC NUM2+1	
F9	85 06		STA NUM2+1	
C2FB	4C 02 C3		JMP C302	BEGIN MULTIPLY ROUTINE.

MULTIPLY ROUTINE
(Part of Logarithm Subroutine)

Enter with 16-bit number in NUM2+1, NUM2 to be multiplied by 24-bit number in KFAC+2, KFAC+1, KFAC.

Exit with BCD results stored in print buffer.

Destroys A. Refer to Figure 4.2, p. 41, for diagram of operation.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C302	A9 00		LDA #00	
04	85 1C		STA VALUE+1	
06	85 1D		STA VALUE+2	
08	A5 2E		LDA STREAM	IS THIS A BACKGROUND SCAN?
0A	29 0F		AND #0F	
0C	D0 0B		BNE REAL	IF NOT, CONTINUE.
0E	A5 05		LDA NUM2	IF SO, STORE IN BACKGROUND
10	85 17		STA BASE	DATA LOCATIONS, AND RETURN
12	A5 06		LDA NUM2+1	TO CONTROL, SKIPPING ALL
14	85 18		STA BASE+1	MATH AND PRINTING.
16	4C B6 C1		JMP TMSTOP	
19	38	REAL:	SEC	
1A	A5 17		LDA BASE	SET NUM2+1, NUM2=
1C	E5 05		SBC NUM2	LOG %T ₀ - LOG %T.
1E	85 05		STA NUM2	
20	A5 18		LDA BASE+1	
22	E5 06		SBC NUM2+1	
24	85 06		STA NUM2+1	
26	A5 05		LDA NUM2	BEGIN 16X24-bit MULTIPLY.
28	85 1F		STA MTPLN	HIGH-ORDER BYTE OF BE IS STORED IN VALUE.
2A	AD 92 C7		LDA KFAC	
2D	85 20		STA MTPLR	
2F	20 D0 C4		JSR MPY	
32	A5 04		LDA PROD+1	
34	85 1B		STA VALUE	
36	AD 93 C7		LDA KFAC+1	BD→VALUE+1, VALUE.
39	85 20		STA MTPLR	
3B	20 D0 C4		JSR MPY	
3E	18		CLC	
3F	65 1B		ADC VALUE	
41	85 1B		STA VALUE	
43	A5 04		LDA PROD+1	
45	65 1C		ADC VALUE+1	
47	85 1C		STA VALUE+1	
49	90 02		BCC BC	
4B	E6 1D		INC VALUE+2	
C34D	AD 94 C7	BC:	LDA KFAC+2	BC→VALUE+2, VALUE+1.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C350	85 20		STA MTPLR	
52	20 D0 C4		JSR MPY	
55	18		CLC	
56	65 1C		ADC VALUE+1	
58	85 1C		STA VALUE+1	
5A	A5 04		LDA PROD+1	
5C	65 1D		ADC VALUE+2	
5E	85 1D		STA VALUE+2	
60	A5 06		LDA NUM2+1	AE→VALUE+1, VALUE. VALUE
62	85 1F		STA MTPLN	IS SHIFTED RIGHT FOUR PLACES.
64	AD 92 C7		LDA KFAC	
67	85 20		STA MTPLR	
69	20 D0 C4		JSR MPY	
6C	18		CLC	
6D	65 1B		ADC VALUE	
6F	85 1B		STA VALUE	
71	A5 04		LDA PROD+1	
73	65 1C		ADC VALUE+1	
75	85 1C		STA VALUE+1	
77	90 02		BCC SHIFTR	
79	E6 1D		INC VALUE+2	
7B	A5 1B	SHIFTR:	LDA VALUE	
7D	4A		LSR A	
7E	4A		LSR A	
7F	4A		LSR A	
80	4A		LSR A	
81	85 1B		STA VALUE	
83	AD 93 C7		LDA KFAC+1	AD→VALUE+2, VALUE+1.
86	85 20		STA MTPLR	
88	20 D0 C4		JSR MPY	
8B	18		CLC	
8C	65 1C		ADC VALUE+1	
8E	85 1C		STA VALUE+1	
90	A5 04		LDA PROD+1	
92	65 1D		ADC VALUE+2	
94	85 1D		STA VALUE+2	LEAST SIGNIFICANT BYTE
96	AD 94 C7		LDA KFAC+2	LEAST SIGNIFICANT BYTE OF AC
99	85 20		STA MTPLR	IS ADDED TO VALUE+2.
9B	20 D0 C4		JSR MPY	
9E	18		CLC	
9F	65 1D		ADC VALUE+2	
A1	0A		ASL A	
A2	0A		ASL A	
A3	0A		ASL A	
A4	0A		ASL A	
A5	85 1D		STA VALUE+2	
A7	A5 1C		LDA VALUE+1	COMBINE MOST SIGNIFICANT
A9	4A		LSR A	FOUR BITS OF VALUE+1 WITH
AA	4A		LSR A	LEAST SIGNIFICANT FOUR
C3AB	4A		LSR A	BITS OF VALUE+2 TO MAKE

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C3AC	4A		LSR A	ONE BYTE IN A.
AD	05 1D		ORA VALUE+2	CONVERT A TO BCD, AND PUT
AF	20 00 C5		JSR BCD	INTO TWO INTEGER LOCATIONS
B2	A5 13		LDA DEC1	IN PRINT BUFFER.
B4	09 30		ORA #30	
B6	85 39		STA LINE3+1	
B8	A5 14		LDA DEC2	
BA	09 30		ORA #30	
BC	85 38		STA LINE3	
BE	A5 1C		LDA VALUE+1	COMBINE MOST SIGNIFICANT
C0	0A		ASL A	FOUR BITS OF VALUE WITH
C1	0A		ASL A	LEAST SIGNIFICANT FOUR BITS
C2	0A		ASL A	OF VALUE+1 TO MAKE ONE BYTE
C3	0A		ASL A	IN A.
C4	05 1B		ORA VALUE	
C6	20 30 C5		JSR DBCD	CONVERT A TO THREE BCD
C9	A5 14		LDA DEC2	DIGITS AND PUT THE TWO
CB	09 30		ORA #30	HIGHER-ORDER DIGITS INTO
CD	85 3C		STA LINE3+4	PRINTER BUFFER.
CF	A5 15		LDA DEC3	
D1	09 30		ORA #30	
D3	85 3B		STA LINE3+3	
D5	60		RTS	BACK TO CONTROL.
D6	A9 27	TLOW:	LDA #27	STARTING ADDRESS OF LINE 1.
D8	85 21		STA LINUML	
DA	A9 00		LDA #00	
DC	85 22		STA LINUMH	
DE	20 00 C4		JSR PRINT	
E1	A9 31		LDA #31	STARTING ADDRESS OF LINE 2.
E3	85 21		STA LINUML	
E5	20 5F C5		JSR ASCII	
E8	20 00 C4		JSR PRINT	
EB	A9 B2		LDA #B2	STARTING ADDRESS OF LINE 7.
ED	85 21		STA LINUML	
EF	A9 C7		LDA #C7	
F1	85 22		STA LINUMH	
F3	20 00 C4		JSR PRINT	
C3F6	4C B6 C1		JMP TMSTOP	

SUBROUTINE PRINT

Enter with starting address of line to be printed in 0021, 0022.

Returns after printing the chosen line.

Destroys X, Y, A.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C400	A0 00	PRINT:	LDY #00	
02	A9 80		LDA #80	CHECK PRINTER BUSY BIT.
04	2D 01 AC		AND AC01	
07	D0 F9		BNE PRINT+2	WAIT UNTIL NOT BUSY (1=BUSY).
09	AD 00 A8		LDA A800	GET DR WITH HIGH FOUR BITS.
0C	29 0F		AND #0F	ZERO PRINTER BITS.
0E	85 09		STA KTEMP	TEMPORARY STORAGE.
10	B1 21		LDA (LINUM),Y	GET CHARACTER FROM BUFFER.
12	C9 00		CMP #00	STOP IF THIS IS NULL.
14	F0 30		BEQ QUIT	
16	29 F0		AND #F0	KEEP ONLY HIGH FOUR BITS.
18	05 09		ORA KTEMP	COMBINE PRINTER AND VALVE BITS.
1A	8D 00 A8		STA A800	OUTPUT HIGH FOUR BITS.
1D	AD 00 AC		LDA AC00	GET DR WITH LOW FOUR BITS.
20	29 F0		AND #F0	ZERO PRINTER BITS.
22	85 09		STA KTEMP	TEMPORARY STORAGE.
24	B1 21		LDA (LINUM),Y	GET SAME CHARACTER FROM BUFFER.
26	29 0F		AND #0F	KEEP ONLY LOW FOUR BITS.
28	05 09		ORA KTEMP	COMBINE PRINTER AND VALVE BITS.
2A	8D 00 AC		STA AC00	OUTPUT LOW FOUR BITS.
2D	AD 01 AC		LDA AC01	GET DR WITH STROBE BIT.
30	29 BF		AND #BF	SET STROBE LOW TO PRINT.
32	8D 01 AC		STA AC01	
35	A2 0A		LDX #0A	WAIT > 50 μ SEC. WHILE
37	CA	WAIT:	DEX	PRINTER LATCHES DATA.
38	D0 FD		BNE WAIT	
3A	AD 01 AC		LDA AC01	GET DR WITH STROBE BIT.
3D	09 40		ORA #40	RESET STROBE BIT.
3F	8D 01 AC		STA AC01	
42	C8		INY	INCREMENT CHARACTER LOCATION.
43	4C 02 C4		JMP PRINT+2	GET NEXT CHARACTER.
C446	60	QUIT:	RTS	BACK TO CONTROL.

SUBROUTINE DELAY

Enter with delay values in registers X and Y, and in memory location 0026 (labeled Z).

Returns after a delay determined by the equation

$$24 + 5x + 1285y + 328,968z - 330,240 \text{ microseconds.}$$

Destroys all registers.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C4 50	CA	DELAY:	DEX	2 CYCLES
51	DO FD		BNE DELAY	3 CYCLES
53	88		DEY	2 CYCLES
54	DO FA		BNE DELAY	3 CYCLES
56	C6 26		DEC Z	5 CYCLES
58	DO F6		BNE DELAY	3 CYCLES
C4 5A	60		RTS	6 CYCLES

SUBROUTINE MPY

Enter with two 8-bit words in MTPLR, MTPLN.

Returns with the most significant 8 bits of the product in PROD+1, and the least significant 8 bits in PROD and the accumulator.

Destroys MTPLR and X register.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C4 D0	A9 00	MPY:	LDA #00	CLEAR HIGH-ORDER BYTE OF PRODUCT.
D2	85 04		STA PROD+1	
D4	A2 08		LDX #08	USE X REG. TO COUNT NO. OF SHIFTS PERFORMED.
D6	0A	SHIFT:	ASL A	
D7	26 04		ROL PROD+1	
D9	06 20		ASL MTPLR	
DB	90 07		BCC SKIP	
DD	18		CLC	
DE	65 1F		ADC MTPLN	
E0	90 02		BCC SKIP	
E2	E6 04		INC PROD+1	
E4	CA	SKIP:	DEX	
E5	D0 EF		BNE SHIFT	
E7	85 03		STA PROD	
C4 E9	60		RTS	

SUBROUTINE BCD

Enter with byte in accumulator to be converted to a 3-digit decimal integer. Each digit will be the low-order nibble of a separate memory location.

Returns with the three BCD digits in DEC1, DEC2, and DEC3, with DEC3 being the most significant. DEC1 is left in the accumulator.

Destroys X register, accumulator.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C5 00	A2 00	BCD:	LDX #00	CLEAR MEMORY LOCATIONS OF
02	86 15		STX DEC3	TWO MOST SIGNIFICANT
04	86 14		STX DEC2	DECIMAL DIGITS.
06	38	HUN:	SEC	
07	E9 64		SBC #64	IS REMAINDER OF NUMBER $\geq$
09	90 05		BCC NOHUN	100_{10} ? SKIP IF NOT.
0B	E6 15		INC DEC3	ADD 1 TO MOST SIGNIFICANT
0D	4C 06 C5		JMP HUN	DECIMAL DIGIT AND CHECK
				AGAIN.
10	69 64	NOHUN:	ADC #64	REMAINDER WAS NOT $\geq 100_{10}$,
12	38	TEN:	SEC	SO ADD BACK THE 100_{10} THAT
				WAS SUBTRACTED.
13	E9 0A		SBC #0A	IS REMAINDER OF NUMBER $\geq$
15	90 05		BCC NOTEN	10_{10} ? SKIP IF NOT.
17	E6 14		INC DEC2	ADD 1 TO NEXT MOST SIGNI-
19	4C 12 C5		JMP TEN	FICANT DECIMAL DIGIT AND
				CHECK AGAIN.
1C	69 0A	NOTEN:	ADC #0A	REMAINDER WAS NOT $\geq 10_{10}$,
1E	85 13		STA DEC1	SO ADD BACK THE 10_{10} THAT
C5 20	60		RTS	WAS SUBTRACTED, AND STORE.

SUBROUTINE DBCD

Enter with byte in accumulator to be converted to a 3-digit decimal fraction. Each digit will be the low-order nibble of a separate memory location.

Returns with the three BCD digits in DEC1, DEC2, and DEC3, with DEC3 being the most significant. DEC1 is left in the accumulator.

Destroys X register, accumulator.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C5 30	A2 00	DBCD:	LDX #00	CLEAR MEMORY LOCATIONS OF TWO MOST SIGNIFICANT DECIMAL DIGITS.
32	86 15		STX DEC3	
34	86 14		STX DEC2	
36	38	TNTHS:	SEC	IS REMAINDER OF NUMBER $\geq 0.1_{10}$? SKIP IF NOT. ADD 1 TO MOST SIGNIFICANT DECIMAL DIGIT AND CHECK AGAIN.
37	E9 1A		SBC #1A	
39	90 05		BCC NTNTHS	
3B	E6 15		INC DEC3	
3D	4C 36 C5		JMP TNTHS	
40	69 1A	NTNTHS:	ADC #1A	REMAINDER WAS NOT $\geq 0.1_{10}$, SO ADD BACK THE 0.1_{10} THAT WAS SUBTRACTED.
42	38	HUNTHS:	SEC	
43	E9 03		SBC #03	IS REMAINDER OF NUMBER $\geq 0.01_{10}$? SKIP IF NOT. ADD 1 TO NEXT MOST SIGNIFICANT DECIMAL DIGIT AND CHECK AGAIN.
45	90 05		BCC NHNTHS	
47	E6 14		INC DEC2	
49	4C 42 C5		JMP HUNTHS	
4C	69 03	NHNTHS:	ADC #03	REMAINDER WAS NOT $\geq 0.01_{10}$, SO ADD BACK THE 0.01_{10} THAT WAS SUBTRACTED AND STORE.
4E	85 13		STA DEC1	
C5 50	60		RTS	

SUBROUTINE ASCII

Enter before printing line 2 (real-time HR/MIN) of the RAM printer buffer.

Returns with latest ASCII real-time hours and minutes stored in line 2 of the printer buffer.

Destroys accumulator.

LOCATION	CODE	LABEL	INSTRUCTION	COMMENTS
C5 5F	78		SEI	
60	A5 00		LDA RTHR	LEAST SIGNIFICANT HOURS
62	29 0F		AND #0F	DIGIT.
64	09 30		ORA #30	
66	85 32		STA LINE2+1	
68	A5 00		LDA RTHR	MOST SIGNIFICANT HOURS DIGIT.
6A	4A		LSR	
6B	4A		LSR	
6C	4A		LSR	
6D	4A		LSR	
6E	09 30		ORA #30	
70	85 31		STA LINE2	
72	A5 01		LDA RTMIN	LEAST SIGNIFICANT MINUTES
74	29 0F		AND #0F	DIGIT.
76	09 30		ORA #30	
78	85 35		STA LINE2+4	
7A	A5 01		LDA RTMIN	MOST SIGNIFICANT MINUTES
7C	4A		LSR	DIGIT.
7D	4A		LSR	
7E	4A		LSR	
7F	4A		LSR	
80	09 30		ORA #30	
82	85 34		STA LINE2+3	
84	58		CLI	
C5 85	60		RTS	

APPENDIX B

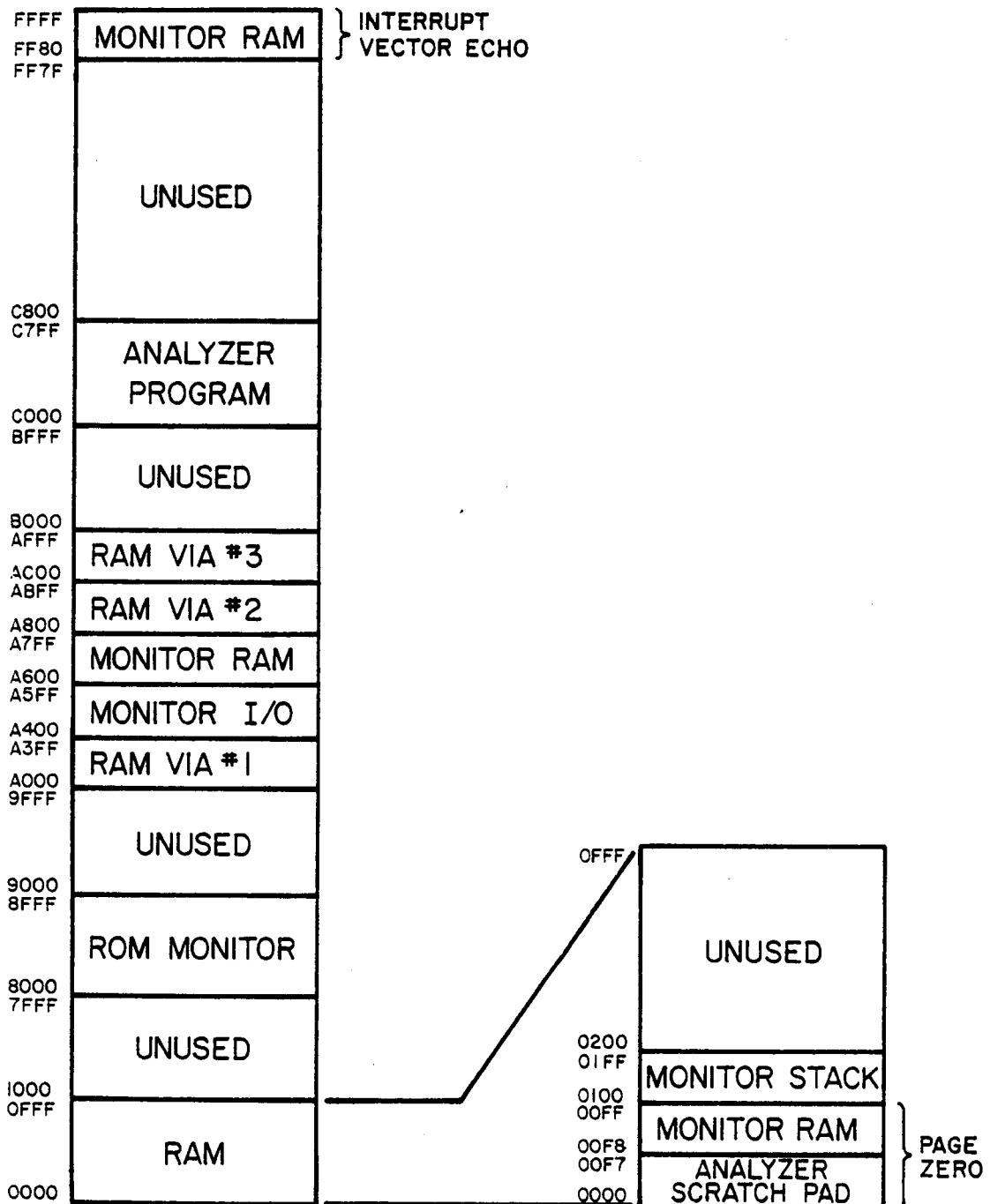


Figure B.1. Prototype system memory map.

OPERATING PARAMETERS AND DATA IN ROM

LOCATION	DATA	LABEL	COMMENTS
C7 92		KFAC	LOW-ORDER BYTE K-FACTOR AT WAVENUMBER. HIGH-ORDER BYTE
		KFAC+1	
C7 94		KFAC+2	
	4C		CLOCK INTERRUPT COMES HERE.
	D0		PERFORM JMP TO CLOCK.
	C1		
C7 98	4D	LINE4	ASCII M
	41		ASCII A
	4E		ASCII N
	55		ASCII U
C7 9C	41		ASCII A
	4C		ASCII L
	0A		ASCII CRLF
	00	LINE4+7	ASCII NULL
C7 A0	41	LINE5	ASCII A
	55		ASCII U
	54		ASCII T
	4F		ASCII O
C7 A4	0A		ASCII CRLF
	00	LINE5+5	ASCII NULL
	0E	LINE6	ASCII BOLDFACE ON
	41		ASCII A
C7 A8	4C		ASCII L
	4C		ASCII L
	20		ASCII SPACE
	53		ASCII S
C7 AC	54		ASCII T
	4F		ASCII O
	50		ASCII P
	0F		ASCII BOLDFACE OFF
C7 B0	0A		ASCII CRLF
	00	LINE6+11	ASCII NULL
	25	LINE7	ASCII %
	54		ASCII T
C7 B4	20		ASCII SPACE
	55		ASCII U
	4E		ASCII N
	44		ASCII D
C7 B8	45		ASCII E
	52		ASCII R
	20		ASCII SPACE
	31		ASCII 1
C7 BC	30		ASCII 0
	25		ASCII %

LOCATION	DATA	LABEL	COMMENTS
	0A		ASCII CRLF
	00	LINE7+13	ASCII NULL
C7 C0		T1MIN	BINARY TIME BETWEEN ANALYZER START AND BEGIN
		T1SEC	TAKING DATA
		T2MIN	BINARY TIME BETWEEN ANALYZER START AND STOP
		T2SEC	TAKING DATA
C7 C4	02	T3MIN	BINARY TIME BETWEEN ANALYZER START AND
	B7	T3SEC	ANALYZER STOP
	53	LINE1	ASCII S (PRINTER LINES 1, 2, & 3, MOVED
	54		ASCII T TO RAM DURING INITIALIZATION)
C7 C8	52		ASCII R
	45		ASCII E
	41		ASCII A
	4D		ASCII M
C7 CC	20		ASCII SPACE
	30		ASCII 0
	0A		ASCII CRLF
	00		ASCII NULL
C7 D0	30	LINE2	ASCII 0
	30		ASCII 0
	3A		ASCII :
	30		ASCII 0
C7 D4	30		ASCII 0
	0A		ASCII CRLF
	00		ASCII NULL
	30	LINE3	ASCII 0
C7 D8	30		ASCII 0
	2E		ASCII .
	30		ASCII 0
	30		ASCII 0
C7 DC	25		ASCII %
	20		ASCII SPACE
	20		ASCII SPACE
	30		ASCII 0
C7 E0	30		ASCII 0
	30		ASCII 0
	30		ASCII 0
	30		ASCII 0
	30		ASCII 0
C7 E4	30		ASCII 0
	30		ASCII 0
	0A		ASCII CRLF
	00		ASCII NULL
C7 E8	D1	LOGTAB	DATA TABLE OF LOG ₁₀ (2 ^k /2 ^{k-1}), K=1,2,3...12.
	04	LOGTAB+1	
	00		
	02		
	EE		
	00		
	73		
C7 EC	00		
			LOG ₁₀ 2=0.4D1 ₁₆
			LOG(4/3)=0.200 ₁₆
			LOG(8/7)=0.0EE ₁₆
			LOG(16/15)=0.073 ₁₆

LOCATION	DATA	LABEL	COMMENTS
C7 F0	38 }		LOG(32/31)=0.038 ₁₆
	00 }		
	1C }		LOG(64/63)=0.01C ₁₆
C7 F4	00 }		
	0E }		LOG(128/127)=0.00E ₁₆
	00 }		
C7 F8	07 }		LOG(256/255)=0.007 ₁₆
	00 }		
	03 }		LOG(512/511)=0.003 ₁₆
C7 FC	00 }		
	02 }		LOG(1024/1023)=0.002 ₁₆
	00 }		
C7 FC	01 }		LOG(2048/2047)=0.001 ₁₆
	00 }		
	00 }		LOG(4096/4095)=0.000 ₁₆

RAM LOCATIONS USED BY OPERATING PROGRAM

LOCATION	DATA	LABEL	COMMENTS
0000		RTHR } RTMIN } RTSEC }	REAL-TIME CLOCK DATA
0004		PROD } PROD+1 }	STORED RESULT OF MPY ROUTINE
		NUM2 } NUM2+1 } NUM3 }	USED BY LOGARITHM ROUTINE
0008		NUM3+1 }	
		KTEMP } TEST }	TEMPORARY STORAGE
		TEST+1 }	
000C		MEM } MEM+1 }	PEAK A/D VALUE
		MEM+2 } MEM+3 }	TEMPORARY STORAGE
0010		OFFSET } OFFSET+1 }	(12-N)LOG ₁₀ 2
		NOT USED	
0014		DEC1 } DEC2 }	STORED RESULT OF BCD AND DBCD SUBROUTINES
		DEC3 }	
		SYSTEM	# OF STREAMS IN SYSTEM
0018		BASE } BASE+1 }	BACKGROUND VALUE AT WAVENUMBER
		NOT USED	
		NOT USED	
001C		VALUE } VALUE+1 }	BINARY MOLE %
		VALUE+2 }	
		NOT USED	
0020		MTPLN } MTPLR }	NUMBERS USED BY MPY SUBROUTINE
		LINUML } LINUMH }	STARTING ADDRESS OF LINE TO BE PRINTED
0024		TIME	TIMER INDEX FOR CLOCK ROUTINE
		ETMIN } ETSEC }	ELAPSED TIME ACCUMULATOR
		Z	INDEX FOR DELAY SUBROUTINE
0028	53	LINE1	ASCII S
	54		ASCII T
	52		ASCII R
	45		ASCII E
	41		ASCII A
002C	4D		ASCII M
	20		ASCII SPACE
	0A	STREAM	ASCII STREAM NO. ON WHICH THIS ANALYSIS WAS MADE
			ASCII CRLF

LOCATION	DATA	LABEL	COMMENTS
0030	00	LINE1+9	ASCII NULL
		LINE2	ASCII } HOURS (0-24)
	3A		ASCII :
0034			ASCII } MINUTES (0-59)
	0A		ASCII CRLF
	00	LINE2+6	ASCII NULL
0038		LINE3	ASCII
	2E		ASCII . } MOLE %
			ASCII
003C			ASCII
	25		ASCII %
	20		ASCII SPACE
	20		ASCII SPACE
0040			ASCII
			ASCII
			ASCII
			ASCII } ALPHANUMERIC CHEMICAL CONTENT
0044			ASCII
			ASCII
			ASCII
	0A		ASCII CRLF
0048	00	LINE3+16	ASCII NULL

I/O PORT ASSIGNMENTS

DDR/DR	BIT	INPUT SOURCE OR OUTPUT DESTINATION	COMPUTER ACTION
A003/A001	APA0	A/D BIT0 (LSB)	BINARY INPUT.
	APA1	A/D BIT1	
	APA2	A/D BIT2	
	APA3	A/D BIT3	
	APA4	A/D BIT4	
	APA5	A/D BIT5	
	APA6	A/D BIT6	
A002/A000	APA7	A/D BIT7	INPUT LOW DURING CONVERSION. OUTPUT HIGH FOR > 100 nsec. INPUT LOW=STOP.
	APB0	A/D BIT8	
	APB1	A/D BIT9	
	APB2	A/D BIT10	
	APB3	A/D BIT11 (MSB)	
	APB4	A/D STATUS	
	APB5	A/D CONVERT COMM.	
A803/A801	APB7	SCAN/STOP SWITCH	OUTPUT LOW TURNS ON SS RELAY.
	2PA0	SSR 0	
	2PA1	SSR 1	
	2PA2	SSR 2	
	2PA3	SSR 3 VALVES	
	2PA4	SSR 4	
	2PA5	SSR 5	
A802/A800	2PA6	SSR 6	SCAN PEN INPUT LOW=MANUAL OUTPUT.
	2PA7	SSR 7	
	2PB0	SSR 8	
	2PB1	SSR 9 IRA	
	2PB2	SSR 10	
	2PB3	AUTO/MAN SWITCH	
	2PB4	PRINTER BIT 4	
AC03/AC01	2PB5	5	OUTPUT LOW CAUSES DATA TRANSFER. INPUT HIGH IF PRINTER BUSY.
	2PB6	6	
	2PB7	7 (MSB)	
AC02/AC00	3PA6	PRINTER STROBE	OUTPUT.
	3PA7	PRINTER BUSY	
AC02/AC00	3PB0	PRINTER BIT 0 (LSB)	OUTPUT.
	3PB1	1	
	3PB2	2	
	3PB3	3	
	3PB4(B)	SPARE	
	3PB5(B)		
	3PB6(B)		
	3PB7(B)		

VITA

Arville McKinley Billings was born in Knoxville, Tennessee, on March 7, 1948. He attended elementary schools in Oak Ridge, Tennessee, and was graduated from Oak Ridge High School in June 1965. After a three-year tour of duty with the U.S. Army Signal Corps, he entered The University of Tennessee, Knoxville, in September 1971. He received the Bachelor of Science in Electrical Engineering in December 1974.

After one quarter of full-time graduate work, Mr. Billings accepted a position with Data-Design Laboratories in Memphis, Tennessee. In May 1976, he accepted a position as a design engineer in the Instrument Engineering department at the Oak Ridge Gaseous Diffusion Plant in Oak Ridge where he is currently employed by Union Carbide Corporation. Graduate work was resumed at The University of Tennessee, and a Master of Science degree was awarded in June 1981.

The author is a member of the Instrument Society of America and serves as business manager of that organization's local newsletter.

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