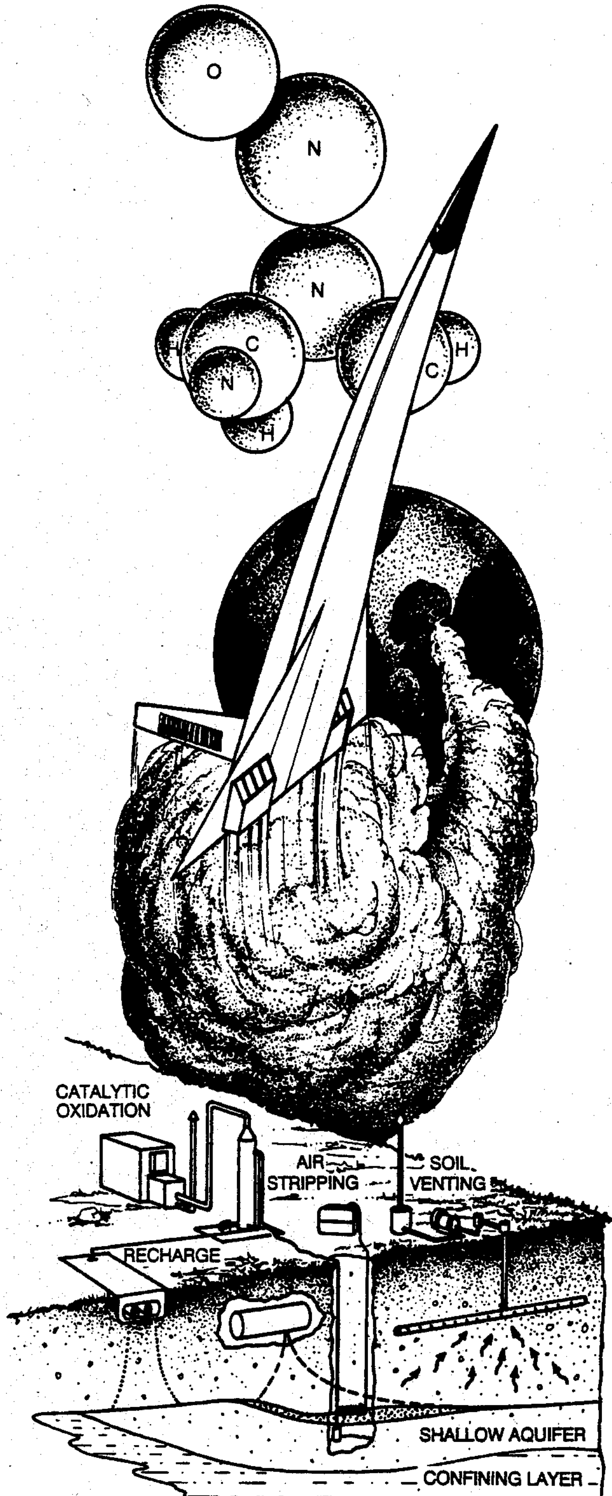

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DISPERSIVE-INFRARED GAS SENSOR SYSTEM DESIGN AND OPERATION MANUAL

T.J. KULP, T.G. McRAE, R. KENNEDY, D. GARVIS

LAWRENCE LIVERMORE NATIONAL LABORATORY
LIVERMORE CA 94550

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T.J. Kulp, T.G. McRae, R. Kennedy, and D. Garvis

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13. ABSTRACT *(Maximum 200 words)*

This technical report describes the methodology to build and operate a remotely operated, radio controlled, battery powered infrared detector for measuring hydrogen chloride (HCL) emissions from Space Launch operations.

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Executive Summary

Infrared radiation is provided by a ceramic broadband IR source. Detection is accomplished using a thermoelectrically-cooled PbS detector. Prior to being focused on the detector, the radiation is filtered through one of four dielectric bandpass filters (mounted on a rotating filter wheel), which define four wavelength channels. The primary channel passes wavelengths that are capable of being absorbed by HCl and water vapor. The secondary channel responds only to water vapor and, thus, is intended to allow the subtraction of water vapor absorption from the primary channel. The remaining two channels serve as references, to correct for baseline transmission changes in the White cell. The present detection limit of the sensor is approximately 1 ppm for HCl and 0.06% for water vapor, at a data collection rate of 1 Hz.

In addition to the sensor itself, the system also contains a data telemetry system that allows the sensor to be remotely controlled and interrogated by a radio base station. A transceiver is installed directly into the sensor and is interfaced with the microprocessor that regulates the sensor operation. A PC-interfaced radio base station that contains the software required to operate the base station is also included in the package. It is capable of remotely starting the sensor, collecting and storing data from it, and plotting that data in a real-time format. Finally, the sensor package also includes a calibration system that can be used to calibrate the sensor both in the field and in the laboratory.

In this report, the principle of operation of the sensor system is described, as well as the construction of the individual sensor components. Operating procedures for the sensor and for the calibration system are also provided. Finally, a comprehensive electronic and mechanical system design manual is provided with the report. These contain the necessary drawings and schematics to reproduce additional sensor units.

PREFACE

This report was prepared by Environmental Sciences Division, Lawrence Livermore National Laboratory, Livermore, California, for the Air Force Engineering and Services Center, Engineering and Services Laboratory (AFESC/RDVS), Tyndall Air Force Base, Florida 32403-6001. Capt Mark D. Smith, was the Government technical program manager. The report summarizes work accomplished between 15 September 1986 and October 1989.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). AT NTIS, it will be available to the general public, including foreign nations

This technical report has been reviewed and is approved for publication.

MARK D. SMITH, Capt, USAF, BSC
Project Officer

NEIL J. LAMB, Colonel, USAF, BSC
Chief, Environics Division

WAYNE P. CHEPREN, Maj, USAF
Chief, Pollution Prevention and
Environmental Compliance Branch

FRANK P. GALLAGHER III, Colonel, USAF
Director, Engineering and Services
Laboratory

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SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of this project was to develop a nondispersive infrared (IR) gas sensor capable of detecting and quantifying gaseous HCl emitted during the launch of rockets using solid propellants. To satisfy the practical requirements of this application, the sensor must be capable of unmanned field operation, remotely addressable, field calibratable, and able to measure low concentrations (1 ppm) of HCl at relatively rapid rates.

B. BACKGROUND

The United States space program requires the use of large launch vehicles such as the Space Shuttle. Most of these launch vehicles use solid rocket motors (SRM) that employ ammonium perchlorate as an oxidizer. During a launch, the SRMs release an exhaust cloud that is a dynamic mixture of water, hydrogen chloride (HCl), aluminum oxide (Al_2O_3), and aluminum chloride ($AlCl_3$) (Reference 1). HCl generation is of great concern because of potentially adverse effects on the surrounding ecosystem. At Vandenberg Air Force Base, CA (VAFB), HCl deposition from the exhaust cloud may affect surrounding farms that produce flowers and vegetables. Accurate measurements of the exhaust cloud properties is vital for assessing and minimizing environmental impacts. The requirements for HCl control technology will largely be derived from monitoring the exhaust products during the postlaunch period. Additionally, the efficiency of control technology cannot be assessed without reliable instrumentation located in the exhaust path.

The postlaunch phase is critical for flight crews and launch-pad personnel. A hazardous environment is created near the pad by the tremendous exhaust expelled by the departing vehicle. Seconds after the launch, the cloud begins to rain HCl in its downwind path. The launch-pad area undergoes a dynamic process of HCl rain-out, followed by periods of revolatilization of the hazardous vapors. Launch control personnel located within 500 feet of the pad must await the dissipation of the HCl cloud, a process totally dependent on the existing meteorological conditions. Accurate real-time measurements are needed before the environment can be considered safe for entry by ground crews for postlaunch activities.

This project was initiated to support space vehicle launch activities at VAFB, when VAFB was being considered as a potential launch site for the Space Shuttle. VAFB is a unique space launch facility that provides a range of launch azimuths. Located approximately 140 miles north of Los Angeles, California, VAFB permits launch azimuths of 158 to 201 degrees to allow insertion of space vehicles for polar orbits (Reference 2). Because of its uniqueness, VAFB is crucial to the Air Force's space mission. To ensure the future of Vandenberg as a launch site, environmental impacts of both current and future systems must be accurately assessed. Research into pollutant monitoring and control technology is vital to the environmental protection program at VAFB. Space systems currently proposed for deployment at VAFB are the Heavy Lift Vehicle and the Expendable Lift Vehicles, both of which require an extensive environmental support mission.

Modelling of the meteorological properties of the cloud is essential to the environmental impact analysis of these launch systems. Without physical and chemical data, the predictions of far-field concentrations derived from an atmospheric dispersion model are uncertain: a model can only be verified for application through actual measurements. An integral part of the VAFB environmental program is the modelling of chemical and physical properties of the exhaust plume and subsequent transport by prevailing winds. The modelling program will be greatly aided by the ability to measure the HCl concentration of the dispersing exhaust cloud.

The generation of HCl was identified as a major environmental concern during the development of these large launch vehicles. However, there was a general lack of available equipment for use in monitoring the HCl content of the rocket exhaust cloud (Reference 3). Environmental monitoring required an instrument capable of measuring HCl concentrations within 2000 feet of the launch pad, as well as distances up to 9 miles in the downwind direction of the launch area (Reference 4). Remote operation was paramount since the instrument would be operated in the rocky and harsh VAFB terrain, which rises from sea level to over 2100 feet in elevation. Furthermore, the ideal instrument would have an internal power supply so it could function in areas of limited road and power-line access. Finally, radio-controlled operation was desirable for data acquisition and transmission from downwind areas.

Although the system described in this manual was designed specifically to support the space mission at VAFB, it has numerous potential applications where chemical sensing is required over long distances. The sensor head can be adapted to measure other infrared absorbing gases and provide a surveillance system to ensure accurate detection of contaminants.

Many different techniques exist for the detection of hazardous gases: electrochemical transducers, chemiluminescence methods, surface-chemistry processes, flame-ionization detection, and dispersive and nondispersive IR absorption, to name a few. The choice of technique depends primarily on the gas of interest and the environment in which the sensor must operate. Air Force HCl measurement requirements generally exceed the measurement capabilities of available HCl sensors. Consequently, as part of an HCl sensor assessment and development program, the Air Force Engineering and Services Center (AFESC) asked the Lawrence Livermore National Laboratory (LLNL) to investigate the possibility of using the technology developed in our field-deployable IR gas sensor systems to monitor the HCl concentrations of launch-vehicle exhaust clouds. The LLNL has two field-deployable IR gas sensor systems in operation at various locations. One is a fast-response CO_2 sensor, capable of resolving atmospheric CO_2 fluctuations as small as 0.1 ppm (Reference 5) The other system is a radio-controlled and interrogated sensor used to measure methane and ethane-plus-propane vapors downwind of large liquified natural gas (LNG) spill tests (Reference 6). The LLNL was requested to combine the appropriate technologies from each of these two IR-gas sensor systems into a field-deployable, fast-response, radio-controlled and interrogated HCl gas measurement system with a minimum sensitivity of 200 ppb.

C. APPROACH

The technique of gas detection by dispersive IR absorption is shown schematically in Figure 1. The radiation from an IR source is collected by an optical system, directed through a sample volume and some form of spectral dispersion mechanism, then focused onto an IR detector. The dispersive mechanism must separate the IR radiation into at least two different spectral intervals (or bands) - a reference band and a sample band. This may be done either before or after the IR radiation passes through the sample volume. The sample band is chosen to correspond with a spectral region in which the gas strongly absorbs. Consequently, with no gas present, the IR-detector signal represents a transmissivity of 1.0. As gas is introduced to the sample volume, the transmissivity is reduced in proportion to the concentration of the gas. The reference band, on the other hand, is chosen to be unaffected by the presence of the gas. The purpose of the reference signal is to account for all effects other than the presence of the gas (electronic, mechanical, thermal) that may cause the sample signal to vary.

The absorption of IR radiation by molecular gases is a well-understood process. For short path lengths and low gas concentrations, operation is in the weak-line absorption region where Beer's law applies. If τ is the IR-radiation transmittance ($0 \leq \tau \leq 1.0$) and L is the optical path length of the sample volume, then Beer's law may be written as

$$-\ln\tau/L = k_1C_1 + k_2C_2 + \ldots + k_iC_i \quad (1)$$

where k_i represents the band-integrated absorption coefficient and C_i the concentration of the gas species which absorbs in the sample band. There will be an Equation (1) for each sample band used. The band-integrated absorption coefficients (k_i) are generally determined by supplying accurately known gas concentrations for each of the i absorbing gases to the sample volume and recording the resulting values of the transmissivity (τ). Because of the linear relationship between concentration and the natural logarithm of transmissivity in the weak-line absorption region, the sensor may be calibrated by obtaining a single data point.

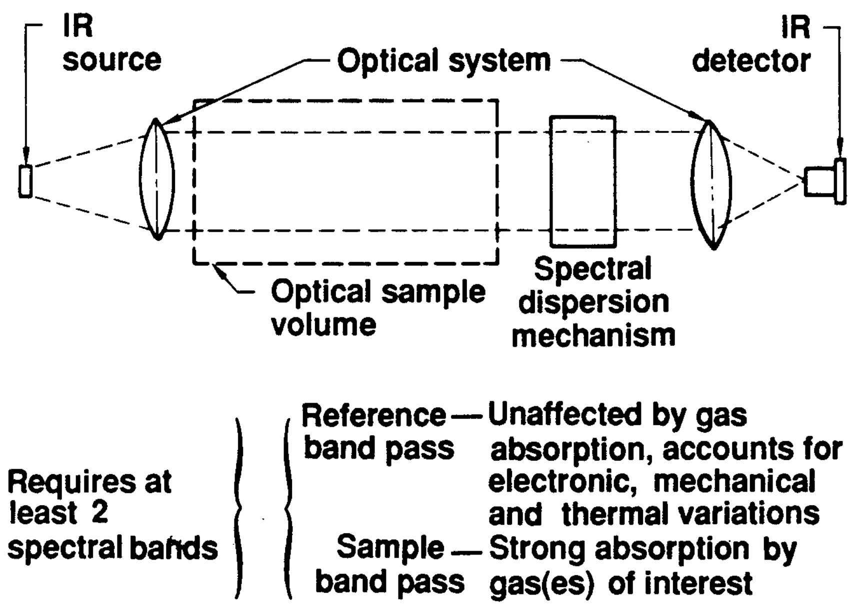


Figure 1. Gas Detection by Dispersive Infrared Absorption.

for each gas. By proper spectral positioning of N sample bands, one may measure the concentrations of N-1 different gases with the dispersive IR-absorption technique. The additional sample-band required is the reference band and the transmissivity used in Equation (1) is actually the ratio of the sample band and reference-band transmissivities.

At higher concentrations and/or longer optical path lengths, the absorption process shifts to the strong-line absorption region where Beer's law no longer applies. In this region, the concentration-transmission relationship is best expressed by

$$-\ln\tau/(L)^{1/2} = k_1C_1^{1/2} + k_2C_2^{1/2} + \ldots + k_iC_i^{1/2} \qquad (2)$$

Calibration of dispersive IR sensors operating in the strong-line absorption region requires several concentration data points to accurately describe the response function. More sophisticated concentration-transmissivity relationships are required for sensors operating in both the weak- and strong-line absorption regions.

SECTION II

INSTRUMENT DESCRIPTION

A. SPECTRAL CHARACTERISTICS

The AFESC prototype HCl sensor utilizes four bands in the 3 to 4 μm spectral region, making it sensitive to HCl, H_2O, and CH_4 vapors. The H_2O and CH_4 sensitivity exists because both of these gases absorb IR radiation in the optimum HCl-absorption region. A literature search of solid rocket motor exhaust product data was conducted as part of the HCl sensor development project. A slight increase (1 to 2 ppm) in the total hydrocarbons from the ground cloud of ATLAS launches has been reported (Reference 7). However, there is no indication as to what fraction of this increase was due to methane alone (typical ambient levels for CH_4 are about 1 to 3 ppm). Since the CH_4 concentration should not change appreciably during a launch, its prelaunch value is assumed constant throughout the launch. There is also the possibility of interference by water vapor (H_2O), since it appears to have a weak continuum absorption throughout the near IR region. Because large amounts of water are injected into the SRM exhaust for cooling and sound suppression, sizeable H_2O concentration fluctuations are expected during the post-launch period. Consequently, the H_2O concentration is measured by one of the other bands. The two remaining bands are used for reference levels and to account for aerosol effects.

The optimum HCl-filter bandpass was determined by superimposing a typical IR-interference bandpass on a calculated HCl spectrum and adjusting the filter half-width and center wavelength until the maximum absorption resulted. Appropriate molecular data were obtained from the Air Force Geophysics Laboratory Trace Gas Absorption Parameter tape (Reference 8) and the HCl absorption spectrum was calculated using a high resolution line-by-line computer code developed at LLNL. The HCl transmission spectrum for a concentration of 1000 ppm and a path length of 10 m at ambient temperature and pressure is shown in Figure 2. These calculated values agree well with published HCl-absorption data. The

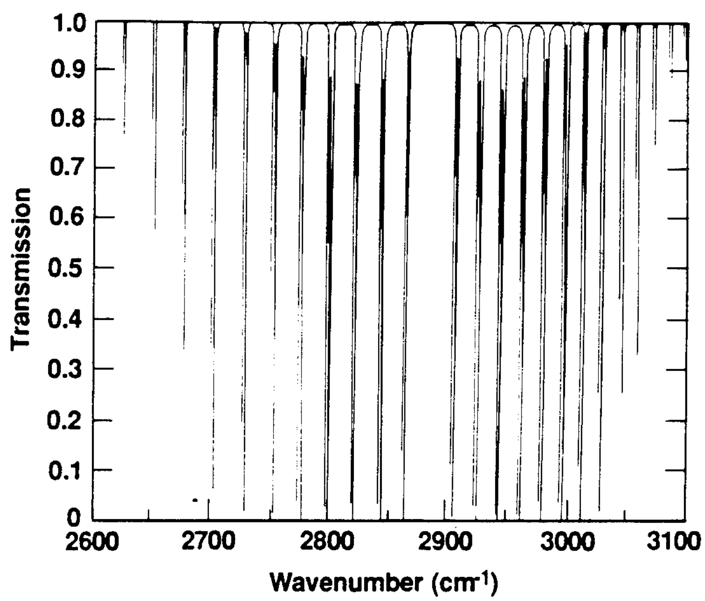


Figure 2. HCl Transmission Spectrum.

line pairs of Figure 2 are due to the two isotopes of HCl (molecular weight = 35 & 37) that occur in a natural abundance of 75 and 25 percent, respectively. The optimum filter bandpass was found to be centered at 3.405 µm and to have a full width at the half maximum transmission point of 0.0465 µm. The calculated optimum filter bandpass and the calculated HCl absorption spectrum are shown in Figure 3. Infrared Industries, Inc. (Orlando, FL) was contracted to fabricate a filter that matched (as closely as possible) the optimum HCl filter characteristics. The two sets of filters fabricated for evaluation are shown in Figure 4, along with the optimum HCl filter. The characteristics of the final four filters used in the AFESC prototype sensor are listed in Table 1.

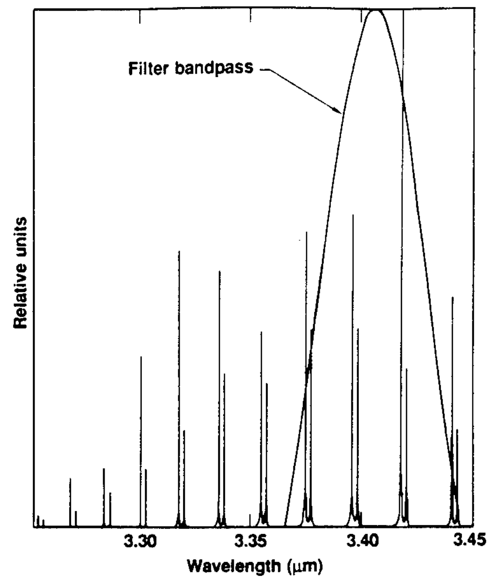


Figure 3. HCl R-Branch Absorption and the Optimum Filter Bandpass.

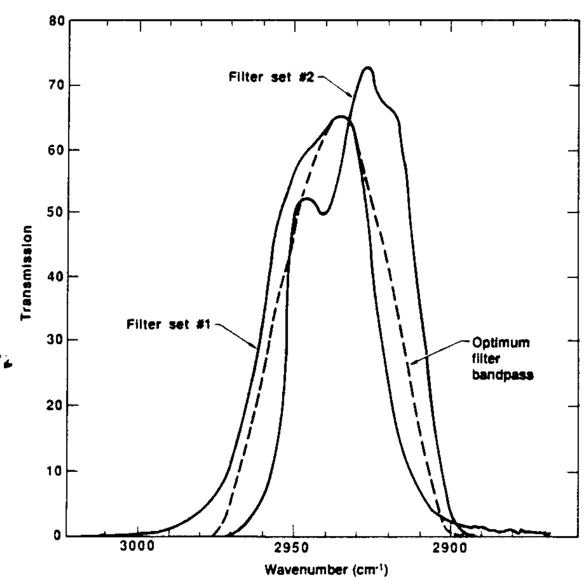


Figure 4. The Optimum Filter Bandpass and the Bandpasses of the Filters Actually Produced (From Filter sets 1 and 2).

TABLE 1. PROTOTYPE HCl SENSOR FILTER CHARACTERISTICS

Detectable gas(es)	H_2O	HCl, H_2O, CH_4	Ref.	Ref.
Center wavelength (µm)	3.1600	3.3996	3.7095	4.0318
Bandwidth (FWHM - µm)	0.0250	0.0435	0.0289	0.0444

B. GENERAL INSTRUMENT LAYOUT

The prototype HCl sensor system shown in Figure 5 consists of four major subsystems: the sensor head, the sensor electronics unit (SEU), and the remote and central data acquisition stations (RDAS and CDAS). The sensor head contains all the optical hardware used to make the infrared absorption measurement. Its operation is controlled by the sensor electronics unit, which provides power to the head and is responsible for the collection and processing of the infrared absorption data. Those data are then passed to the remote data acquisition station (a radio transmitter), then transmitted to the central data acquisition station (a central radio base station linked to a personal computer). The first three components are incorporated into the fieldable sensor unit. Ultimately, many of these units can be deployed in the field to form a sensor array. During a launch, each of these units will transmit its measurements by radio to the CDAS.

In terms of actual physical structure, the fieldable portion of the sensor consists of four modules: the sensor head, a main chassis that contains the SEU and the RDAS, a battery box that contains the power supplies for the sensor, and a pump chassis that provides cooling water to the sensor head. The following sections provide a general discussion of each of the system components. A detailed set of mechanical drawings of all parts accompanies this manual. Similarly, a complete set of electronic schematics is also provided. More specific information regarding the construction of the components is given in the Appendices.

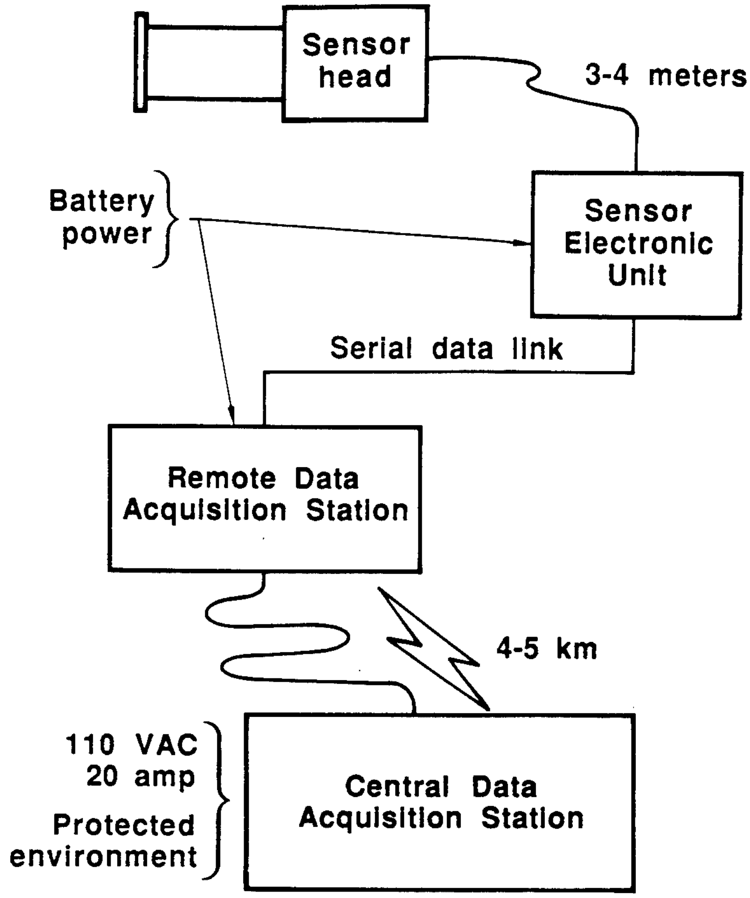


Figure 5. Block Diagram of the Major Components of the Sensor System.

C. SENSOR HEAD

A photograph of the prototype HCl sensor head is shown in Figure 6. The broadband IR radiation emitted by the source unit is collimated by a lead-silica (Corning, 9454) lens, and directed into a three-mirror, off-axis White cell (Reference 5), open to the environment. After the desired number of passes through the optical sample cell, the IR beam is collected by another lens and focused onto a PbSe detector. The four bandpass filters are mounted on a rotating wheel, which sequentially inserts each filter into the optical path in front of the detector. The filter wheel rotates at 60 revolutions per minute, providing a system response time of one second. The signals are amplified and conducted to the sensor electronic unit for processing and digitization. Each of the major components of the sensor head is described below:

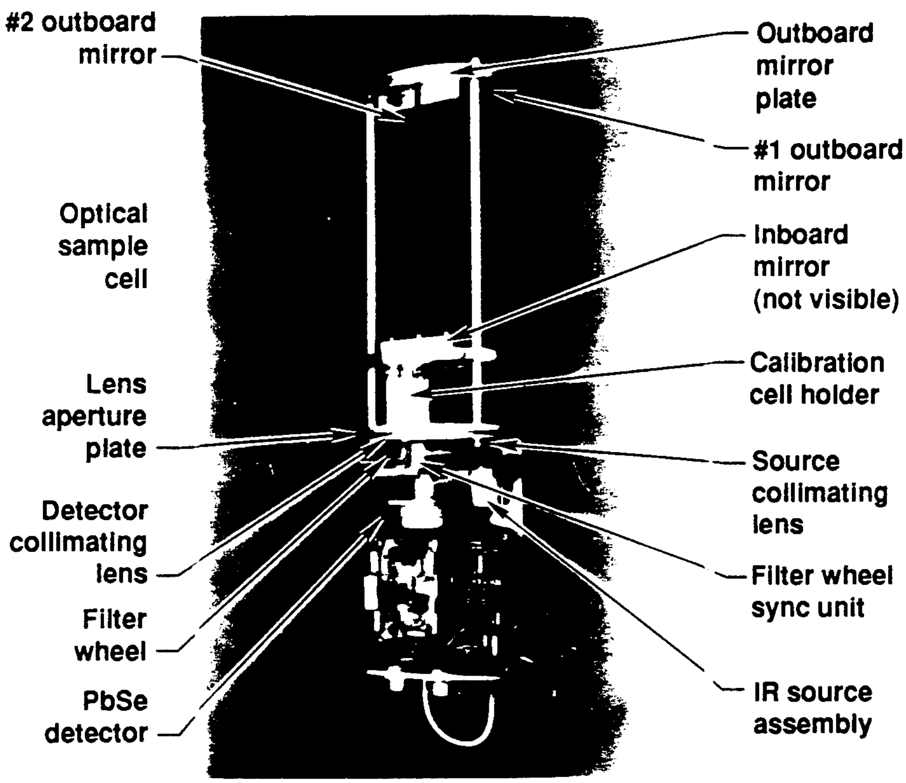


Figure 6. Photograph of the Prototype Sensor Head.

1. IR SOURCE UNIT

The purpose of the IR source unit is to produce a stable, broad-band source of IR radiation as efficiently as possible. A cross-section of the IR source unit used in the AFESC prototype HCl sensor is shown in Figure 7. The IR source element is a machinable ceramic material (Cotronics 902) supported by an insulating material (Dow Corning SEACOR) within a metallic housing. The heated end of the Cotronic 902 (C902) element is threaded (96 threads/in) to a depth of 0.005 inch to facilitate wrapping and separation of the 0.005-inch diameter platinum wire. A heavier guage wire is welded to the platinum wire at the base of the C902 element to confine the ohmic heating to the threaded region. A shallow, conical hole is machined in the end of the element to increase the apparent emissivity. The platinum wire is covered with a high temperature, zirconia-base ceramic adhesive to further confine the heat to the end of the C902 element. The SEACOR insulation is machined to hold the C902 element on centerline and at the desired distance from the water-cooled copper aperture stop. The SEACOR is then pressed into an aluminum sleeve and glued in place.

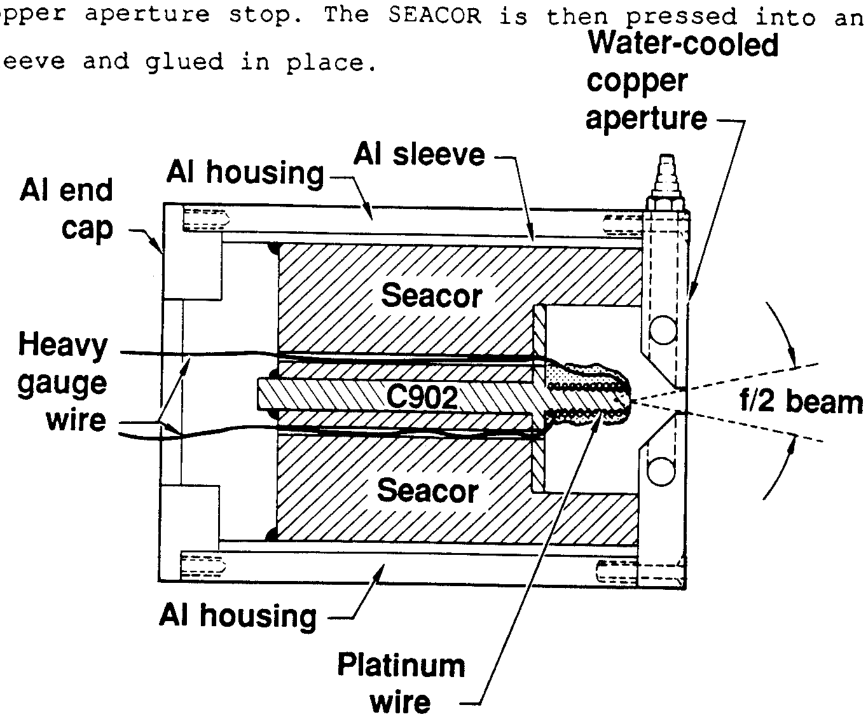


Figure 7. The Prototype Sensor IR Source Assembly.

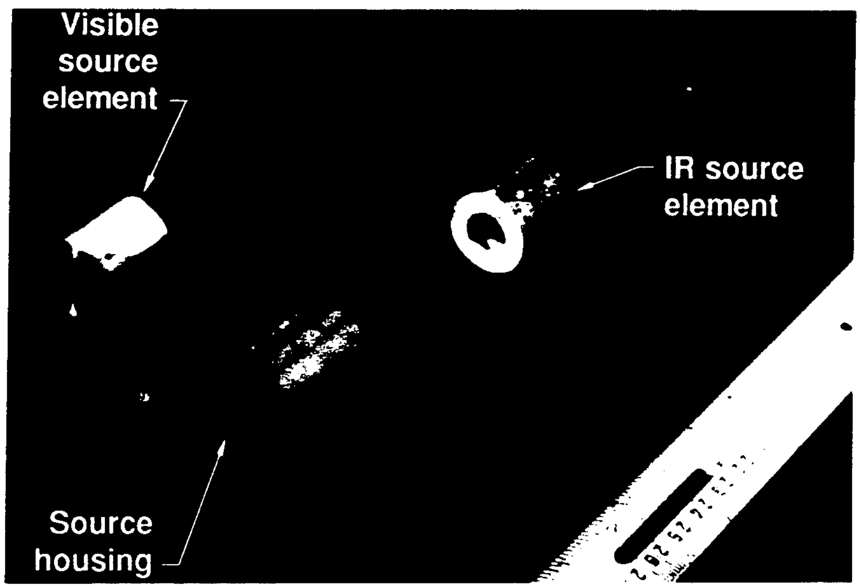


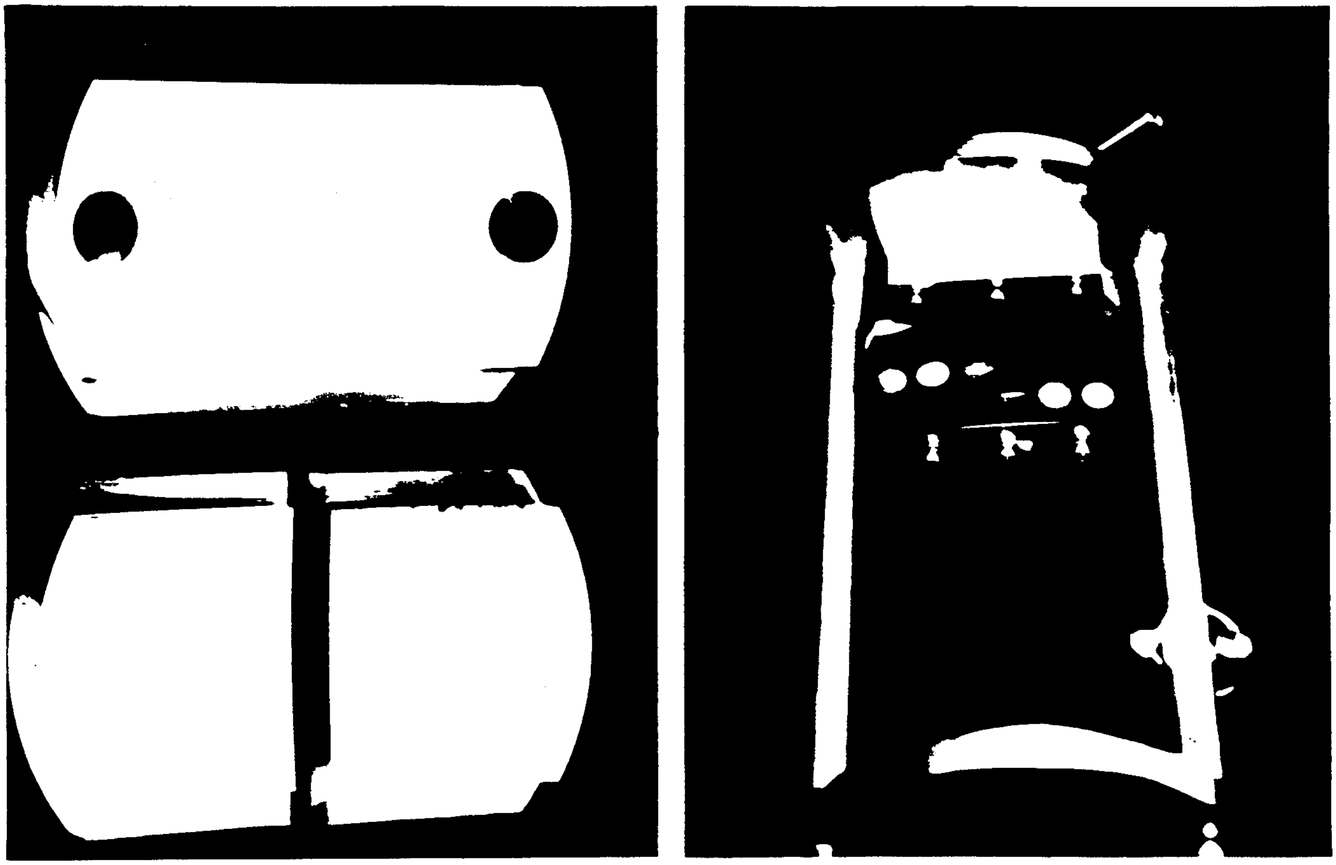
Figure 8. Components of the Gas Sensor Source Unit.

The external housing for the IR source element consists of a copper aperture stop bolted to an aluminum cylinder. The inner diameter of the aluminum housing is machined for a snug fit to the aluminum sleeve of the IR source element. After an initial alignment, the source housing may be locked into place in the sensor head (see Figure 6). With this design, IR source elements may be replaced in the field with little effect on the optical alignment of the sensor. The IR source element is easily replaced with a visible source element to aid in the alignment of the optical sample cell mirrors. The visible source element consists of an optical fiber mounted in a cylindrical aluminum block to position the end of the fiber in the IR source assembly at the same location as the end of the IR source element. A picture of the IR source element, IR source element housing, and the visible source element is shown in Figure 8.

The aperture stop of the IR source assembly produces an f/2 beam that just fills the source collimating lens. The water flow required to cool the copper aperture stop is minimal (100 cc/min). The output power of the source is maintained at a constant level by a closed-loop high-gain feedback circuit. The source operates at 1.4 amperes and 4.5 volts (6.3 watts), which produces an element temperature of about 600° C. The total output radiant power in the f/2 beam is 0.05 watt for an overall efficiency of 0.8 percent. This design is about twice as efficient as the source used in the LLNL CO_2 sensor (Reference 5).

2. Optical Sample Cell

The optical sample cell is an open-path gas-sample arrangement capable of from 4 to 24 passes, in steps of four. Each pass represents an absorption path length of 20 cm, giving the sample cell a maximum optical path of 4.8 meters. The optical arrangement consists of three borosilicate glass, gold-coated front-surface mirror elements, each with a radius of curvature of 20 cm (see Figure 9). The larger mirror element (Figure 9a, top) is mounted to an aluminum plate that has been drilled with two holes to coincide with the lens apertures. The two smaller mirror elements (Figure 9a, bottom) are mounted on a flat aluminum plate



(a) (b)

Figure 9. The Optical Sample Cell Assembly.

supported at the opposite end of the cell from the lens aperture plate by three 0.5-inch diameter aluminum rods. The plate to which the larger mirror is attached is also mounted on these rods. The spacing between this plate and the main canister housing the source and electronics (see Figure 6) provides an area into which the quartz-field calibration cells can be placed. A special holder for these cells is mounted where the optical path passes through this gap enroute to the detector. The two mirror plates are separated so that the inboard and outboard mirror surfaces are 20 cm apart. Our goal was to develop an optical sample cell with inexpensive mirrors that may be easily replaced and realigned in the field. This approach is preferable to trying to design a permanent, essentially indestructible optical unit.

The installation and alignment of the mirrors in the optical sample cell are quite simple. Pins are used to align the holes in the inboard mirror with the collimating lens apertures, and the mirror is clamped to the lens-aperture plate. This is a fixed mounting and requires no further adjustment. The Number 1 outboard mirror (Figure 6) is also a fixed-mount mirror, positioned by two guide pins and the vertical spacebar that separates the Number 1 and Number 2 outboard mirrors. The Number 2 outboard mirror is held flat to the outboard mirror plate and is adjustable in the horizontal and vertical directions. This is the only adjustment necessary to select the number of passes and to optimize the IR source throughput of the optical sample cell.

The horizontal plane containing the optical axis of the two outboard mirrors is 0.5 inches lower than the horizontal plane containing the optical axis and aperture centers of the inboard mirror. This produces an off-axis White cell (Reference 9) arrangement allowing for up to 24 passes of the sample region for this particular lens separation distance. A 20-pass alignment of the optical sample cell is shown in Figure 9b. The collimated light enters the optical sample cell through the aperture at the upper left side of the inboard mirror and is collected by the number 1 outboard mirror. The image of the entrance aperture is focused back onto the inboard mirror as the right-hand spot in the lower row of spots. The image of this spot (lower right), focused by the number 2 outboard mirror back to the inboard mirror, is the spot just to the right of the entrance aperture in the upper row of spots. The successive transfer of the spot images by the two outboard mirrors follows a zig-zag pattern that moves from right-to-left in the upper row. In the arrangement shown here, the number 2 outboard mirror is adjusted so that the 10th spot passes through the exit aperture of the inboard mirror. Each spot represents an absorption path length equivalent to twice the separation distance of the inboard and outboard mirrors (40 cm). The optical sample cell arrangement of Figure 9b produces an absorption path of 4.0 meters. In the 24-pass configuration (4.8-meter absorption path), the 12 spots on the inboard mirror are tangent to each other.

Several sets of mirrors were fabricated to loose tolerances. We found that the mirror elements could be replaced (totally or partially), and realigned in less than 20 minutes. Once the mirror elements are locked in place, the throughput of the optical sample cell appears to only be affected by degradation of the mirror surfaces.

3. Filter Wheel Assembly

During operation, the four IR-bandpass filters are sequentially passed through the IR source beam before it is focused onto the PbSe detector (see Figure 6). The four filters are mounted on an aluminum wheel assembly, which also momentarily blocks the beam between the IR source and the source collimating lens, and provides the synchronization pulses necessary for signal processing. A photo of the filter wheel is shown in Figure 10. Each filter is a quarter segment of a 1-in diameter filter which has been glued at 90-degree intervals on a 3.0-inch diameter circle on the wheel. Four chopper blades are positioned on a 4.25-

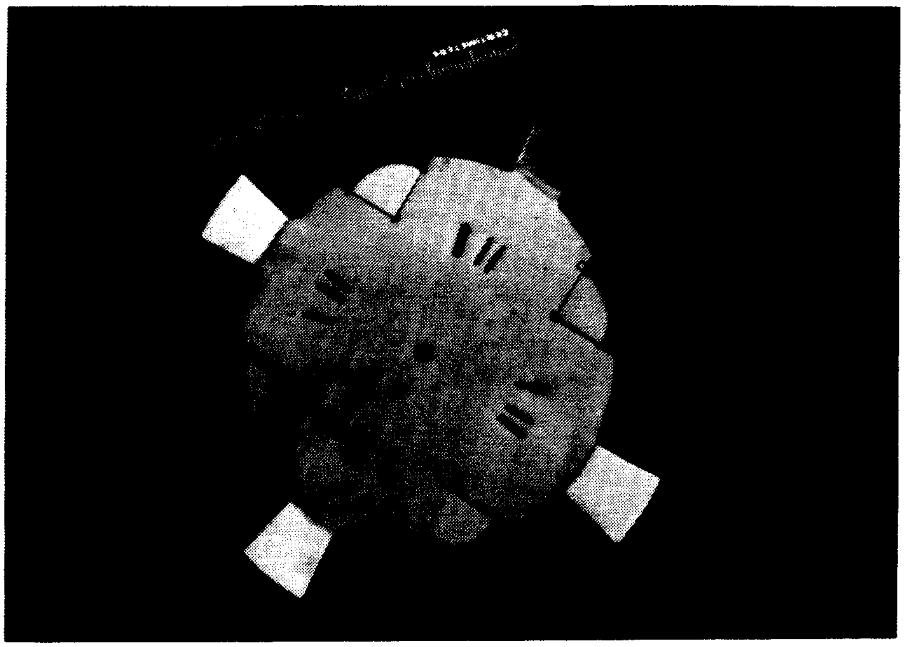


Figure 10. The Filter Wheel Assembly.

inch diameter circle. The surfaces of the chopper blades have been polished to reflect the blocked IR source beam back to the water-cooled aperture stop, thereby reducing the heating of the filter wheel. Twelve timing slots are located on a 1-inch diameter circle on the wheel. The timing signals are generated by an LED-photocell unit positioned so that the LED light beam periodically passes through the timing slots as the filter wheel rotates. The filter wheel is rotated at 60 rpm by a stepping motor. The location of the axis of rotation of the wheel is such that the filters pass through the IR beam at the detector side, but not at the source side. The relative position of each chopper blade is such that it blocks the IR source beam during the last half of the filter residence time in the beam at the detector side. The timing slots are located to provide signals that correspond to the open and blocked position of each filter as it passes through the IR beam.

The filter wheel rotates counterclockwise as viewed in Figure 10. The first of each group of three timing slots announces the arrival of the filter. The second slot corresponds to the point at which the filter is halfway through its passage of the IR beam at the detector side of the optical path. The third slot corresponds to the arrival of the trailing edge of the filter. The extra-wide slot in the group of three at the bottom of Figure 10 provides a unique once-per-revolution signal as a check on the proper sequence of the filter signals.

4. Detector

The variations in the intensity of the IR beam due to absorption and blockage of the source are monitored by a 1-mm square lead selenide (PbSe) detector selected to have a detectivity greater than 2.5×10^{10} cm $Hz^{1/2}$ W^{-1}. The detector temperature is maintained at -35°C with a two-stage thermoelectric cooler. The detector and cooler are packaged in a TO-3 type container, which is attached to a water-cooled copper heat sink. The complete unit is mounted on an adjustable X-Y stage, which is also capable of adjustment along the optical axis of the detector collimating lens (see Figure 6). The detector output signal is amplified by a preamplifier that is contained in the sensor head, and transmitted by a cable to the sensor electronics unit, which is described in detail in the next section.

D. SENSOR ELECTRONIC UNIT (SEU)

This section provides a brief overview of the sensor electronics unit. A detailed set of electronic schematics accompanies this manual. They are described in more depth in Appendix A.

A diagram of the sensor electronics unit is shown in Figures 11(a) and 11(b). Note that a small part of this circuitry is contained in the sensor head (Figure 11(a)). This includes the detector preamplifier (mentioned in the last section), the stepping motor driver, the detector thermoelectric cooler controller, and the circuits that generate various timing pulses from the photocell that monitors the filter wheel timing slots.

The sensor signal processing can be explained by reference to the timing diagram in Figure 12, where the processing of a single filter measurement is depicted. The upper trace of the figure represents the PbSe-detector signal before, during, and after the passage of one of the filter segments through the IR beam. The second trace, also generated in the sensor head, represents the signals produced by the timing slots as each passes the synchronization LED/photocell unit. The temporal location of the three synchronization pulses relative to the filter signal waveform is critical to the performance of the sensor. The leading edge of the first of the three synchronization pulses initiates an autozero circuit, that adjusts the detector preamp output to a set reference level (A, Figure 12). The autozero is performed prior to each filter signal to ensure that all signals are referenced to the same level. The time delays from the synchronization pulse leading edges are set with a combination counter/one-shot circuit. In addition to the autozero signal, signal peak/hold pulses (B, Figure 12), analog/digital (A/D) conversion pulses (C, Figure 12), and signal peak/hold reset pulses (D, Figure 12) are also generated in the sensor head. These pulses, along with the signal output from the preamplifier, are conducted by cable from the sensor head to the SEU where the final signal processing is performed.

At the SEU (Figure 11(b)), the preamplified detector signal and the pulses are first input into a signal conditioning card, where they are buffered and amplified. As with the preamp, the autozero pulse is used here to trigger the zeroing of the signal amplifier output to a fixed reference level prior to each filter signal. Next, the conditioned detector signal and the convert and autozero pulses are sent to the

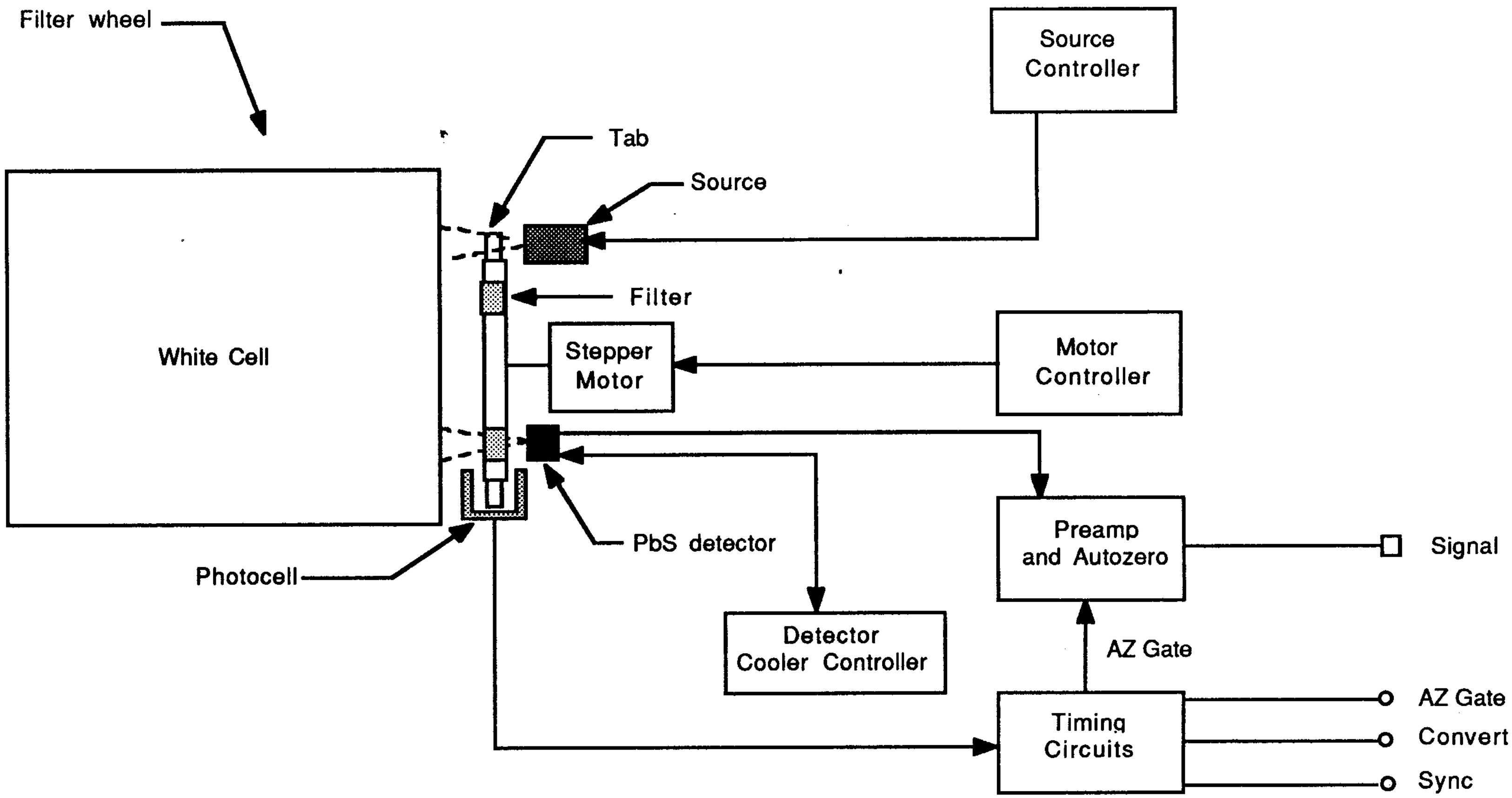


Figure 11a. Diagram of the SEU Circuitry Contained in the Sensor Head.

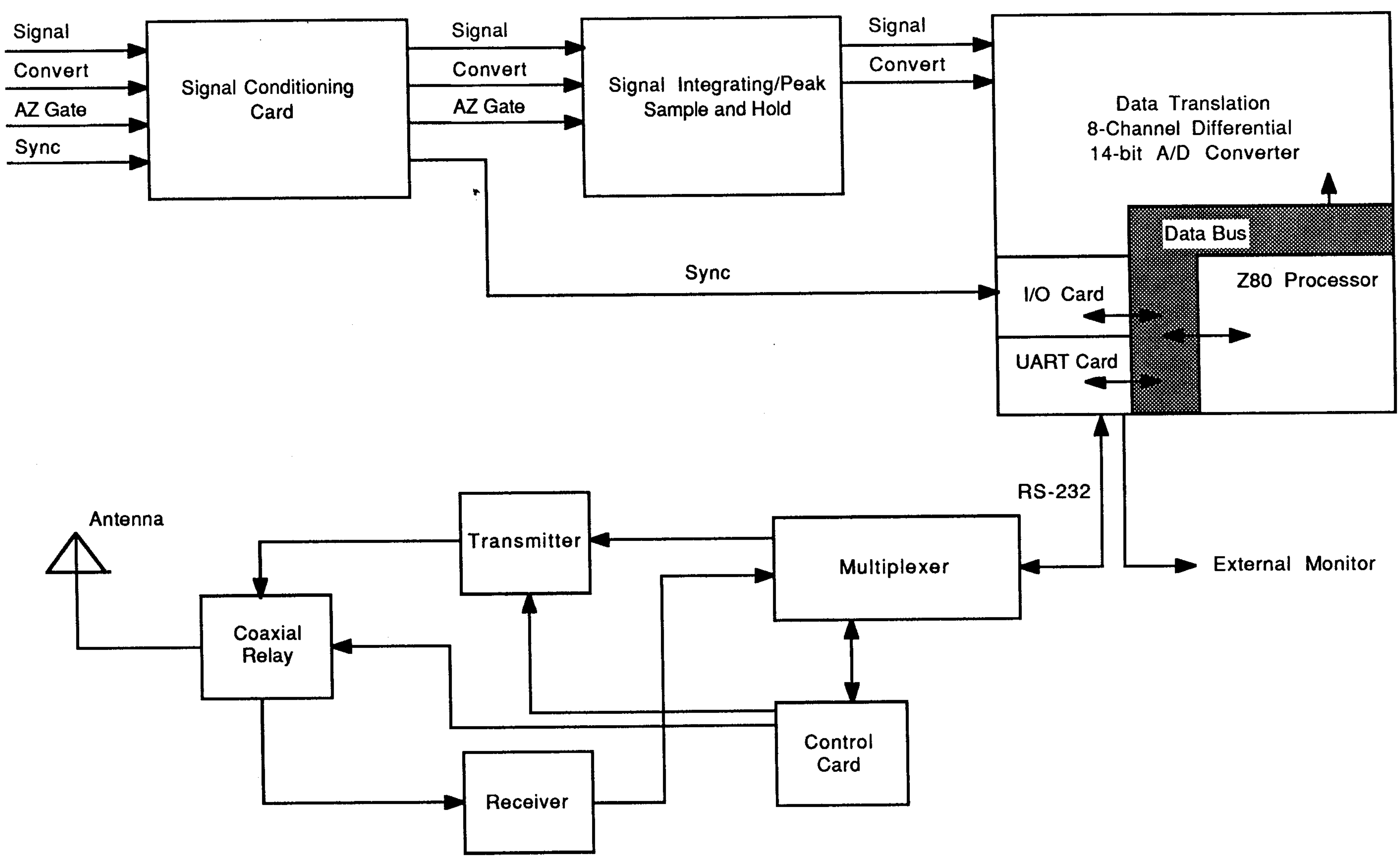


Figure 11b. General Diagram of the SEU

signal card, which contains a signal integrating and peak/hold circuit. The signal peak/hold circuit closely tracks the generally increasing PbSe-detector signal until the signal begins to decrease due to the blockage of the IR source beam by the chopper blade. At this point, the circuit maintains the peak signal level, until set to zero by the signal peak/hold reset pulse (D, Figure 12). The peak signal level is applied to an input of a 14-bit analog-to-digital converter card (Data Translation, 8 input channels), where it is digitized prior to the peak/hold reset at the time of the A/D convert pulse. When the beam is blocked by the chopper blade, the peak/hold-A/D convert process is

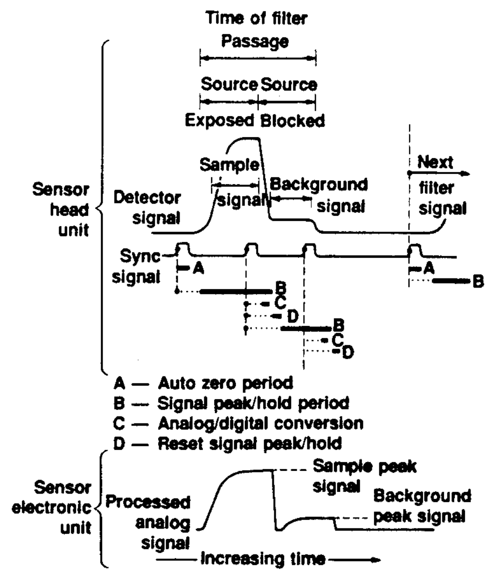


Figure 12. Prototype Sensor Filter Signal Processing.

repeated to obtain the background signal reading. The processed analog signal for a single filter is shown at the bottom of Figure 12.

For a single filter wheel revolution, the sensor output signal consists of four pairs of sample and background values - one pair for each filter. These data are further processed by a Z-80 microprocessor that is connected by a bus (Standard Bus) to the A/D card, and runs a FORTH system control program that is loaded into the sensor's onboard

RAM from ROM when the sensor is powered up. A detailed description of the Z-80 control program is given in Appendix B.

E. REMOTE AND CENTRAL DATA ACQUISITION STATIONS

The transmission of the data pairs to the CDAS is accomplished by a dedicated radio transmitter/receiver unit (see Figure 5). This link allows the sensor to be placed large distances (km) from the CDAS, without the need for any physical connection between the units. Ultimately, it is intended that an array of sensors can be used in conjunction with a single CDAS. This will, however, require modification of the existing control software.

The RDAS is able to exchange information with the Z-80 through an RS-232 serial data port that is resident on the microprocessor data bus. A signal conditioning multiplexer is interposed between the radio module and the data port, and is used in the radio-frequency modulation and demodulation the the RS-232 signal as input to and received from the radios. A separate control card is used to regulate the operation of the multiplexer. It receives signals from the microprocessor (through a channel on the I/O card) that indicate which direction the data are to flow (i.e. whether data are to be transmitted or received). The control card also uses these signals to switch a coaxial relay that selectively connects the transmitter or receiver to the antenna and to switch off the power to the transmitter when it is not needed.

During normal operation, the system is in a free-running mode in which the transmittance of the four channels is continually monitored at the rate of one measurement per channel per second. As described in the previous section, each set of four filter and four background readings is stored in onboard RAM until eight sets have been collected; at that point, the eight measurements are averaged to give a single value per channel, which is then transmitted to the CDAS. At the CDAS, a separate program is used to collect and display the data in real time. This program can also send certain commands to the sensor. These include messages that turn the system on and off, and commands to open and close the hood to cover the White cell. The hood open and close messages cause a channel of the microprocessor I/O card to be toggled high and low. Although there is no hood for the White cell, this activation mechanism has been implemented in the system in case one is added. Then, the hood I/O channel could be used to activate an electrical device, such as a solenoid, to mechanically open and close the hood. In fact, there are several unused I/O channels on that card that could be used to remotely control other potential features of the system. The CDAS operating system software is described in detail in Appendix C.

SECTION III

SENSOR CALIBRATION SYSTEM

A. LABORATORY CALIBRATION SYSTEM AND SENSOR RESPONSE

To calibrate the HCl sensor in the laboratory, a sensor-calibration system was designed and built that can supply accurately known mixtures of gas to a calibration chamber that houses the prototype sensor. A schematic of the sensor-calibration system is shown in Figure 13. The main components of the system are a precision gas-mixture generator (PGMG), a humidity control system (HCS) and a Pyrex calibration chamber.

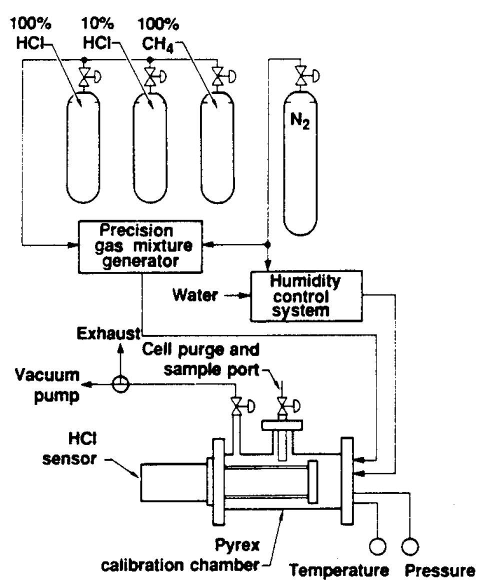


Figure 13. Prototype Sensor Laboratory Calibration System.

The PGMG is a flowing-gas mixing system purchased from Kin-Tek Laboratories, Inc. (Model 585A). The primary gas source results from the carefully controlled permeation of the component gas through a Teflon® membrane. A line drawing of the PGMG is shown in Figure 14. The component gas is supplied to the trace source module, which is housed in a temperature-controlled and pressure-regulated oven unit. The dilution gas flows through 1 m of Teflon® tubing within the trace source module. The permeation of the component gas through the tubing and into the dilution gas flow is a well-documented function of the Teflon® tube length, temperature, and the pressure difference across the tube wall. Each trace source module is calibrated for a particular gas at a range of temperatures and pressures. The gas mixture may be varied further by changing the dilution gas flow rate. Generally a pure (100 percent) gas is used for the component gas; however, if a reliably diluted gas supply can be obtained, proportionately lower mixture concentrations may be created with the same trace source module. The LLNL calibration system, using 100 percent and 10 percent HCl/N_2 gas cylinders, can generate HCl concentrations from 280 ppb to 10,000 ppm. The current system's methane concentration range is 500 ppb to 200 ppm. The stated accuracy of the PGMG is ±2 percent.

Calibration of the sensor for water vapor is also performed using a flowing-gas system (Figure 13). The humidity control system (HCS) was manufactured by Miller-Nelson Research, Inc. (Model HCS-301) and is capable of a relative humidity range of 20-90 percent at an accuracy of ±3 percent. A schematic of the HCS is shown in Figure 15. Dry N_2 is delivered to the HCS, humidified, and exhausted. The humidified N_2 passes through a humidity sensor before entering the calibration chamber. A feedback loop between the humidity sensor and the HCS regulates the humidified N_2 to the desired level. The temperature of the humidified N_2 supply is always set to be a few degrees cooler than the temperature of the calibration chamber to prevent condensation. The calibration water vapor concentration is calculated using the chamber temperature.

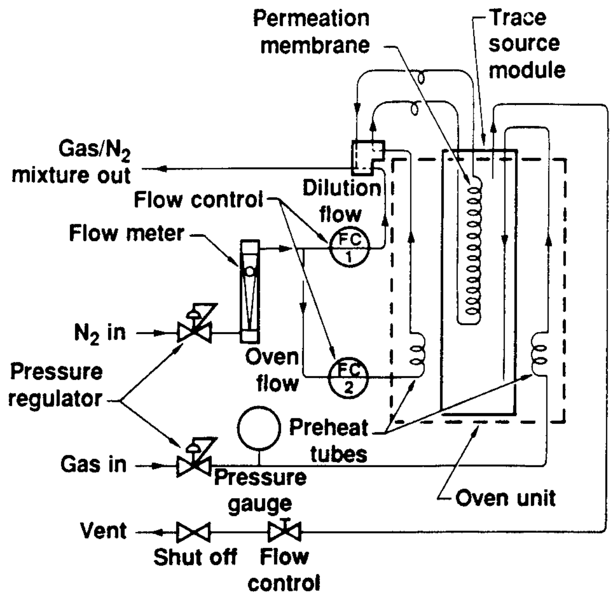


Figure 14. The Kin-Tek Precision Gas Mixture Generator.

As shown in Figure 13, the prototype HCl sensor is mounted in a Pyrex® calibration chamber so that the optical sample volume is completely enclosed. All chamber flanges, valves and fittings are either stainless steel or Teflon®. The calibration chamber will maintain a vacuum of 15 µm Hg (2×10^{-5} atm) with a leak rate of 0.5 mm Hg/min. The chamber is wrapped with a heat-tape and may be baked-out at temperatures up to 50°C. The calibration gas and humidified N_2 may be injected separately or simultaneously and may provide either a stagnant or flowing environment within the chamber. The chamber temperature is monitored with a chromel-alumel thermocouple and the pressure is monitored with a capacitance manometer. The entire sensor calibration system is located in an exhaust hood.

A typical calibration sequence begins by evacuating and baking out the chamber for 4 to 5 hours. When the chamber has cooled to ambient temperature, the prototype sensor is turned on and allowed to warm up for about 30 minutes. At this time, absolute (vacuum) transmissivity baseline data are obtained. The chamber is then filled with dry N_2 from the same cylinders as used for the PGMG and the HCS, and N_2 baseline data are obtained. Although the N_2 has been prepurified, it still contains trace amounts of hydrocarbons and and water vapor, which are detectable by the prototype sensor. With the initial baseline established, various gas and/or humidified N_2 concentration are supplied to the chamber and the corresponding sensor response is recorded. When the calibration sequence is complete, the chamber is evacuated and refilled with dry N_2 for the postcalibration baseline data.

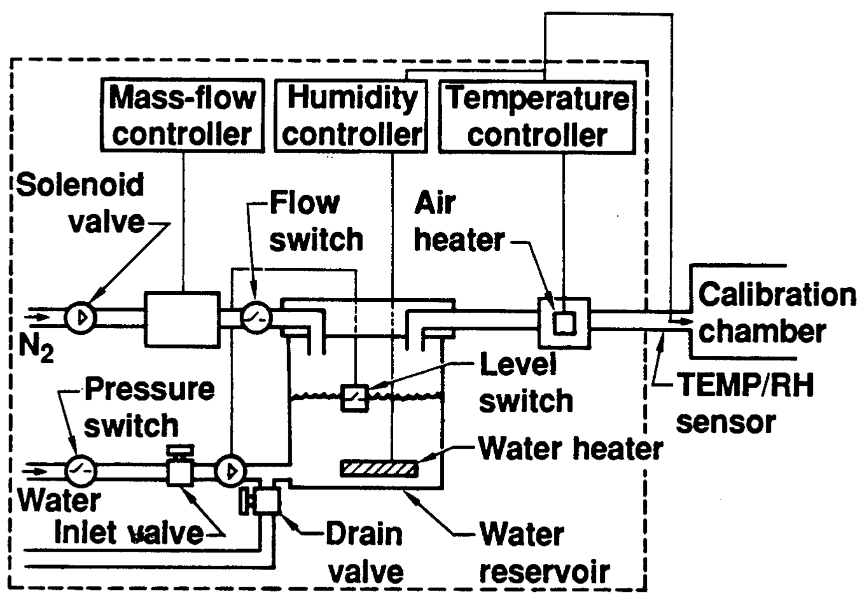


Figure 15. Schematic Diagram of the Miller-Nelson Humidity Control System.

The calibration data are recorded and processed through a direct-line serial link (i.e. a cable - - the radios are bypassed) between the sensor and the CDAS personal computer. The calibration concentrations are adjusted to a pressure of 760 Torr and a temperature of 300 K using the chamber temperatures and pressures recorded at each calibration data point. These data are used to calculate the band-integrated absorption coefficients (k_i) of Equations (1) and (2). Detailed calibration instructions are provided in Section V.

The prototype HCl sensor was calibrated with accurately known mixtures of nitrogen and HCl, CH_4 and H_2O vapors using the gas-calibration system described above. As mentioned above, this is done in a hard-wired mode, using the "Lab calibrate" command in the CDAS software. The raw data are displayed at eight-second intervals on the computer monitor in real-time. Background corrections are made for each filter datum, then Channels 1, 2, and 4 are divided by Channel 3 (the primary reference channel). These three ratios are normalized to their respective N_2 baseline values obtained at the beginning of each calibration set, and then used to calculate the three species calibration constants for each of the three data ratio channels as expressed in Equations (1) and (2).

The response of Filter 2 (Channel 2) is approximately the same for CH_4 as for HCl. Its response to water vapor is much less; however, the concentration of H_2O is expected to be many times greater than the HCl concentration. The channel 1 signal will be used to account for the variation in the H_2O concentration during the HCl-concentration measurement. In this sensor configuration, the Channel 4 data will serve as a second reference to be used to correct for aerosol effects. In the absence of aerosols, this channel could be used to monitor another gas species. We have decided not to monitor methane concentration with a separate filter channel. As mentioned earlier, we assume that the methane concentration is constant throughout a measurement run and, therefore, do not require knowledge of its concentration.

The sensor response is linear with concentration (weak-line region) for CH_4 concentrations as large as 18 ppm and all expected humidity levels. However, deviation from the weak-line region appears to occur for HCl concentrations above 40 ppm. This effect is shown in Fig. 16, where the Channel 2 response function ($-\ln\tau/L$) is plotted against the HCl concentration. At concentrations below 40 ppm, only the slope of the linear region is required to characterize the sensor response. Above 40 ppm, the curve can be described by Equation (2), as can be seen in Fig. 17, where (-lnτ/L) is plotted against the square-root of the concentration. To calculate the HCl concentration in this region, it is necessary to know both the slope and intercept of the line in Figure 17.

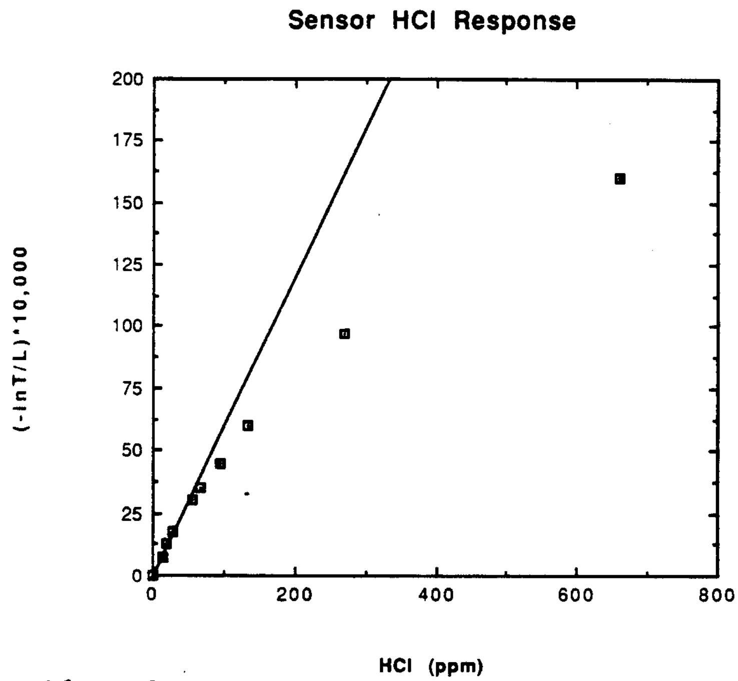


Figure 16. Plot of the Sensor Response to HCl as a Function of HCl Concentration.

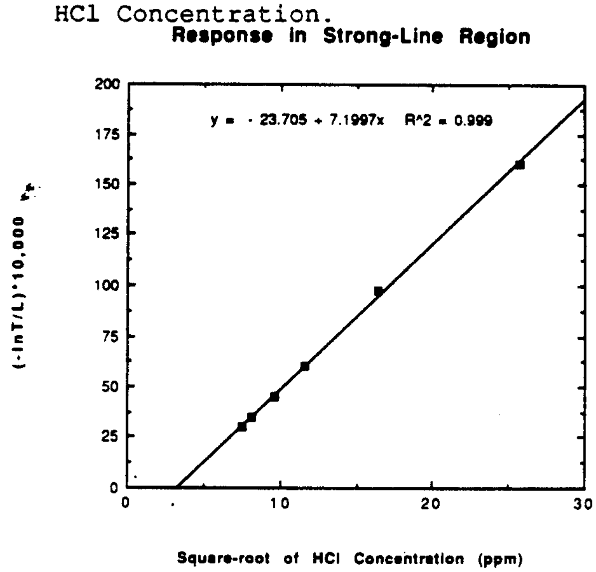


Figure 17. Plot of the Sensor Response to HCl Plotted as a Function of the Square-Root of HCl Concentration.

The calibration coefficients of the sensor are shown in Table 2. This includes the slopes of the methane, water, and HCl (weak-line) responses and the slope and intercept of the HCl (strong-line) response curves. The general response characteristics of the sensor are given in Table 3.

TABLE 2. CURRENT OPERATING SPECIFICATIONS OF THE AFESC PROTOTYPE HCl SENSOR SYSTEM

Detectable gases	HCl	H_2O	CH_4
Minimum detectable conc.	500 ppb	0.06%	720 ppb
Sample cell absorption path	4.0 m (variable from 0.8 m - 4.8 m)		
Detector	PbSe @ -35°C		
Sample rate	8 sec average (1 sample/sec max)		
Power requirements	70 watts (5 hours operation w/o charge)		
Data-transmission rate	9600 baud		
RDAS-polling interval	8 sec		

TABLE 3. CALIBRATION CONSTANTS (k) FOR THE PROTOTYPE HCl SENSOR $(ppmm)^{-1}$

Filter ratio	HCl	H_2O	CH_4
Channel 1	0	3.52×10^{-7}	0
Channel 2*	6.38×10^{-5}	1.09×10^{-7}	6.48×10^{-5}
Channel 3,4	0	0	0

*for the strong-line HCl response, see Figure 17

B. FIELD CALIBRATION

During extended field applications, it is desirable to calibrate the infrared sensor outside of the laboratory. Because of its size and complexity, it is not possible to transport the gas-calibration system to the remote location. Thus, a field calibration technique was developed that employs gas standard cells that can be filled in the laboratory and transported to the field for the calibration procedure. Two field calibration protocols were developed: one for HCl and one for H_2O. These are described in the following two sections.

HCl FIELD CALIBRATION

Field calibration of the sensor HCl response is accomplished using a set of five quartz cells. Before use, each cell is filled with a different (but precisely known) HCl/N_2 mixture using the PGMG. The cells are then transported to the sensor for the calibration procedure. To make a measurement, the cell is placed in the optical path using a specially designed holder. The transmission of the HCl channel (Channel 2) is noted with each cell in place. Following this reading, the gas is flushed out of the cell with pure nitrogen, and a baseline transmission reading is made. The two values are then used to generate an absorbance reading for that gas concentration. Once all five gas concentrations have been measured, a calibration curve for the sensor is generated. This includes the slope of the weak-line region and the slope and intercept of the appropriate strong-line response curve.

Because of the short pathlength of the cells, the concentration of HCl to be used in the calibration procedure must be increased to provide the same absorbance as a particular concentration measured at the full multipass length of the White cell. By reference to Equation. (1), the logarithm of the cell transmittance is related to the product of absorption pathlength and gas concentration in the linear region of the response curve. Thus, to compare measurements at short and long optical paths, we must relate the value of the product CL, which we will refer to as the optical density. The calibration cell concentration (C_{cc}) required to produce the same absorbance as a White-cell measurement (C_{wc}) is given by:

$$C_{cc} = (L_{wc}/L_{cc}) * C_{wc} \qquad (3)$$

where L_{wc} and L_{cc} are the pathlengths of the White and calibration cells, respectively.

Using Equation (3), the calibration cell concentrations required to span the linear response range of the sensor (0 - 40 ppm) vary between 0 and 3200 ppm. The linear-range calibration coefficients derived from each method are found to be in good agreement, demonstrating the accuracy of the field calibration method in this concentration range.

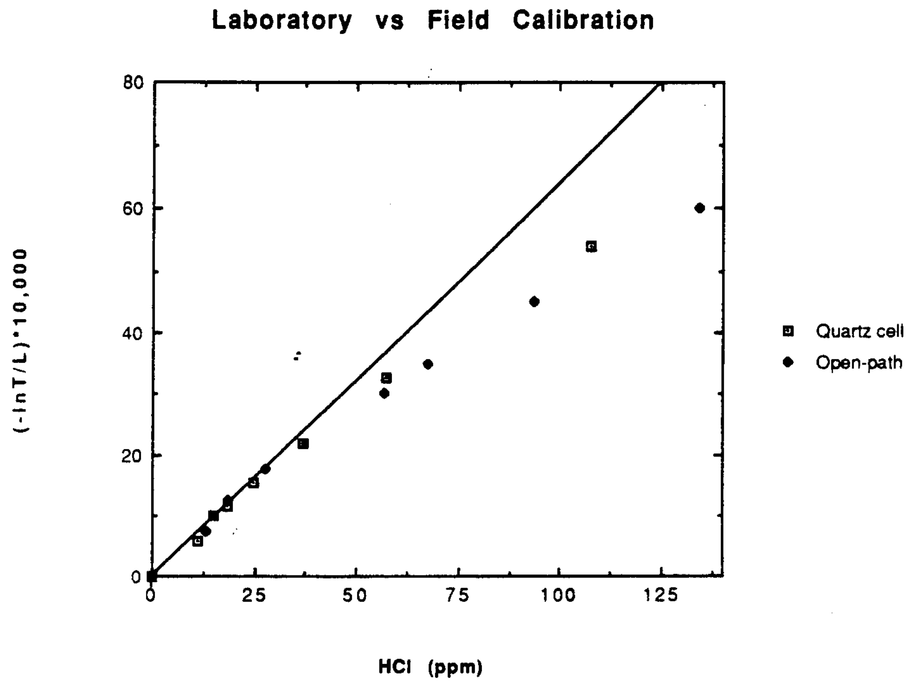


Figure 18. Sensor HCl Response Plot Obtained with the Laboratory and Field Calibration Systems.

For the nonlinear portion of the response curve, reference to Equation (2) indicates that the calibration cell concentration is similarly scaled, according to:

$$C_{CC} = [(L_{wc}C_{wc}/L_{cc})^{1/2}]^2 = (L_{wc}/L_{cc})*C_{wc} \qquad (4)$$

The maximum calibration cell concentration that can be used is limited by the capability of the PGMG to about 9000 ppm. This corresponds to an open-path optical density obtained at a concentration of 112 ppm.

An overlay of calibration curves obtained with the gas cells and with the laboratory calibration apparatus is shown in Figure 18.

H_2O FIELD CALIBRATION

It is not possible to use a short cell to calibrate the water channel because the increased water vapor concentration that is required to replicate the open-path optical density is higher than the saturation point of water in air. Thus, we have chosen to use a calibration hood that covers the entire White cell and which can be filled with various water vapor mixtures. The White-cell portion of the sensor head is sealed within the open-sleeve portion of the hood and water vapor is produced within the hood by evaporation from a solution contained in the reservoir below the cell. A small electric fan is installed above the solution to equilibrate the vapor. The humidity in the hood is varied by changing the composition of the water solution in the reservoir. Two humidity levels are used in the calibration procedure: a saturated magnesium chloride solution that produces an equilibrium relative humidity of about 40-50 percent, and a saturated potassium chloride solution that generates a relative humidity of about 60-70% (both at 20° C). It is not our intention to produce a true equilibrium humidity above these salt solutions, but to generate two distinct, uniform humidity levels in the chamber that can be measured by the sensor and by an independent method. The exact humidity within the hood is measured by a portable humidity sensor (purchased from Vaisala, Inc.) that can be inserted in the port on top of the calibration device. In the calibration process, the first solution is poured into the reservoir, and the hood is sealed for a certain amount of time to allow equilibration. The humidity level is noted on the sensor, and the transmittance of Channels 1 and 2 are recorded. This procedure is then repeated for the second calibration solution.

SECTION IV

SENSOR OPERATION PROCEDURE

A. SENSOR STARTUP AND LABORATORY CALIBRATION

The sensor system can draw power from either the gel-cell batteries contained in the battery box, or from 110 Volts-AC. When the system is connected to 110 Volts-AC, the battery chargers are switched on, and the system draws all its power from the AC line. For laboratory use, it is probably most convenient to leave the system connected to AC power.

Sensor control is accomplished in either a local or remote mode, depending upon the position of the local/remote switch on the digital voltmeter (DVM) panel in the main chassis. In the local mode, the sensor is operated by a program that is automatically entered when power is turned on. This program continuously sends data out of the serial line at 8-second intervals. The data is accessible at Plug P6 on the main chassis. In the remote mode, a more complicated program is run that relies on communication with the radios. For laboratory calibration, it is most desirable to run in local mode.

To turn the sensor on in local mode, set the local/remote switch to local, turn the main power switch (in the battery box) on, and set the on/off switch on the DVM to on. Among other things, one should hear the pump turn on and see the filter wheel begin to spin at this point.

For sensor calibration in the laboratory, it is not necessary to use the radio-link. The computer serial port can be connected with a hardwire connection to the serial line at Plug P6 on the main chassis.

1. HCl CALIBRATION PROCEDURE

Before attempting to operate the sensor calibration system, the user should be thoroughly familiar with the operation of the Kin-Tek gas standard generator and the Miller-Nelson humidity standard generator by reading their respective instruction manuals. Particular attention should be paid to the safety considerations associated with the use of HCl gas. The glass calibration chamber, the gas-standard generator, the HCl cylinder, and all associated tubing should be operated within a well-ventilated chemical hood. Note that HCl is a highly corrosive gas and that some degradation of the metal surfaces within the hood is inevitable. The maximum HCl exposure within the hood will occur at the various exhaust purges that are associated with the system. These include:

- Fast purge for the concentrated HCl manifold
- Kin-Tek system purge line
- Exhaust for the dilute gas manifold (two for HCl and one for H_2O)
- Cell exhaust
- Field calibration cell exhaust

The terminal ends of these lines should be securely attached near the ceiling exhaust port of the hood.

Note from the PGSG manual that the concentration of the diluted gas is determined by three basic parameters: (1) the component gas (HCl) pressure in the gas dilution cartridge, (2) the oven temperature, (3) the diluent gas (nitrogen) flow rate. Prior to performing a calibration run, it is useful to enumerate the concentrations to be attained and the values of the parameters that are necessary to achieve those concentrations. In general, a run can usually be done at a single oven temperature, with the pressure and flow rate being used to vary the concentration. Once again, the Kin-Tek manual must be used for detailed operating instructions. The PGSG concentration can be calculated according to information provided in Section 4.1 of the PGSG manual. Information peculiar to specific dilution cartridge installed in the system is required to make this calculation. For the cartridge presently installed in the system, the HCl concentration can be calculated according to:

$$C_{ppm} = 1.0706 \times 10^{-3}(E(T)/F)(P_g + P_{cell}/760)$$

where:

F is the nitrogen flow rate in l/min
P_g is the HCl pressure in bars
P_{cell} is the pressure in the calibration chamber

and E(T) is equal to the following values (at the three oven temperatures):

E(T) = 52,076 @ 30°C
118,812 @ 60°C
423,914 @120°C

The PGSG has been modified to allow two different ranges of nitrogen flow rates to be attained. The stock flow meter that was installed in the system at the time of purchase is capable of producing flows between 2 and 20 L/min. A second flow meter has since been added to generate flows between 0.2 and 2.0 L/min. This was necessary to obtain the high concentrations needed for the field calibration system. Switching between the high or low flow rate channels is accomplished using the T-valve that is mounted on the rear wall of the PGSG. When facing the rear wall, setting the valve toward the right selects the high (2 - 20 L/min) channel, and setting it to the left selects the low (0.2 - 2.0 L/min) channel. It is also necessary to switch the flow digital display to high or low range using the switch mounted on the front panel of the PGSG.

A brief description of the calibration operation follows. With regard to detailed operation of the PGSG, the user must consult the Kin-Tek manual.

a.About 4 hours before the run, evacuate the calibration chamber (with the cell installed in it) using the vacuum pump. The pump hose is connected to the chamber exhaust port, and the HCl and H_2O inlet valves must be closed for evacuation. While the pump is on, bake the cell at about 50°C using the heating tape. Turn the heat off about 1 hour before the start of the run.

b.Turn on the PGSG and set its oven temperature to the desired level about 1 hour before the run. The temperature can be monitored on the digital readout to determine when the temperature has been attained.

c.When the temperature has been reached, the HCl source gas can be introduced into the system. First, close the valve (post cylinder valve) on the stainless steel line between the cylinder and the concentrated gas manifold. Open the cylinder main valve. Ensure that the valves leading to the nitrogen purge and the vent are closed. Turn the PGSG component gas pressure valve fully counter-clockwise (valve closed). Open the post-cylinder valve to let HCl into the concentrated gas manifold. Pressure on the low pressure side of the regulator should be about 50 psi.

d.The oven must now be purged with HCl. The PGSG manual recommends a slight flow of component gas through the oven during operation. We have generally operated by initially flowing HCl through the oven for a short period of time, and then repeating this process periodically during the run (rather than setting up a continuous flow). To perform the purge, first turn the component gas regulator clockwise to some positive HCl pressure (about 1-2 bars). Open the HCl purge valves slightly to allow some flow through the oven. Allow this flow to continue for about 5-10 minutes, and then shut the purge valves. Set the HCl pressure to the desired level.

e. The nitrogen flow rate can now be set. Before doing this, set the HCl T-valve on the dilute gas manifold (the one that allows selection between cell and vent) to vent the output of the PGSG to the hood exhaust (the gas will not be allowed to flow into the calibration chamber at this point). Adjust the flow rate using the needle valve on the PGSG.

f. Allow pure nitrogen to fill the calibration chamber. This is done using the Miller-Nelson humidity generator. This device has been modified to allow a regulated flow of pure nitrogen (with no humidity) to be generated. This was done by installing a T-valve in the nitrogen flow prior to the point where it enters the water chamber (inside the humidity generator chassis). The valve can be used to divert the flow to the bulkhead fitting on the rear panel of the MNHG. This flow can be injected into the calibration chamber through the normal humidified air inlet. First turn the vacuum pump off. Remove the pump line from the chamber and reattach the exhaust line. Set the humidity T-valve on the dilute gas manifold to divert gas into the chamber. Open the humidity chamber inlet valve and set the nitrogen flow on the MNHG to a reasonable level (i.e. about 2-5 L/min). Allow the gas to flow through the chamber until it is time to introduce HCl.

g. Ensure that the computer is connected via a serial line to plug P6 on the sensor. Start the computer and enter the program by typing "SENSOR". First press F6 (field calibrate) and enter a high number of points such as 1000. This will allow a continuous display of the channel readings. Monitor the signals on the four channels that are displayed on the computer until they have stabilized at the pure nitrogen transmission levels. This will occur after approximately five volumes of gas have flowed through the chamber.

g. The sensor is now ready for the first measurement. Press control-break to exit the field calibration mode, and press F5 (laboratory calibration). The program will request the 100 percent transmission values of the three ratios (Channels 1,2, and 4 over channel 3). It will also request a high and low value for the Y-axis scale (for HCl runs at a maximum concentration of about 1000 ppm, set the minimum to 0.90 and the maximum to 1.01) and the total number of points to be collected (the maximum is 1000). Upon entering the appropriate values, the sensor will begin to collect and plot the data. Record the 100 percent transmission ratio for Channel 2 from the 10-point running average in the "AVERAGE" window display area. Shut off the MNHG nitrogen flow, and close the humidity inlet valve.

h.Open the HCl inlet valve. Divert the gas flow into the chamber. Once again, allow about 5 purge volumes of the chamber for a stabilized reading. When the system is stable, take readings from the numbers that correspond to a 10-point average of the four channel readings (in the "AVERAGE" window display area - see Figure C.1). For HCl calibration, only the Channel 2 ratio needs to be recorded.

i.Once a reading has been taken, the concentration can be changed for the next reading. Set flow (and, if necessary, pressure) and allow time for equilibration. Take readings. Repeat these steps for all necessary concentrations.

j.When the run is completed, it is necessary to purge the PGSG with pure nitrogen to prevent corrosion of the inner components. Shut the main valve of the HCl cylinder. Open the concentrated HCl purge valve to release the high pressure HCl from the concentrated gas manifold (a momentary hiss will be heard when this is being done). Open the valve that allows nitrogen into the high-pressure side of the HCl regulator on the manifold. This will pressurize the HCl inlet side with high pressure nitrogen. Open the HCl purge valve on the PGSG and allow nitrogen to purge the system for at least 45 minutes.

k.To generate the sensor calibration coefficients, run the program HCLCAL (exit SENSOR first by typing "BYE"). Once in the program, type HCLLO.LAB to generate the weak-line coefficient from lab data. The program will prompt for the number of concentration points (not including zero) and the 100 percent transmission ratio (Channel 2). It will then prompt for the individual concentration and Channel 2 ratio values. Finally, it will give the weak-line slope. Use this for concentrations below 40 ppm. Above 40 ppm, execute HCLHI.LAB. The program will provide similar prompts, but will then generate the strong-line slope and intercept.

The data obtained during a typical laboratory HCl calibration are shown in Table 4.

TABLE 4. TYPICAL HCl LABORATORY CALIBRATION PARAMETERS

HCl Pressure(bar)	Flow (l/min)	C(ppm)	Ratio	τ
Run#1				
0	0	0	1.6535	1.0
1.11	20.2	13.2	1.6479	0.9966
1.17	15.0	18.3	1.6460	0.9955
1.22	10.1	27.8	1.6426	0.9934
1.25	5.0	56.9	1.6332	0.9877
Run#2				
0	0	0	1.6510	1.0
2.02	20.3	67.2	1.6282	0.9862
2.06	14.8	93.4	1.6212	0.9820
2.06	10.3	134.2	1.6122	0.9765
2.05	5.1	270.3	1.5877	0.9617
2.07	2.1	660.6	1.5491	0.9383

NOTE
Oven temperatures were 60°C for Run 1 and 120°C for Run 2

2. HUMIDITY CALIBRATION PROCEDURE

Before opening the MNHG, the user must become familiar with the contents of the manual for that instrument. A brief set of instructions for calibrating the humidity channel follows:

a. Evacuate and purge the calibration chamber as above.

b. Ensure that the water and nitrogen are supplied to the MNHG at the correct pressures.

c. Dial the humidity and airflow settings to zero and turn the MNHG on.

d. Dial the temperature setting to a level that is lower than the ambient room temperature.

e. Note the comments made above regarding the additions made to the MNHG system that allow selection between two flow channels for the nitrogen. Set the T-valve to direct nitrogen to the rear bulkhead fitting (i.e. bypass the water cell).

f. Insert the Vaisala humidity sensor into the port on top of the glass calibration chamber. All humidity and temperature readings should be taken from it rather than the MNHG, since some water is lost in the plumbing between the MNHG and the chamber. Ensure that the HCl inlet valve to the calibration cell is closed. Open the inlet valve for the humidity line. Set the flow rate for the MNHG to a level of 5 L/min. Allow the pure nitrogen to enter the system, and purge for approximately three chamber volumes. As above, use the F6 (field calibration) command to monitor the throughput during this time, and to provide the 100 percent values for the cell transmission.

g. When ready to add humidity, close the humidity inlet valve to the chamber, set the bulkhead T-valve to vent the humid air to the hood, and flip the MNHG internal T-valve so that nitrogen flows through the water cell. Press F5 to execute the laboratory calibration command, as in the case of the HCl calibration.

h. After a pure nitrogen baseline has been established, set the humidity to the desired level on the dial. Note that this will not always equal the humidity actually measured in the cell, due to the losses in the tubing. Once the desired level has been reached, allow three chamber volumes for purge and take readings of the ratios for the water and HCl channels (1 and 2). Also record the humidity and cell temperature from the Vaisala probe.

i. Repeat this for each level desired.

j. When the run has been completed, flush the chamber with pure nitrogen and shut off the MNHG.

k. To generate the water vapor slope, run HCLCAL, as was done for the HCl calibration above. Execute the word "H2O.LAB". The program will ask for similar prompts as requested for HCl (see (12) in HCl lab calibration, above), although now the water volume fraction must be provided rather than the HCl concentration It is necessary to obtain water volume fraction using the recorded relative humidity and temperature values, and standard water vapor tables. Once data has been entered, the program will calculate the response slope. The same program is used for Channels 1 and 2.

The data obtained during a typical laboratory water vapor calibration run are shown in Table 5. These values were used to generate the lab curve in the plot of Figure 19.

TABLE 5. TYPICAL WATER VAPOR LABORATORY CALIBRATION PARAMETERS

Rel. Humidity	V% H20	Ratio (Ch1)	τ (Ch1)	Ratio (Ch2)	τ(Ch2)
0	0	1.0287	1.0	1.6093	1.0
20.4	0.69	1.0178	0.9894	1.6037	0.9965
30.0	1.01	1.0144	0.9861	1.6018	0.9953
40.0	1.35	1.0106	0.9824	1.5997	0.9940
50.0	1.68	1.0058	0.9777	1.5970	0.9924
60.0	2.01	0.9991	0.9712	1.5930	0.9899

NOTE: Chamber temperature was 26.0°C, flow rate was 10 l/min.

B. FIELD OPERATION AND CALIBRATION

For calibration in the field, the computer must be transported to the sensor along with the quartz cells, a small bottle of nitrogen, and the water calibration hood. Thus, since the portable computer that is supplied with the sensor requires 110 Volts-AC, this power must be available at the sensor. In the future, it would be better to obtain either a battery supply that will operate this computer, or a smaller, battery operated portable computer.

1. HCl

a. Before the calibration run, the quartz calibration cells should be cleaned and dried overnight in an oven. Cleaning can be accomplished by removing the Teflon® stopcocks, and dropping a small amount of ethanol into the cell, which can then be shaken to rinse the inner surfaces. The outside of the windows can also be cleaned using ethanol and lens tissue (do not use lens tissue made for eyeglasses, since this usually has silicone oil in it). The cells (without the stopcocks) can then be dried overnight in a 100° C oven. From the oven, they should be allowed to cool in a desiccated chamber. The stopcocks can then be reinstalled and the cells are ready for use.

b. Set up the cells for filling with the PGSG. A separate valve setting on the dilute gas manifold is provided to supply a hose to fill the cells. Attach this hose to the quartz-cell inlet and attach the outlet to an exhaust hose.

c. Set the valves on the dilute gas manifold to direct the diluted HCl to the exhaust. Set up the PGSG for the desired HCl concentration. Allow the gas to flow for 5 minutes Then direct the gas through the quartz cell and allow flow to occur for another 5 minutes Vent the gas to the hood again, close the cell stopcocks, and remove the quartz cell. Repeat this for the other cells.

d. Once the cells have been filled, they can be transported to the sensor. At the sensor, connect the computer to the same serial plug that was used to collect laboratory calibration data. Type "SENSOR" to enter the sensor program, insert one of the cells in the cell holder, and press the F6 key to execute the field calibration mode. Enter 20 for the number of averaged data points. Once the command has completed, record the averaged counts for Channel 2.

e. Now flush the cell out with pure nitrogen at a moderate flow-rate for about 2 min. Return it to the cell holder and repeat step (d). Record the Channel 2 counts.

f. Repeat steps (d) and (e) for each cell to be measured.

g. The HCl calibration coefficients are generated using HCLCAL as for the lab data described above. The only difference is that the words HCLLO.FIELD and HCLHI.FIELD are executed, and the average counts (rather than ratios) are inputted. The concentrations input into the computer are the effective full-path values obtained from Equations (4) and (5). These must be calculated using the individually measured lengths of each cell.

h. The HCl calibration is now complete.

The data for a typical field calibration of the HCl sensor are shown in Table 6. These data were used to make the plot of Figure 17.

TABLE 6. TYPICAL HCL FIELD CALIBRATION PARAMETERS

HCl P(bar)	Flow (l/min)	C_{eff}(ppm)	#(full)	#(empty)	τ
3.01	2.00	11.0	4773.70	4785.3	0.9976
3.00	1.48	14.9	4765.35	4784.65	0.9960
2.97	1.19	18.4	4761.85	4784.25	0.9953
2.95	0.88	24.2	4755.90	4785.80	0.9937
2.96	0.59	37.0	4739.00	4781.75	0.9911
2.95	0.38	57.3	4718.40	4781.80	0.9867
2.91	0.20	107.7	4680.30	4785.25	0.9781

NOTE:

Oven temperature was 120°C

Ceff is the effective concentration for a 4.11m pathlength. It was obtained by dividing the real concentration by 82.2, the ratio of the open to quartz cell lengths.

2. H_2O

The calibration of Channels 1 and 2 for the H_2O concentration is especially straightforward because the same pathlength is used as in actual sensor operation.

a. Insert and bolt the sensor head into the lucite chamber. Place one of the solutions in the reservoir and start the fan. Allow about 20 min for equilibration. Run the computer in the field calibration mode and record the ratios for Channels 1 and 2. Insert the humidity sensor into the port and record the actual humidity in cell.

b. Repeat this for the other solution.

c. Calibration slopes are generated using HCL.CAL and the word H2OCAL.FIELD, which will request the two water volume fraction ratios and their corresponding ratios to generate the slope. It is used for both Channels 1 and 2.

C. MAINTENANCE

1. Cell Alignment

The cell mirrors are held quite firmly in place by their mounting brackets, and alignment of the White cell will probably not have to be performed very often. If it is necessary, however, the procedure is as follows.

a. If the cell is not very badly out of alignment, restoration of the proper signal levels may be possible through an adjustment of the x-y stage in which the detector is mounted. To monitor the signal of the detector it is best to use an oscilloscope. Connect the signal contact to the marked pin on the large top PC board mounted within the sensor head. Connect the ground to the other marked pin. The scope display should show the detector pulses generated as the filters pass through the beam. Adjust the x-y position of the detector to maximize the signal.

b. If this does not restore signal to the original range, it is necessary to realign the mirrors. Remove the retaining ring at the rear of the source and slide out the source core. Replace it with the visible source element. Turn on its light source and turn off the room lights. It should be possible to trace the beam as it makes the transit through the White cell. Attach the assembly containing the threaded adjustment screw at the left side of the number 2 outboard mirror (see Figures 6 and 9) and loosen the mounts of that mirror (it is the only mirror to be adjusted). Position the mirror so that the 4-meter spot pattern described in Section II is attained. Make sure that all apertures are cleared by the beam. Tie down the mirror with its brackets and remove the adjusting screw. Repeat step 1 for the final adjustment of the detector position.

2. Mirror Cleaning

The gold mirror surfaces are quite fragile, so some care is necessary in handling them. They should not be cleaned routinely, but only when it is necessary. To do so, place a piece of lens paper on the mirror surface (not eyeglass paper, but optical paper) and drop some optical grade ethanol or methanol onto it so that it wets completely. Slowly drag the paper off the mirror and allow the alcohol to evaporate. Repeat if necessary.

3. Pump Reservoir Filling

The only other routine maintenance involving the sensor is to ensure that the pump reservoir remains full.

SECTION V

CONCLUSIONS

•The LLNL/AFESC dispersive infrared gas sensor has been shown to measure HCl concentrations as low as 0.5 ppm with an instrumental response time of 1 second. Four spectral channels provided in the system allow correction for the effects of water vapor absorption and aerosol attenuation. These channels can easily be adapted to the measure other gaseous species. Thus, the sensor can be considered to be a generic instrument, rather than one that can be used solely for HCl detection.

•The sensor is equipped with a radio transmitter/receiver pair that allows real-time data transmission to a remotely located base station. The base station is configured with software that lets the data be received and plotted on-screen in real-time, and permits commands to be sent to the sensor. In the future, the base station could be configured to receive data from more than one remote sensor.

•An HCl/humidity calibration system is also provided with the sensor that can be used to calibrate the sensor response to those species. Two calibration modes are possible. In the first, the calibration is accomplished in the laboratory, using a calibration chamber that encloses the entire optical path of the sensor. In the second mode, the sensor is calibrated in the field, using a set of quartz HCl calibration cells and a portable humidity calibration hood.

SECTION VI

RECOMMENDATIONS

Although the operation of the sensor system is satisfactory, some areas of possible improvement in performance have been noted. These modifications have not been pursued because of the lack of additional time or money, but they will be listed here so that they may be added in future engineering phases.

A. OPTICAL CELL MODIFICATIONS

1. TITAN 34D Test Firing

The only field test of the sensor occurred at the static test firing of a Titan 34D solid rocket booster segment at Edwards Air Force Base on 15 June, 1987[10]. The test was conducted in Experimental Area 1-125 of the High Thrust Space Booster Complex - - a testbed that had been formerly used by Rockwell International's Rocketdyne Division during production testing of the F-1 liquid rocket engines that powered the Saturn V. The sensor was mounted about 2 meters off the ground outside a camera bunker (Building 8814) that was located about 150 meters from the pad area. The CDAS was located inside that building, and connected through modems and standard telephone lines to the sensor.

Several aborted firing attempts occurred before the actual ignition on June 15. During those trials, the equipment operated properly and tests of the data transmission system indicated that the modem hookup is a practical and effective method of linking the sensor and the CDAS. During the actual firing of the rocket motor, the sensor head optical components were fouled by rainout from the rocket plume, which passed directly over the sensor location. Consequently, no measurements of HCl concentration were made. The rainout appeared as a green-colored material of unknown composition that coated all the external surfaces of the sensor. It was impossible to remove this coating from the gold-coated mirrors without destroying their surfaces.

As a result of this experience, as well as other observations of the fragility and sensitivity of the gold optical surfaces, it is suggested that some attempt be made to ruggedize the optical head in the future. This may include:

- Replacement of the gold mirror surface with more rugged dielectrically-coated surfaces

- The addition of a mechanical hood to cover the White cell that could be opened remotely from the CDAS when the bulk of the plume had passed. As noted in earlier sections, the control circuitry and software for this hood have already been implemented in the sensor.

- The addition of a filtration system to process the air samples prior to the cell to remove solid and liquid components.

Without these modifications, it is not advisable to attempt to use the sensor to measure HCl concentrations in the heart of a rocket exhaust plume, where significant rainout may occur.

2. HCl Measurements In The Presence Of High Humidity

In addition to this problem, occasional difficulties with measuring HCl in the presence of moderate and high humidities in the laboratory have been noted. An example of this is given in Figure 19, where the transmittance of Channels 1,2, and 4 is plotted for several HCl concentrations at 40 percent relative humidity. Note that when the system is purged (at the right side of the graph) the transmittance levels off at a value less than 1.0. The system did eventually return to the baseline transmittance; however, it took longer than the nominal purge time of the cell. Although we have not been able to directly pinpoint the source of this behavior, we feel that it may be due to an aerosol deposition process in which either (a) the HCl is incorporated into a water film that coats the inner surfaces of the calibration chamber and degasses or (b) the water vapor / HCl combination leaves a deposit on the White Cell mirrors that does not readily vaporize. A potential solution to this problem is the incorporation of heating elements into the mirrors that would rapidly vaporize water droplets impinging onto the mirror surfaces. If it is mainly a degassing effect within the chamber, it should not affect open-path operation in the environment.

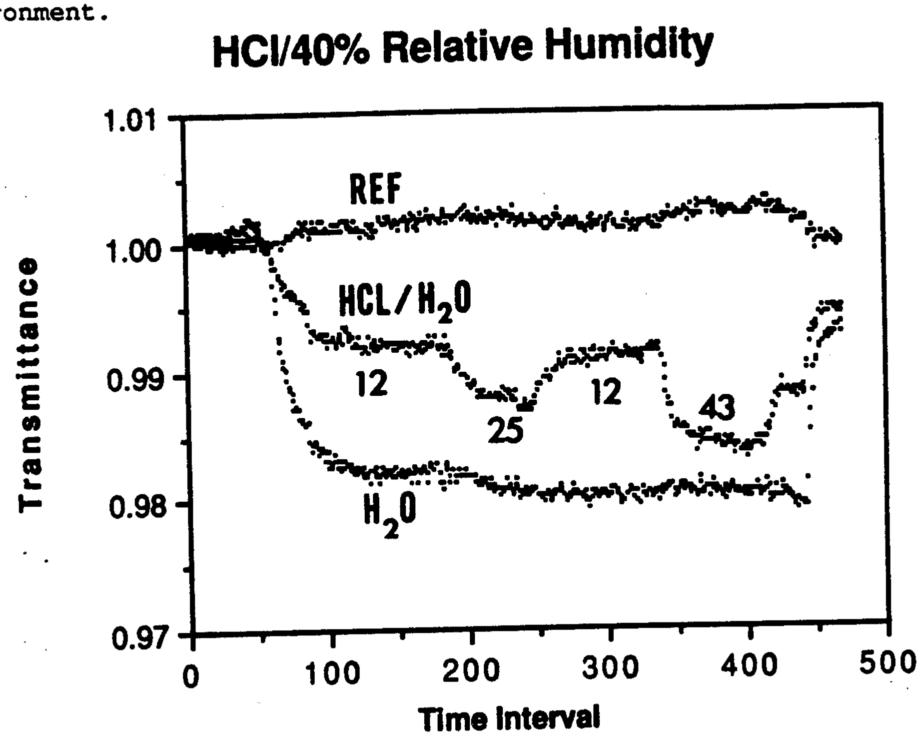


Figure 19. Sensor Transmission Measurement in the Presence of 40 Percent Relative Humidity.

B. FILTER WHEEL MODIFICATIONS

Two modifications to the filter wheel have been considered. These would improve the stability and drift characteristics of the system. In the first modification, the quarter-segment filter elements presently installed on the wheel would be replaced by uncut circular filters. The small size of the existing segments causes the adjustment of the filter wheel timing to be very critical. Larger filters would ease this constraint, and, thus, make the system more stable. A set of uncut filters is being delivered with the system.

The second filter wheel modification would result in a reduction of the sensor drift. At present, significant baseline drift occurs over several hours. We believe that this is caused by spectral variations of the IR source. To compensate for this, it is necessary to monitor the filtered source output for each channel. The measurement must be made on the beam before spectral attenuation within the optical sample cell. A potential way to make this measurement involves the addition of fiber-optic channels on the filter wheel. The fiber lightguides could be positioned so that one end of the fiber is mounted in the filter wheel tab that covers the source, while the other end is mounted so that its output is directed through a filter into the detector. Thus, each time the source is blocked by the tab, a small fraction of its radiation would be filtered and measured by the detector. This would allow the source intensity at the filter bandpass wavelength to be continually monitored. A separate fiber would be required for each filter channel.

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APPENDIX A

ELECTRONIC SCHEMATIC DESCRIPTIONS

A. HCl SENSOR OPTICAL HEAD

The circuits in Table A.1 are on the main PC board (LEA-88-163200-10) mounted in the head, with the exception of the power transistors (LEA-88-163200-20). They are mounted on the head framework itself, to allow better heat dissipation. See (LEA-88-163200-5) for a head block diagram, and (LEA-88-163200-21) for more circuit information.

TABLE A.1. HCl SENSOR HEAD CIRCUIT SCHEMATICS

Detector and preamplifier	(LEA-88-163200-25)
Detector cooler controller	(LEA-88-163200-14)
Source controller	(LEA-88-163200-15)
Stepper motor controller	(LEA-88-163200-13)
Photocell circuit	(LEA-88-163200-16)
Timing circuits	(LEA-88-163200-17)

1. Detector and amplifier (LEA-88-163200-25)

The detector is biased by the current through resistor R_L. The value of RL is chosen to give 0.0 V at the input of U1 (Pin 2) when the filter wheel is blocking the detector and -8 V at pin 7 of U4. This is called the zero signal (or dark signal). When the detector is blocked, the current amplifier U1 amplifies this signal. The amplified signal is sent to U4 (Pin 2). This sample/hold IC (U4) compares the amplified signal from U1 to ground (i.e., 0.0 volts), and produces an amplified error signal at pin 7 that is in the range of 0 to -8.0 volts. This closed-loop system is the autozero circuit. It zeroes the voltage at amplifier U1 (Pin 6) each time the filter wheel blocks the IR detector. The IR detector signal is further amplified by U3, buffered by U2, and then sent to the main chassis (i.e. to the sensor electronic unit

(SEU)). The autozero circuit is gated by a pulse generated in the timing circuits on the main control board using the timing slots on the filter wheel. The sample/hold circuit (U4) is gated only when the IR detector is blocked. This autozero circuit operates four times each revolution of the filter wheel, just before the IR data signals are generated. The preamp is a separate board that is mounted on top of the main control board.

2. Detector cooler circuit (LEA-88-163200-14)

The detector cooler circuit is a closed-loop control system that maintains the 1 mm-square PbSe detector chip at a temperature of about -35°C. The detector is mounted on a two-stage Peltier cooling block enclosed within the detector can. A thermistor is also attached to the cooling block, allowing the detector temperature to be measured. The thermistor is connected to Pin D6 of the main circuit board, where it is part of a bridge network that also contains resistors R1, R14, and R12. The bridge voltage (or error voltage) is amplified by U13, U12 and sent to a power amplifier consisting of U11, Q1, and Q2. Power transistor Q2 drives the Peltier block. In this closed-loop control, any change in detector temperature is compensated for by the drive current through the cooling block.

The detector thermistor voltage at Pin D6 of the control board is buffered by amplifier U10, then input in amplifier U9, where it is amplified and inverted. An offset voltage whose level is determined by variable resistor R53 and resistors R3, R4, R5 and R6 is added to this to allow the temperature of the detector to be read directly in volts (i.e. 1.0 volt equals 10°C). This voltage is then sent to the chassis where it can be read on the digital voltmeter.

3. Source controller circuit (LEA-88-163200-15)

The temperature controller senses changes in the source resistance as a means of detecting changes in the source temperature. The source resistance is compared to a known resistor in a resistor bridge configuration. This bridge is composed of R63, R12, R16, and the source winding. The error voltage of the bridge is amplified by the differential Amplifier U5 and Amplifier U6. The amplified error signal from U6 (Pin 6) goes through jumper J2 to the power amplifier driver consisting of U6 and Q2. The output of the driver amplifier then drives the source amplifier, Q3. The bridge resistors and amplifier Q3 are mounted on heat sinks external to the board. The temperature of the source can be adjusted by R63, and is typically set to 800°C. External control of the source is possible through Buffer Amplifier U7 (through jumper J1). To allow this, it is necessary to remove jumper J2, and to connect J1. This disconnects the source control loop. The source temperature can then be controlled with an input voltage at pin P13 on the board.

4. Stepper motor controller (LEA-88-163200-13)

The clock frequency for the stepper motor is generated by OSC-1, a single-chip programmable oscillator (pxo-1000). This drives U16, a photo-isolator chip, which, in turn, drives the motor driver chip U15. The isolator chip isolates the oscillator from the motor circuit, to prevent interference by noise generated in the motor. The motor driver chip, U15 (SAA-1027) drives the motor directly. The motor control circuit is filtered by C19, C20, C21, C17, and R39. This filtering also helps reduce electrical noise from the motor..

5. Photocell circuit (LEA-88-163200-16)

The photocell circuit is straightforward. The LED/photocell pickup unit is used to monitor the passage of the timing slots on the filter wheel. When a timing slot passes the pickup, the photocell produces a voltage pulse that is amplified, inverted by U1A, sent to the timing circuits.

6. Timing circuit (LEA-88-163200-17)

Timing pulses generated by the photocell circuit are inverted by U1B and shaped by U1C. The shaped timing pulse from U1C is then sent to one-shot U18A. This component, along with U20B and U2A are used to separate the sync pulse from the timing pulses. (Recall that the sync pulse is generated from the wider timing slot on the filter wheel, and is produced once every revolution of the wheel. The timing pulses originate from narrower slots, and occur four times per revolution). The sync pulses are inverted and buffered by U4F and U4E and are sent to the chassis. The sync pulses are also used to reset the counter U17 through the OR gate U3A.

The purpose of counter U17 is to generate pulses that are synchronized with the filter wheel data pulses. This is done by clocking the counter with the shaped timing pulses from U1C. Since the counter is reset by the sync pulse, it generates a gate for every data pulse. These gate pulses are output at U17 (Pins 3, 2, 4, and 7).

The lagging edge of the gate pulse from U17 (Pin 4) along with R67, C33, and U1F generate the autozero pulse. This pulse is sent to the chassis and to the preamp board.

The gate pulses generated from counter U17 are used with one-shots U19A, U18B, U19B, and U20A, and gates U1E, U1D, U3B, and U3C to generate a convert pulse and a hold/reset pulse. The convert pulse is used to tell the A/D when to digitize the data. The hold/reset pulse is used to control the peak sample/hold circuit in the chassis.

7. Head temperature circuit (LEA-88-163200-11)

The head temperature circuit is very simple. It uses a standard commercial temperature sensor (AD590) made by Analog Devices. It is used in the circuit recommended by Analog Devices. The resistors R47 and R50 are used to calibrate the temperature.

B. MAIN CHASSIS

The main chassis block diagram is (LEA-88-163200-30). The main chassis contains the circuits listed in Table A.2.

TABLE A.2. MAIN CHASSIS CIRCUIT SCHEMATICS

Chassis power and control	(LEA-88-163200-31)
Z80 processor	(commercial manual)
14-bit A/D card	(commercial manual)
Card cage	(LEA-88-163200-46)
Input/output card	(LEA-88-163200-41)
Power supply card	(LEA-88-163200-42)
Signal card	(LEA-88-163200-43)
Monitron radio block diagram	(LEA-88-163200-55)
Radio wiring and cabling	(LEA-88-163200-56)

1. Chassis block diagram (LEA-88-163200-30)

The main chassis contains a number of components, including:

(a) Card cage containing:

- Z80 processor card
- A/D card
- I/O card
- Dual +/- 15 V power supply card

(b) Control panel. This has a digital voltmeter (DVM) to measure test signals and voltages. The signal that is displayed on the DVM is selected by a control panel test switch. The panel also has BNC outputs that allow the sync pulses and the signal to be monitored, and two serial outputs – one for an external computer monitor, and one for a printer.

(c) Three terminal strips, used for:

- Main power (TB1)
- Power and control of the radio system (TB2)
- Access to the hood relay contacts (TB3)

(d) Remote radio system, consisting of:

- Transmitter
- Receiver
- Transmit/Receive multiplex
- Control card
- Antennae coax relay

2. Chassis power and control (LEA-88-163200-31)

The power for the chassis comes in on Plug PG5 from the battery box. This power is derived from four separate (and isolated) supplies. They are: a +5 V and +12 V supply for the head, and a +5 V and +12 V supply for the chassis. From PG5, the current is directed through fuses F1 - F4. The +5 V and +12 V head voltages are passed through power relay R1 to the power distribution block TB1. They are then directed to the head power plug PG3. These two voltages are isolated from the ground.

The +5 V chassis power goes from F1 to TB1, terminal 9. From this point, it is directed to the Z80 processor, allowing the processor to be on whenever power is applied to the main box. It is also used to Power Relay R2, and (through TB1, Terminal 10) to power the card cage, the test switch, and the DVM.

The +12 V chassis power is directed from F2 to TB1, Terminal 1. From this point, it is connected to the control panel to power SW1 and DIP relay R3. It is then directed through power relay R2 to TB1, terminal 3. From there, it powers the pump at plug PG2,, the test switch, the card cage, and terminal strip TB2. The latter strip controls the power distribution for the radios.

The power-up control sequence is as follows: When power is applied to the main box, the Z80 processor is powered up. The Z80 processor can run in different modes (using different programs) depending upon the configuration of the setting of the program switch on the I/O card (see I/O card, (LEA-88-163200-35). If the switch is set for test, then the processor will be in the monitor mode, allowing one to connect the portable computer to the main box. This mode is for troubleshooting and calibration. If the switch is set for program, the processor runs the FORTH program to take data. In this mode, the main box waits for a transmitted command from the base-station. If the local/remote switch is in the local position, an "on" command from the base station will turn on the sensor. This is done by switching RY3, which, in turn, switches RY1 and RY2, the main power relays. It also switches the auxiliary relay, RY4 (a DPDT relay). RY4 is used to control external equipment.

If the local/remote switch is in the local position, the sensor can be turned on by the power switch SW1 and not by RY3.

When the +12 volt is applied to the cardcage, the power supplies contained within that unit produce power at ± 15 V which is connected to signal head plug PG4. The card cage also produces another source of ± 15 volt, which powers the Z80 processor assembly and the test switch. A +10 volt source is produced and used by the card cage and the test switch.

3. Z80 Processor (Standard Bus) - Block diagram (LEA-88-163200-32)

4. Utility I/O card (LEA-88-163200-35)

This is a Standard Bus I/O breadboard card that is set up for 8 bits of input data at E55 (bit 0) through E59 (bit 7) and 8 bits of output data at E44 (bit 0) through E51 (bit 7). The card is commercially made and has all the necessary chips to interface to the standard bus.

Input bit E55 (bit 0) is connected to switch 1, which is mounted on the back of the card. When this switch is in the +5 V position, bit 0 is set. During the startup routine, the Z80 checks this bit. If it is set, the Z80 runs the data collection program. If it is not set (switch in ground position) the Z80 goes into the monitor program that allows the user to run FORTH programs, run diagnostics, and have general access to the onboard FORTH system.

Bit E56 can be set by Flip-Flop U1A. This is the sync flip-flop and is set by the sync signal from the head. This signal comes in on PG1 and passes through U2B and U2A, where it is buffered. It is then directed to pin 6 of U1A. The flip-flop is reset on the lagging edge of the Z80 write pulse (U7, pin 8). The Z80 program looks at this bit (E56) at the start of each digitized data pulse. If the bit is set, the program recognizes that that data pulse is the first one in the data string. The program then uses this information to store and process the data, and to synchronize the data collection. Input bits E52 through E59 are not used at this time.

Output bits E44 (bit 0) and E45 (bit 1) are set by the program. They control Flip-Flop U1B, which turns Q1 on and off. Q1 is a switch that is connected to PG2, on the back of the card. The Q1 output is directed from PG2 to the control panel where it switches the main power relay.

Output bits E46 and 47 control Flip-Flop U5A, which activates DIP relay K1 by controlling transistor Q2. The open/close contacts of K1 are connected through PG2 to the radio control board. These contacts then turn the transmitter on and off.

Output bits E48 and E49 control Flip-Flop U5B. This controls relay K2, the hood control relay. The contact closure of Relay K2 is connected through PG2 to TB3.

The I/O output card can be changed to give more input or output bits, which can be used if the need for more control channels arises.

5. Input/output card (LEA-88-163200-41)
   (also refer to Card cage wiring (LEA-88-163200-46))

The function of the input/output card is to buffer and distribute signals from the head. The detector signal is brought from the signal card and input to this card on Pin 1. It then passes through Voltage Follower U3, and to the output front panel BNC. The buffered detector signal from U2 goes to the test switch.

The convert pulse is brought from the head onto Pin 2. It is buffered by U1B, U1A, and U1C. The buffered convert pulses from Pin 14 are sent to the A/D card. The buffered convert pulse from Pin B is sent to Pin B of the signal card.

The sync pulse from the head comes in on Pin 3 and is then sent through U1E and U1D (where it is buffered), and out on Pin R to the I/O card.

The detector temperature signal from the head comes in on Pin F and is buffered by U6 and U7. The output of U7 is sent to Pin T, and then to Position 7 of the test switch. The output of U6 is sent to Pin 11, then to Channel 1 of the A/D card. The software does not access A/D Channel 1; therefore, the data transmitted to the base station does not include the detector temperature. The system could, however, be modified to include this capability.

The head temperature signal is brought onto the card on Pin 7. and is buffered by U6 and U8. The output from U8 goes to Pin 18 and to Position 10 on the test switch. The buffered output from U9 goes to Pin 12, whereupon it is sent to Channel 3 of the A/D card. As mentioned in the case of the detector temperature, the software does not access A/D channels numbered above 0 (the detector signal channel). Thus, the head temperature is also not input by the software.

The source temperature signal comes in on Pin 4 and is meant to be buffered by U4 and U5, whose outputs go to Pin 10 and Pin 16. The latest source design does not have a thermistor incorporated into it; therefore, this signal line is not presently used. The Voltage Followers U4 and U5 are also not used at this time, but are wired to pins 10 and 16 and are connected to A/D Channel 2 and Test Switch Position 8. They are, therefore available for any use one desires.

6. Signal card (LEA-88-163200-43)

The function of the signal card is to perform auto-zeroing of the detector signal and to provide the A/D with an integrated sample-and-hold signal (that is derived from the detector signal). The detector signal enters the board on pins 1 and A, from which it is sent to the differential amplifier U2. Amplifier U2 is set for unity gain and is used to convert the differential signal to a single ended signal. The output of U2 goes to the + side (pin 3) of the differential auto-zero amplifier U3. U3 is also operated in the unity gain mode.

The auto-zero function is performed by taking output from U3 and sending it to the + input of U4, a differential amplifier set for maximum gain. It compares the signal from U3 to the signal at the wiper of R10. The voltage at R10 is a small offset voltage and is sent to the - input of U4. U4 then gives an amplified signal of the difference in voltage of R10 and U3. This difference in voltage (or error signal) goes to the sample-and-hold IC U6 (AD582). The output of U6 then goes to the - input of U3. These circuits form a closed servoloop. The auto-zero gate comes in on Pin 3 and goes to U6, the sample-and-hold IC. During the auto-zero period, (auto-zero gate low), the sample-and-hold IC is in the sample mode, making the servo loop active. In this state, increasing output at U3 causes the voltage error at U4 to increase. Capacitor C5 of the sample-and-hold IC is charged to this voltage. This voltage is then sent back to the input to U3, which forces the output of U3 down. This auto-zero loop then charges C5 to the voltage needed to give a zero output at U3. When the auto-zero gate goes high (auto-zero period over), the sample-and-hold IC goes into the hold mode, in which the voltage on capacitor C5 is held at the zeroing voltage until the next auto-zero period. During the non-auto-zero period, U3 acts like a normal unity-gain signal amplifier. However, because of the zeroing voltage, it has a zero offset. The auto-zero period occurs just before each of the 8 detector signals. The signal output of U3 is sent to buffer amplifier U1. The output of U1 goes to pin 2 and then to the input/output card. The signal from U3 is also sent to switch 1, which gives the option of selecting an external (test) signal or the detector signal from U3. The output of switch 1 goes to the IC U5 (PDK-01, an integrating peak-hold IC), which is used to integrate and hold the detector signal, thus allowing it to be digitized. The hold and reset gates are generated by the hold/reset signals from the head and one-shots U8A, U8B, and or-gate U9A. The hold capacitor is C2. The held output signal from U5 goes to Pin 6 and then to the A/D card.

7. Power card (LEA-88-163200-42)

The power card has two ±15 voltage 180 mA DC-to-DC power supplies mounted on it. One power supply is for the head and the other is for the chassis. Both supplies take a +12 voltage input. A +10 voltage reference is also produced for use in the chassis. Q1 is a +10 voltage precision regulator IC (LH0070) and is driven from the +15 voltage chassis supply.

8. Radio system block diagram (LEA-88-163200-55)
(also see radio manuals)

The radio system is a commercial product purchased for use in the sensor. It is composed of a 2 watt transmitter operating at 407.5 MHz and a receiver operating at the same frequency. Both the transmitter and receiver operate at data transmission rates of 4800 baud. Also used with the radios is an NDS signal conditioning unit that interfaces the transmitter and receiver signals to standard RS232 format, and a control board that controls both the power to the transmitter and the coax relay. When the radios are operating, the receiver is left continuously on, as its power consumption is relatively low. Because the system uses only one antennae, the coax relay is used to switch that antennae between the transmitter and the receiver. The transmitter is turned on only when transmission of data is required due to its large power consumption. The radio system uses the chassis +12 V source for its operation.

9. Radio wiring and cabling (LEA-88-163200-56)

The radio systems receive their power and control from TB3. The power switch is mounted on the NDS mounting. Power at +12 V is supplied to Terminal 15 and then, through the switch, to Terminals 9, 11, and 13. Terminal 13 is connected to NDS plug J2-A, to supply power to the NDS unit. The receiver is powered from Terminal 11 through receiver plug J2-A. The transmitter receives its power from Terminal 3 on the control board (red wire, switched +12 V) through transmitter plug J2-A. The transmitter is only turned on when transmitting data. The control board receives its power from Terminal 9 of TB3.

The RF transmitter output signal is directed from the transmitter plug J1 to the coax relay. The receiver RF signal comes from the coax relay to the receiver plug J1. The coax relay is controlled by the control board from Terminal 1 on TB3. The coax relay switches the antenna between the transmitter and the receiver.

The demodulated RF signal from the receiver is sent to the NDS unit through Receiver Plug J2 (pin B). The NDS unit serves as the interface to the computer. It takes the signal from the receiver and converts it into RS-232 format. The resulting RS-232 signal is sent to the Z80 processor through pin B.

The RS-232 signal to be transmitted (from the Z80 processor) comes into the NDS at J1 (pin D). The NDS then formats the signal to a serial audio string which is sent from the NDS (at J1, pin E) to the transmitter (at J2, pin B). This signal is transmitted if the transmitter is on and the coax relay is in the transmit position.

The transmitter and coax relay are controlled by a signal from the control board available at Terminal 4 of TB3. This signal originates at the Z80 IO card, and is directed to the control board from Terminal 4.

In addition to controlling the coax relay and transmitter, the control board also regulates the delay time between the point at which the transmitter is switched on and the time at which the coax relay is set in the transmit position. This is necessary to ensure that the transmitter has stabilized and is ready to transmit when the antenna is connected. The control board also regulates the squelch in the receiver through Terminal 6, TB3 and J2, Pin C of the receiver.

C. Battery Box

The battery box block diagram is (LEA-88-163200-60). The battery box contains the circuits listed in Table A.3:

TABLE A.3. BATTERY BOX CIRCUIT SCHEMATICS

Batteries	(commercial units)
Battery chargers	(commercial units)
Power supplies	(commercial units)
Battery box cables	(LEA-88-163200-62)

The battery box provides all the power to the sensor. It supplies +12 volts @ 6.8 A and +5 volts @ 3 A for use by the main chassis. It also supplies +12 volts @ 6.8 A and +5 volts @ 3 A to the sensor head (through the main chassis). The battery box contains two +12 volts 24 Amp-hr gel- cells. There are also two 12 volts gel-cell chargers, two +5 volts, 5 A DC-to-DC power supplies, and two +12 volts 6.8 A 110 volts operated supplies.

When 110-volts AC power is supplied to the box, the chargers continually charge the batteries. If the main power switch is turned on, the chargers are turned off and the two +12 volts, 110-volts-driven power supplies are turned on. At the same time, the +12 volts supplies provide power to the DC-to-DC converters, producing the two +5 volts sources. In this configuration, the batteries are floating across the +12 volts supplies.

If AC power is not supplied to the box, the chargers are not turned on. When the main power switch is activated, the batteries now supply the power for the DC-to-DC converters, producing the two +5 volts sources. At the same time, the batteries supply the two +12 volts sources.

Battery box wiring (LEA-88-163200-60)

The 110 V AC enters the box on plug PG2, through Fuse F1 and Switch SW1A to terminal block TB1 (Terminals 7 and 10). The AC also goes from the fuse F1 to Terminal 5. Switch SW1 is a 3PST and is the main power switch for the box. With switch SW1 off and 110 V applied to the box, relay RY1 is energized through the relay NC contacts of relay RY2. The unswitched 110 VAC goes from terminal 5 of TB1 through the NC contacts of RY2 to RY1 and terminals 1 and 3 of TB1. The power from Terminal 1 of TB1 is used to power the +12 V battery chargers through the NO contacts of RY1 (which are now closed). The battery chargers now charge the batteries. This is the standby condition when 110 VAC is supplied to the box and the main power switch is off.

If 110-volt AC is supplied to the box and the main power switch is turned <u>on</u>, power is applied to relay RY2 to energize it. This causes the NC contacts (RY2C) to open, preventing RY1 from energizing and keeping the battery chargers off. The 110 VAC from SW1 is also applied to the +12 VDC supplies, thus turning them on. The energizing of RY2 also causes the output of the two +12 volts supplies to be applied to Terminals 6 and 8 of TB2, through the NO contacts of RY2. From Terminals 6 and 8 of TB2, the two +12 volts sources are connected (through F2, F3, and SW1B and SW1C) to Terminals 7 and 12 of TB2. The voltages supplied at Terminals 7 and 12 are connected to pins E and G of the output plug PG1. The voltages from Terminals 7 and 12 are also used to power the +5 volts DC-to-DC converters. The outputs of the converters are directed to terminals 1 and 3 of TB2 and then to output plug PG1 (Pins A and C). The outputs of the +12 volts gel-cells go to Terminals 5 and 10 of TB2 and then to Terminals 6 and 11, allowing them to float across the two +12 volts, 6.8 A supplies.

When 110 VAC is <u>not</u> applied to the box and the power switch is <u>on</u>, relays RY1 and RY2 are not energized, thus disconnecting both +12 volts, 6.8 A supplies and both battery chargers from the output. The battery power is applied to the output Terminals 7 and 12 of TB2 through F2 and F3, and power switches SW1B and SW1C. Under these conditions, the batteries supply +12 volts to the chassis and the DC-to-DC converters.

D. Pump Box

The pump box has the following mounted within it:

Pump	(commercial manual)
Pump wiring	(LEA-88-163200-70)

Pump wiring (LEA-88-163200-70)

The pump wiring is straightforward. The +12 volts from the chassis comes from PG1 to the fan motor and the pump motor. When the sensor unit is on, the pump unit is on. The head is water-cooled. Heat generated by the filter wheel motor, the IR source, and the detector cooler circuit is removed from the head by the cooling pump.

APPENDIX B

Z80 MICROPROCESSOR CONTROL SOFTWARE

This section describes the general operation of the FORTH code resident on the Z-80 card (it is burned into two ROMs on that card) and is used to control the data collection and timing of the sensor. A FORTH operating system is also contained on that board. Figure B.1 contains flow diagrams of the major FORTH words that are used to run the sensor.

The detector data arrives at the SEU from the head at the rate of 8 data points per second. Because the filter wheel runs continuously, the data is continuously produced as long as the sensor unit is powered up. To accommodate the data flow, the microprocessor software is run on an interrupt system. This means that the digitization and storage of data takes precedence over all other software functions. The data is processed using the 14-bit Data Translation A/D conversion card. The card has a range of ± 10 V . The card is gain programmable. For use in this sensor, it is set for 0 - 2.5 volts = 0 - 8200 counts.

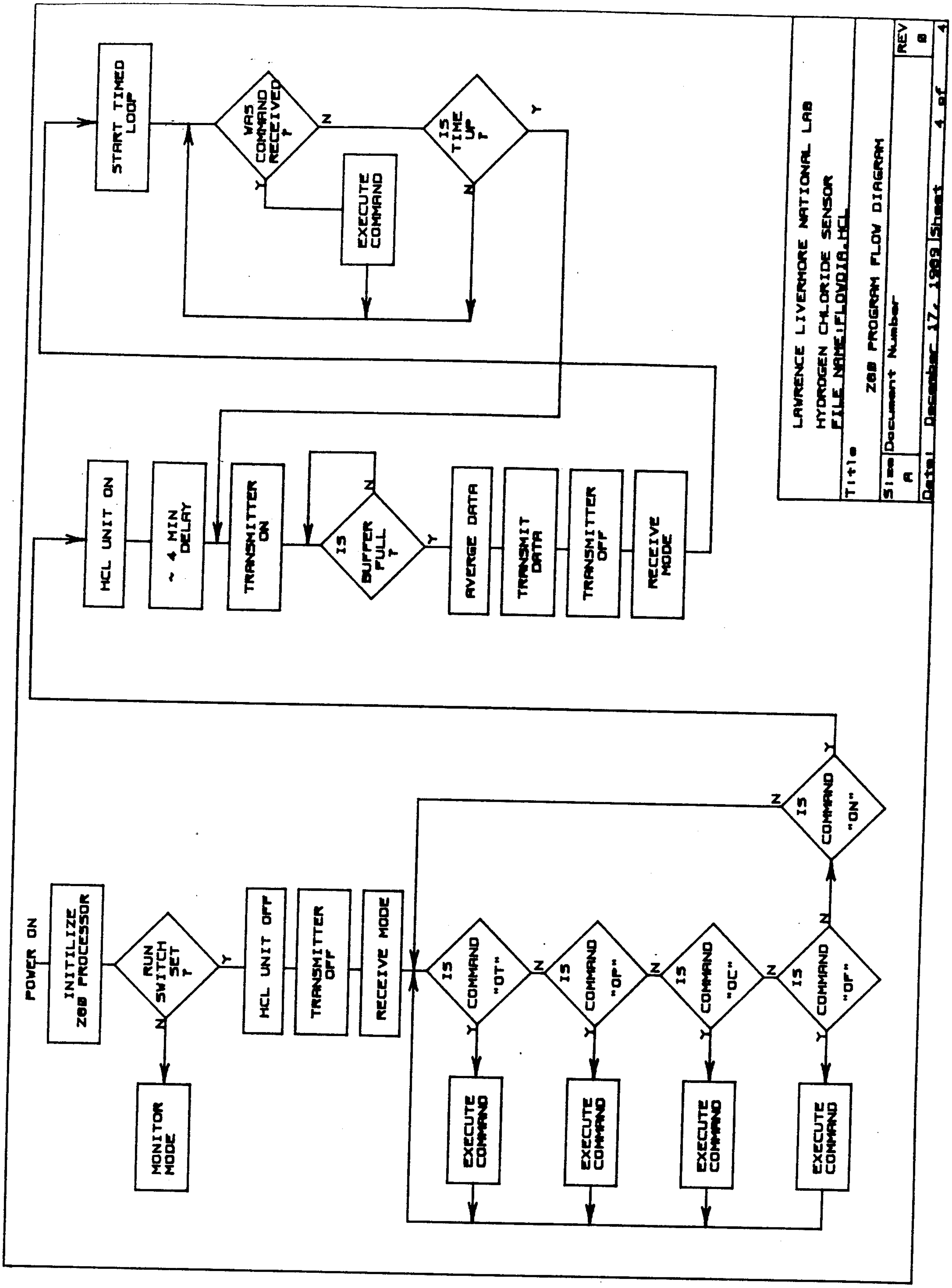
Each data point uses 2 bytes of storage. The data is saved in a 256-byte circular buffer (see the FORTH word INT-SERVICE-A). Because the A/D requires only 14 bits, the last two bits of storage are free for other uses. Bit 15 is set to 1 at the beginning of the data cycle by the sync pulse. This bit indicates the beginning of the filter wheel revolution. The sequence of the data point collection is as follows: REF1 (Reference #1), DARK1 (Background #1), REF2 (Reference #2), DARK2 (Background #2), SIG (HCl signal), DARK3 (background #3), H_2O (H_2O

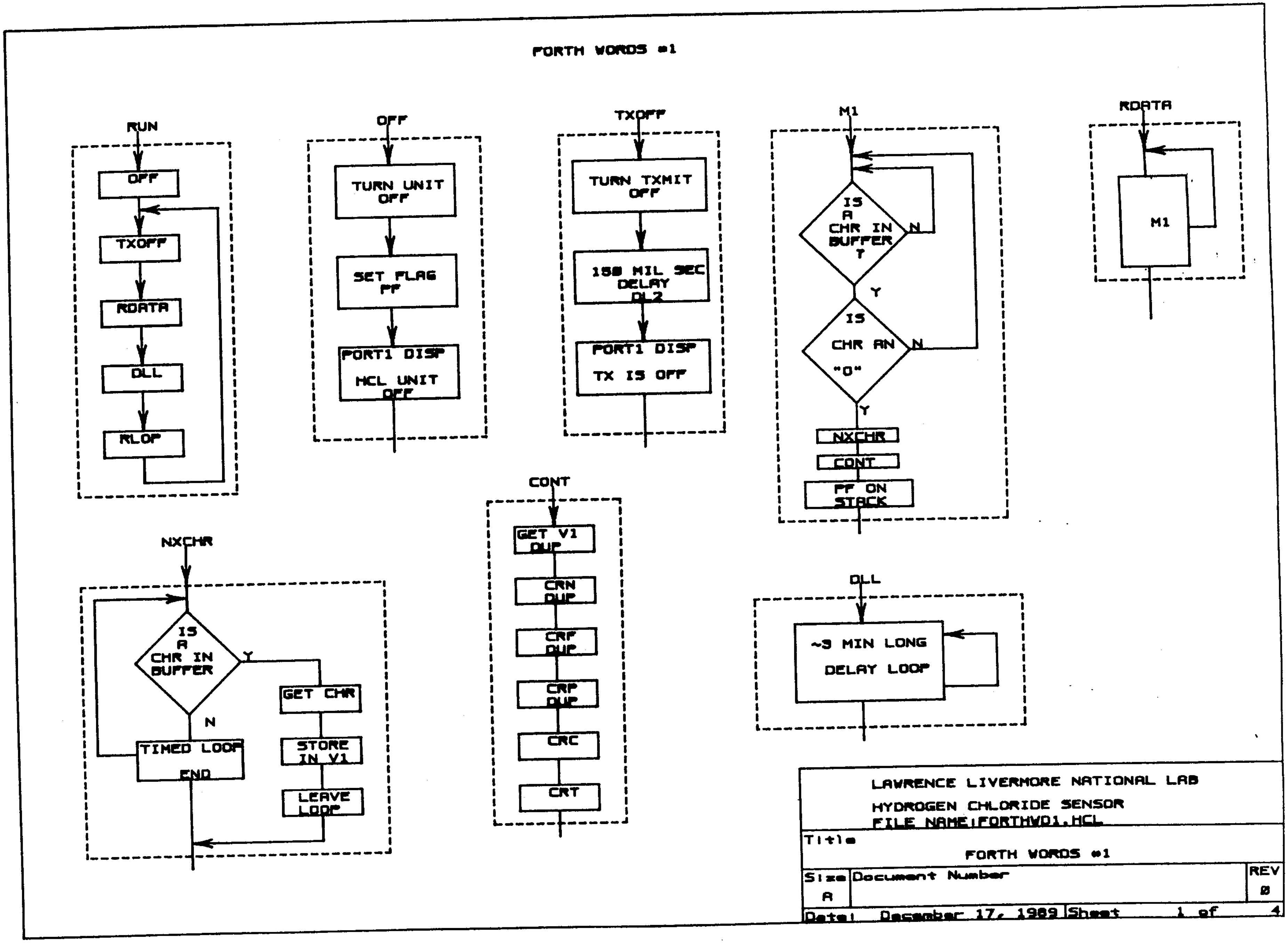
signal), DARK4 (Background #4). The software uses the sync bit (bit 15) to synchronize the storage and processing of the data.

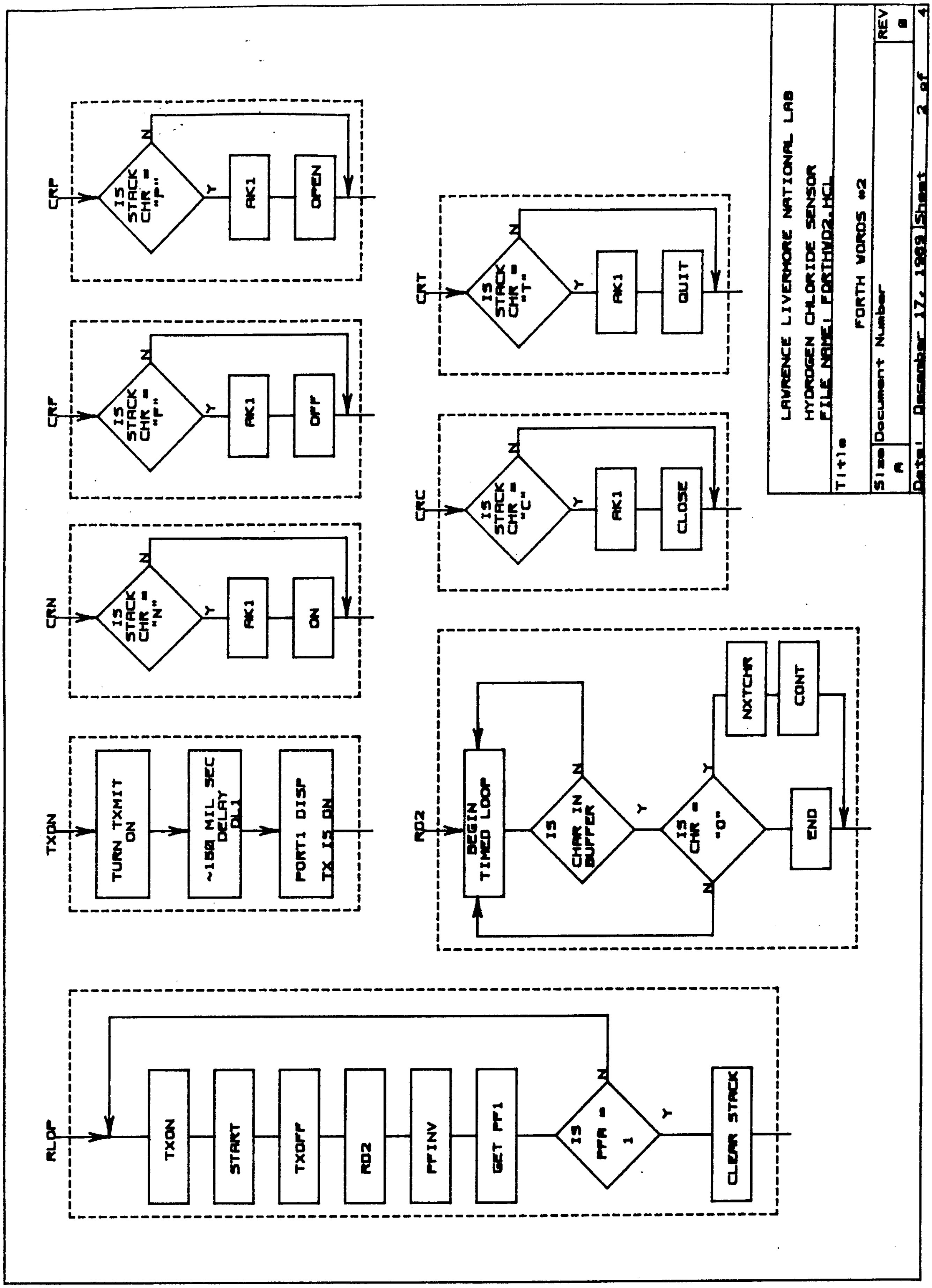
When the FORTH word "RUN" is executed, the following sequence occurs. The sensor unit is turned off (default condition), the transmitter is shut off and the radio remains in the receiving mode. The FORTH word "RDATA" is executed. The processor now looks for characters that arrive at the receiver. When a character is received, it is tested to see if it is an "O," since all commands are two characters long with the first one being an "O." If it is an "O," the program then attempts to identify the second character. If the second character is not valid, or if no character is received during the timeout of the loop, the program returns to looking for the "O" again. It will stay in this loop until that character is received. Now, if a valid second character is received, the program will leave this loop and match the character pair with the corresponding command. That command is then executed. The possible commands and their two letter designations are: "ON" (HCl unit on), "OF" (HCl unit off), "OP" (hood open), "OC" (hood close), "OT" (exit or break out or program). For all commands except "ON", the processor returns to the command receiving loop following command execution. When "ON" has been executed, the program then also executes the FORTH word "DLL." This causes a 3 minute delay, allowing the sensor unit to stabilize to some extent (a 30-minute warmup is recommended before data is taken). After the delay, the word "RLOP" is executed.

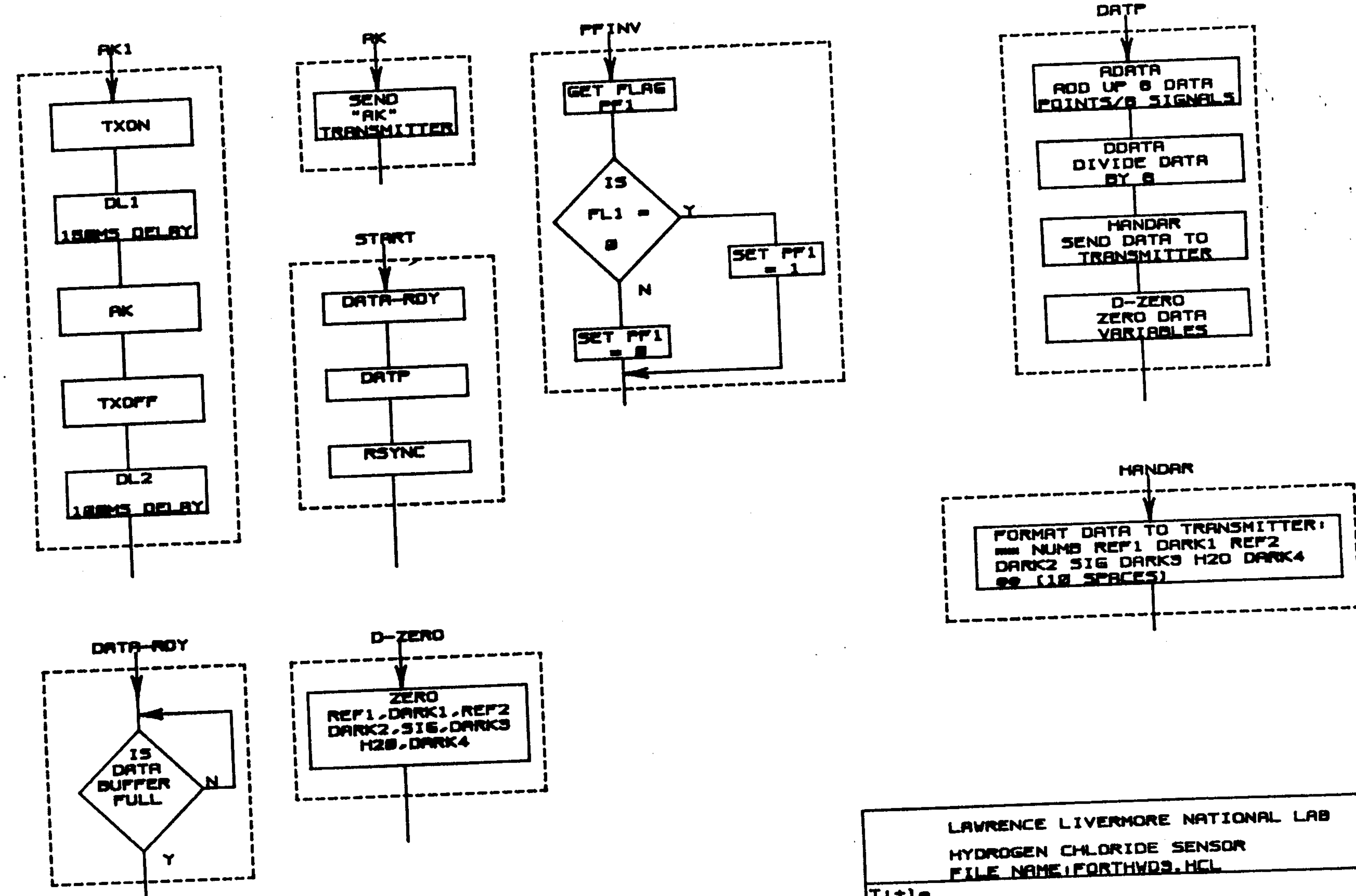
When running "RLOP" the sensor enters the data collection mode. At that point, the program is interrupt controlled. The interrupts are driven by the filter wheel sync pulse. Because the system is collecting data in real time, data must be stored at the proper time interval. Thus, the data is stored in the circular buffer at a rate of 8Hz. The storage occurs regardless of what the program is doing at the time. At the start of the data collection mode, the program turns on the transmitter, waits 150 msec to allow the transmitter to warm up, and then executes the word "START". The program now enters a loop and waits for the data buffer to accumulate the required 8 data points. When the data points are stored, they are averaged and transmitted to the base station (thus, the data received at the base station is actually the average of 8 real data points). The transmitter is then turned off. The program returns to the command receiving mode for a time window of about 4 to 5 seconds, where it awaits additional commands from the base station. When the buffer is nearly full again, the transmitter is turned on again. The full buffer is then transmitted to the base station and this cycle is repeated. The base station must be ready to receive the data, since the HCl unit is transmitting it in real-time.

A printout of the FORTH microprocessor control software follows. This code is burned onto two ROMS installed within the SEU.


POWER ON
INITILIZE Z80 PROCESSOR
RUN SWITCH SET ?
MONITOR MODE
HCL UNIT OFF
TRANSMITTER OFF
RECEIVE MODE
IS COMMAND "OT"
IS COMMAND "OP"
IS COMMAND "OC"
IS COMMAND "OF"
IS COMMAND "ON"
EXECUTE COMMAND
EXECUTE COMMAND
EXECUTE COMMAND
EXECUTE COMMAND
HCL UNIT ON
~ 4 MIN DELAY
TRANSMITTER ON
IS BUFFER FULL ?
AVERGE DATA
TRANSMIT DATA
TRANSMITTER OFF
RECEIVE MODE
START TIMED LOOP
WAS COMMAND RECEIVED ?
EXECUTE COMMAND
IS TIME UP ?
LAWRENCE LIVERMORE NATIONAL LAB
HYDROGEN CHLORIDE SENSOR
FILE NAME:FLOWDIA.HCL
Title
Z80 PROGRAM FLOW DIAGRAM
Size
A
Document Number
REV
B
Date: December 17, 1989
Sheet 4 of 4


FORTH WORDS #1
RUN
OFF
TXOFF
RDATA
DLL
RLOP
OFF
TURN UNIT OFF
SET FLAG PF
PORT1 DISP HCL UNIT OFF
TXOFF
TURN TXMIT OFF
150 MIL SEC DELAY DL2
PORT1 DISP TX IS OFF
M1
IS A CHR IN BUFFER ?
N
Y
IS CHR AN "O"
N
Y
NXCHR
CONT
PF ON STACK
RDATA
M1
NXCHR
IS A CHR IN BUFFER
Y
N
GET CHR
STORE IN V1
LEAVE LOOP
TIMED LOOP END
CONT
GET V1 DUP
CRN DUP
CRF DUP
CRP DUP
CRC
CRT
DLL
~3 MIN LONG DELAY LOOP
LAWRENCE LIVERMORE NATIONAL LAB
HYDROGEN CHLORIDE SENSOR
FILE NAME:FORTHWD1.HCL
Title
FORTH WORDS #1
Size
A
Document Number
REV
0
Date: December 17, 1989
Sheet 1 of 4


RLOP
TXON
START
TXOFF
RD2
PFINV
GET PF1
IS PFA = 1
Y
N
CLEAR STACK
TXON
TURN TXMIT ON
~150 MIL SEC DELAY DL1
PORT1 DISP TX IS ON
RD2
BEGIN TIMED LOOP
IS CHAR IN BUFFER
IS CHR = "0"
NXTCHR
CONT
END
CRN
IS STACK CHR = "N"
AK1
ON
CRF
IS STACK CHR = "F"
OFF
CRP
IS STACK CHR = "P"
OPEN
CRC
IS STACK CHR = "C"
CLOSE
CRT
IS STACK CHR = "T"
QUIT
LAWRENCE LIVERMORE NATIONAL LAB
HYDROGEN CHLORIDE SENSOR
FILE NAME: FORTHWD2.HCL
Title
FORTH WORDS #2
Size
A
Document Number
REV
B
Date: December 17, 1989
Sheet 2 of 4



LAWRENCE LIVERMORE NATIONAL LAB
HYDROGEN CHLORIDE SENSOR
FILE NAME:FORTHWDS.HCL

Title	FORTH WORDS #3	
Size A	Document Number	REV 0
Date: December 17, 1989	Sheet 3 of 4	

```
SCREEN # 0
( STAND-ALONE ROMABLE Z-80 FORTH SOURCE CODE )
;S
FOR USE WITH NAUTILUS SYSTEMS CROSS COMPILER
( Z-80 TARGET VERSION )

(C) 1981 BY
RAY DUNCAN
LABORATORY MICROSYSTEMS
4147 BEETHOVEN STREET
LOS ANGELES, CA 90066
213-390-9292
```

```
SCREEN # 1
( EXPLANATION OF LOAD SCREENS )
;S

( CROSS-COMPILING:                                              )
( FIRST EDIT SCREEN 9 TO SET ORIGIN AND MEMORY SIZE.            )
( FROM CP/M, TYPE: A>CROSSZ80 ROMZ80.SCR <RETURN>.              )
( WAIT FOR SYSTEM ID.  THEN TYPE:                               )
( 7 LOAD   <RETURN>                                             )
( TARGET IMAGE IS LEFT IN FILE IMAGE.COM ON CURRENT DISK.       )
;S
```

```
SCREEN # 2
( SCREEN PRINTING UTILITY SHOW )
( DISPLAYS TRIADS ON LIST DEVICE )
( COMMAND FORMAT:  N1 N2 SHOW   )
0 VARIABLE FF.FLAG
: SHOW
  FF.FLAG @ 0=
  IF CR ." DOES YOUR PRINTER HAVE FORM FEED CAPABILITY? " KEY
  DUP EMIT 89 = IF 2 ELSE 1 ENDIF FF.FLAG ! CR ENDIF
  SWAP PRINTER
  DO I TRIAD
```

```
SCREEN # 3
( PROM PROGRAMMER SUPPORT - PDUMP )
HEX
: PREAMBLE ." !M0000 " ; : COMMA ." , " CR ;
: ZERO ." 0" ;
: C@[T]  80 /MOD BLOCK + C@ ;

: PDUMP PREAMBLE  BASE @ >R  HEX
  OVER + SWAP DO ." ," CR
   I 10 + I DO I C@[T] 0 <# # # #> TYPE LOOP
  10 +LOOP CR R> BASE ! ;





  ;S
```

```
SCREEN # 4
( SYSTEM MESSAGES )
EMPTY STACK
DICTIONARY FULL
HAS INCORRECT ADDRESS MODE
ISN'T UNIQUE

DISC RANGE ?
FULL STACK
DISC ERROR !




BASE MUST BE DECIMAL
MISSING DECIMAL POINT
Z-80 FORTH                                    LABORATORY MICROSYSTEMS
```

```
SCREEN # 5
( SYSTEM MESSAGES )
COMPILATION ONLY, USE IN DEFINITION
EXECUTION ONLY
CONDITIONALS NOT PAIRED
DEFINITION NOT FINISHED
IN PROTECTED DICTIONARY
USE ONLY WHEN LOADING
OFF CURRENT EDITING SCREEN
DECLARE VOCABULARY







Z-80 FORTH                                    LABORATORY MICROSYSTEMS
```

SCREEN # 6

```
( ERROR MESSAGES FOR CROSS COMPILER'S Z-80 ASSEMBLER )
16 BIT REGISTER NOT ALLOWED
8 BIT REGISTER NOT ALLOWED
ADDRESS OUT OF RANGE
IMMEDIATE DATA VALUE NOT ALLOWED
MISSING SOURCE REGISTER
MISSING DESTINATION REGISTER
ILLEGAL OPERATION
ILLEGAL OPERAND
INSTRUCTION NOT IMPLEMENTED
ILLEGAL DESTINATION REGISTER
ILLEGAL SOURCE REGISTER
ILLEGAL CONDITION CODE
REGISTER MISMATCH
DESTINATION ADDRESS MISSING
```

SCREEN # 7

```
( LOAD SCREEN FOR CROSS-COMPILATION OF Z-80 ROMABLE SYSTEM )

DECIMAL
IMG.FCB FILENAME IMAGE.SCR
CROSS-COMPILE

09 72 THRU

;S
```

SCREEN # 8

```
SCREEN # 9
( ROMABLE Z-80 FORTH --- EQUATES )
   HEX 0 0 ORG/DB

4100 3F00 ROM/RAM
8000     MEM-END

1 EQU FIGREL      1 EQU FIGVER      0 EQU USRVER      20 EQU ABL
0D EQU ACR        2E EQU ADOT       07 EQU BELL       8 EQU BSIN
8 EQU BSOUT       10 EQU DLE        0A EQU LF         0C EQU FFEED
E4 EQU A-STATUS-PORT   E3 EQU A-DATA-PORT   E4 EQU A-COMMAND-PORT
040 EQU US                          0A0 EQU RTS
EM US - EQU INIT-R0                 INIT-R0 RTS - EQU INIT-S0
FA EQU MODE-PORT      FB EQU COMMAND-PORT
F9 EQU STATUS-PORT    02 EQU RDA   ( RECEIVE DATA AVAILABLE )
F8 EQU DATA-PORT      01 EQU TBE   ( TRANSMIT BUFFER EMPTY )
;S

SCREEN # 10
( ROMABLE Z-80 FORTH --- INITIALIZATION )
ASSEMBLER
NOP ECLD JP   NOP  EWRM JP
FORTH
FIGREL C, FIGVER C, USRVER C, 0E C,
HERE LABEL INIT-FORTH 0 ,
BSIN , INIT-R0 , INIT-S0 , INIT-R0 , INIT-S0 , 01F , 0 ,
HERE LABEL INIT-FENCE 0 ,
HERE LABEL INIT-DP 0 ,
HERE LABEL INIT-VOC-LINK 0 , BASE-36 Z80. , , HEX
THERE LABEL RPP   INIT-R0 THERE !  2 ALLOT-RAM
THERE LABEL UP    INIT-R0 THERE !  2 ALLOT-RAM
FORTH ;S

SCREEN # 11
( ROMABLE Z-80 FORTH --- COLD START )
100 ALLOT(T) ASSEMBLER
HERE LABEL ECLD

          BC, # CLD1     LD
          SP, # INIT-S0  LD
          IY, # INIT-R0  LD
           3E C,(T) EE C,(T)   D3 C,(T) MODE-PORT C,(T)
           3E C,(T) 7E C,(T)   D3 C,(T) MODE-PORT C,(T)
           3E C,(T) 27 C,(T)   D3 C,(T) COMMAND-PORT C,(T)
          NEXT JP

HERE LABEL CLD1   ] COLD [

FORTH ;S
```

```
SCREEN # 12
( ROMABLE Z-80 FORTH --- INNER INTERPRETER AND WARM START )
ASSEMBLER
HERE LABEL EWRM      BC, # WRM1 LD     NEXT JP
HERE LABEL WRM1      ] WARM [
ASSEMBLER
HERE LABEL DPUSH     DE PUSH
HERE LABEL HPUSH     HL PUSH
HERE LABEL NEXT      A, (BC) LD      BC INC      L, A LD
                     A, (BC) LD      BC INC      H, A LD
HERE LABEL NEXT1     E, (HL) LD      HL INC      D, (HL) LD
                     DE, HL EX       (HL) JP
FORTH ;S

SCREEN # 13
( ROMABLE Z-80 FORTH --- LIT EXECUTE BRANCH OBRANCH )
FORTH DEFINITIONS
CODE LIT          A, (BC) LD        BC INC            L, A LD
                  A, (BC) LD        BC INC            H, A LD
                  HPUSH JP          END-CODE
CODE EXECUTE      HL POP            NEXT1 JP          END-CODE
CODE BRANCH       HERE LABEL BRAN1                    H, B LD
                  L, C LD           C, (HL) LD        HL INC
                  B, (HL) LD        NEXT JP           END-CODE
CODE OBRANCH      HL POP            A, L LD           A, H OR
                  Z, BRAN1 JP       BC INC            BC INC
                  NEXT JP           END-CODE
;S

SCREEN # 14
( ROMABLE Z-80 FORTH --- (LOOP (DO )
CODE (LOOP)       (IY) INC          NZ, XLOO1 JP      1 (IY) INC
                  HERE LABEL XLOO1                    A, (IY) LD
                  A, 2 (IY) SUB     A, 1 (IY) LD      A, 3 (IY) SBC
                  M, BRAN1 JP       DE, # 4 LD        IY, DE ADD
                  BC INC            BC INC            NEXT JP
                  END-CODE
CODE (DO)         DE, # -4 LD       IY, DE ADD        DE POP
                  (IY), E LD        1 (IY), D LD      DE POP
                  2 (IY), E LD      3 (IY), D LD      NEXT JP
                  END-CODE
;S
```

```
SCREEN # 15
( ROMABLE Z-80 FORTH --- (+LOOP )

CODE (+LOOP)      DE POP             A, D LD            A, A OR
                  M, XPLOO1 JP       L, (IY) LD         H, 1 (IY) LD
                  HL, DE ADD         (IY), L LD         1 (IY), H LD
                  E, 2 (IY) LD       D, 3 (IY) LD       A, A OR
                  HL, DE SBC         M, BRAN1 JP
                  HERE LABEL XPLOO0                     DE, # 4 LD
                  IY, DE ADD         BC INC             BC INC
                  NEXT JP
                  HERE LABEL XPLOO1                     L, (IY) LD
                  H, 1 (IY) LD       HL, DE ADD         (IY), L LD
                  1 (IY), H LD       E, 2 (IY) LD       D, 3 (IY) LD
                  DE, HL EX          A, A OR            HL, DE SBC
                  M, BRAN1 JP        XPLOO0 JR          END-CODE
;S

SCREEN # 16
( ROMABLE Z-80 FORTH --- I J DIGIT )

CODE I            E, (IY) LD         D, 1 (IY) LD       DE PUSH
                  NEXT JP            END-CODE

CODE J            E, 4 (IY) LD       D, 5 (IY) LD       DE PUSH
                  NEXT JP            END-CODE

CODE DIGIT        HL POP             DE POP             A, E LD
                  A, # 30 SUB        M, DIGI2 JP        A, # 0A CP
                  M, DIGI1 JP        A, # 7 SUB         A, # 0A CP
                  M, DIGI2 JP        HERE LABEL DIGI1
                  A, L CP            P, DIGI2 JP        E, A LD
                  HL, # 1 LD         DPUSH JP
                  HERE LABEL DIGI2                      L, H LD
                  HPUSH JP           END-CODE                   ;S

SCREEN # 17
( ROMABLE Z-80 FORTH --- (FIND )

CODE (FIND)       DE POP             HERE LABEL PFIN1
                  HL POP             HL PUSH            A, (DE) LD
                  A, (HL) XOR        A, # 03F AND       NZ, PFIN4 JP
                  HERE LABEL PFIN2                      HL INC
                  DE INC             A, (DE) LD         A, (HL) XOR
                  A, A ADD           NZ, PFIN3 JP       NCY, PFIN2 JP
                  HL, # 5 LD         HL, DE ADD         (SP), HL EX
                  HERE LABEL PFIN6                      DE DEC
                  A, (DE) LD         A, A OR            P, PFIN6 JP
                  E, A LD            D, # 0 LD          HL, # 1 LD
                  DPUSH JP

;S
```

SCREEN # 18

```
( ROMABLE Z-80 FORTH --- (FIND )

                 HERE LABEL PFIN3                          CY, PFIN5 JR
                 HERE LABEL PFIN4                          DE INC
                 A, (DE) LD          A, A OR               P, PFIN4 JP
                 HERE LABEL PFIN5                          DE INC
                 DE, HL EX           E, (HL) LD            HL INC
                 D, (HL) LD          A, D LD               A, E OR
                 NZ, PFIN1 JR        HL POP                HL, # 0 LD
                 HPUSH JP
                 END-CODE
;S
```

SCREEN # 19

```
( ROMABLE Z-80 FORTH --- ENCLOSE )

CODE ENCLOSE     DE POP              HL POP                HL PUSH
                 A, E LD             D, A LD               E, # -1 LD
                 HL DEC
                 HERE LABEL ENCL1                          HL INC
                 E INC               A, (HL) CP            Z, ENCL1 JR
                 D, # 0 LD           DE PUSH               D, A LD
                 A, (HL) LD          A, A AND              NZ, ENCL2 JR
                 D, # 0 LD           E INC                 DE PUSH
                 E DEC               DE PUSH               NEXT JP
                 HERE LABEL ENCL2
                 A, D LD             HL INC                E INC
                 A, (HL) CP          Z, ENCL4 JR           A, (HL) LD
                 A, A AND            NZ, ENCL2 JR
;S
```

SCREEN # 20

```
( ROMABLE Z-80 FORTH --- CMOVE )

                 HERE LABEL ENCL3                          D, # 0 LD
                 DE PUSH             DE PUSH               NEXT JP
                 HERE LABEL ENCL4                          D, # 0 LD
                 DE PUSH             E INC                 DE PUSH
                 NEXT JP
                 END-CODE

CODE CMOVE       EXX                 BC POP                DE POP
                 HL POP              A, B LD               A, C OR
                 Z, CMOVE2 JR        LDIR
                 HERE LABEL CMOVE2
                 EXX                 NEXT JP               END-CODE
```

```
SCREEN # 21
 ( ROMABLE Z-80 FORTH --- U* )

 CODE U*                DE POP          HL POP          BC PUSH
                        B, H LD         A, L LD         MPYX CALL
                        HL PUSH         H, A LD         A, B LD
                        B, H LD         MPYX CALL       DE POP
                        C, D LD         HL, BC ADD      A, # 0 ADC
                        D, L LD         L, H LD         H, A LD
                        BC POP          DE PUSH         HPUSH JP
                        END-CODE
 ;S
```

```
SCREEN # 22
 ( ROMABLE Z-80 FORTH --- MPYX )
 ASSEMBLER

 HERE LABEL MPYX
                        HL, # 0 LD      C, # 8 LD
                        HERE LABEL MPYX1
                        HL, HL ADD      RLA
                        NCY, MPYX2 JP   HL, DE ADD      A, # 0 ADC
                        HERE LABEL MPYX2
                        C DEC           NZ, MPYX1 JP    RET

 FORTH
 ;S
```

```
SCREEN # 23
 ( ROMABLE Z-80 FORTH --- U/ )

 CODE U/                EXX             BC POP          HL POP
                        DE POP          A, L LD         A, C SUB
                        A, H LD         A, B SBC        CY, USLA1 JP
                        HL, # -1 LD     DE, # -1 LD     USLA7 JP
                        HERE LABEL USLA1                A, # 10 LD
                        HERE LABEL USLA2                HL, HL ADD
                        RLA             DE, HL EX       HL, HL ADD
                        NCY, USLA3 JR   DE INC          A, A AND
                        HERE LABEL USLA3                DE, HL EX
                        RRA             AF PUSH         NCY, USLA4 JR
                        A, A OR         HL, BC SBC      USLA5 JR
 ;S
```

SCREEN # 24

```
( ROMABLE Z-80 FORTH --- U/ )
                  HERE LABEL USLA4                        A, A OR
                  HL, BC SBC          NCY, USLA5 JR       HL, BC ADD
                  DE DEC
                  HERE LABEL USLA5                        DE INC
                  HERE LABEL USLA6                        AF POP
                  A DEC               NZ, USLA2 JR
                  HERE LABEL USLA7                        HL PUSH
                  DE PUSH             EXX                 NEXT JP
                  END-CODE
;S
```

SCREEN # 25

```
( ROMABLE Z-80 FORTH --- AND OR XOR )
CODE AND          DE POP              HL POP              A, E LD
                  A, L AND            L, A LD             A, D LD
                  A, H AND            H, A LD             HPUSH JP
                  END-CODE
CODE OR           DE POP              HL POP              A, E LD
                  A, L OR             L, A LD             A, D LD
                  A, H OR             H, A LD             HPUSH JP
                  END-CODE
CODE XOR          DE POP              HL POP              A, E LD
                  A, L XOR            L, A LD             A, D LD
                  A, H XOR            H, A LD             HPUSH JP
                  END-CODE            ;S
```

SCREEN # 26

```
( ROMABLE Z-80 FORTH --- SP@ SP! RP@ RP! )
CODE SP@          HL, # 0 LD          HL, SP ADD          HPUSH JP
                  END-CODE
CODE SP!          HL, UP LD           DE, # 6 LD          HL, DE ADD
                  E, (HL) LD          HL INC              D, (HL) LD
                  DE, HL EX           SP, HL LD           NEXT JP
                  END-CODE
CODE RP@          IY PUSH             NEXT JP             END-CODE
CODE RP!          HL, UP LD           DE, # 8 LD          HL, DE ADD
                  E, (HL) LD          HL INC              D, (HL) LD
                  DE PUSH             IY POP              NEXT JP
                  END-CODE            ;S
```

```
SCREEN # 27
( ROMABLE Z-80 FORTH --- ;S LEAVE >R R> )
CODE ;S           C, (IY) LD      IY INC          B, (IY) LD
                  IY INC          NEXT JP         END-CODE
CODE LEAVE        E, (IY) LD      D, 1 (IY) LD    2 (IY), E LD
                  3 (IY), D LD    NEXT JP         END-CODE
CODE >R           DE POP          IY DEC          IY DEC
                  (IY), E LD      1 (IY), D LD    NEXT JP
                  END-CODE
CODE R>           E, (IY) LD      IY INC          D, (IY) LD
                  IY INC          DE PUSH         NEXT JP
                  END-CODE
;S

SCREEN # 28
( ROMABLE Z-80 FORTH --- R 0= 0< + )
CODE R            E, (IY) LD      D, 1 (IY) LD    DE PUSH
                  NEXT JP         END-CODE
CODE 0=           HL POP          A, L LD         A, H OR
                  HL, # 0 LD      NZ, HPUSH JP    HL INC
                  HPUSH JP        END-CODE
CODE 0<           HL POP          A, H LD         A, A OR
                  HL, # 0 LD      P, HPUSH JP     HL INC
                  HPUSH JP        END-CODE
CODE +            DE POP          HL POP          HL, DE ADD
                  HPUSH JP        END-CODE
;S

SCREEN # 29
( ROMABLE Z-80 FORTH --- D+ D- )
CODE D+           EXX             BC POP          DE POP
                  HL POP          (SP), HL EX     HL, DE ADD
                  DE, HL EX       HL POP          HL, BC ADC
                  DE PUSH         HL PUSH         EXX
                  NEXT JP         END-CODE
CODE D-           EXX             BC POP          DE POP
                  HL POP          (SP), HL EX     A, A OR
                  HL, DE SBC      DE, HL EX       HL POP
                  HL, BC SBC      DE PUSH         HL PUSH
                  EXX             NEXT JP         END-CODE
;S
```

```
SCREEN # 30
( ROMABLE Z-80 FORTH --- MINUS DMINUS OVER )

CODE MINUS        DE POP          HL, # 0 LD      A, A OR
                  HL, DE SBC      HPUSH JP        END-CODE

CODE DMINUS       EXX             DE POP          BC POP
                  HL, # 0 LD      A, A OR         HL, BC SBC
                  HL PUSH         HL, # 0 LD      HL, DE SBC
                  HL PUSH         EXX             NEXT JP
                  END-CODE

CODE OVER         DE POP          HL POP          HL PUSH
                  DPUSH JP        END-CODE
;S
```

```
SCREEN # 31
( ROMABLE Z-80 FORTH --- DROP 2DROP SWAP DUP 2DUP )

CODE DROP         HL POP          NEXT JP         END-CODE

CODE 2DROP        HL POP          HL POP          NEXT JP
                  END-CODE

CODE SWAP         HL POP          (SP), HL EX     HPUSH JP
                  END-CODE

CODE DUP          HL POP          HL PUSH         HPUSH JP
                  END-CODE

CODE 2DUP         HL POP          DE POP          DE PUSH
                  HL PUSH         DPUSH JP        END-CODE
;S
```

```
SCREEN # 32
( ROMABLE Z-80 FORTH --- +! TOGGLE @ )

CODE +!           HL POP          DE POP          A, (HL) LD
                  A, E ADD        (HL), A LD      HL INC
                  A, (HL) LD      A, D ADC        (HL), A LD
                  NEXT JP         END-CODE

CODE TOGGLE       DE POP          HL POP          A, (HL) LD
                  A, E XOR        (HL), A LD      NEXT JP
                  END-CODE

CODE @            HL POP          E, (HL) LD      HL INC
                  D, (HL) LD      DE PUSH         NEXT JP
                  END-CODE

;S
```

```
SCREEN # 33
( ROMABLE Z-80 FORTH --- C@ 2@ ! )

CODE C@     HL POP        L, (HL) LD     H, # 0 LD
            HPUSH JP      END-CODE

CODE 2@     HL POP        DE, # 3 LD     HL, DE ADD
            D, (HL) LD    HL DEC         E, (HL) LD
            DE PUSH       HL DEC         D, (HL) LD
            HL DEC        E, (HL) LD     DE PUSH
            NEXT JP       END-CODE

CODE !      HL POP        DE POP         (HL), E LD
            HL INC        (HL), D LD     NEXT JP
            END-CODE
;S
```

```
SCREEN # 34
( ROMABLE Z-80 FORTH --- C! 2! 1+ 2+ )

CODE C!     HL POP        DE POP         (HL), E LD
            NEXT JP       END-CODE

CODE 2!     HL POP        DE POP         (HL), E LD
            HL INC        (HL), D LD     HL INC
            DE POP        (HL), E LD     HL INC
            (HL), D LD    NEXT JP

CODE 1+     HL POP        HL INC         HPUSH JP
            END-CODE

CODE 2+     HL POP        HL INC         HL INC
            HPUSH JP      END-CODE
;S
```

```
SCREEN # 35
( ROMABLE Z-80 FORTH --- 1- 2- - = )

CODE 1-     HL POP        HL DEC         HPUSH JP
            END-CODE

CODE 2-     HL POP        HL DEC         HL DEC
            HPUSH JP      END-CODE

CODE -      DE POP        HL POP         A, A OR
            HL, DE SBC    HPUSH JP       END-CODE

CODE =      HL POP        DE POP         A, A XOR
            HL, DE SBC    H, A LD        L, A LD
            NZ, HPUSH JP  HL INC         HPUSH JP
            END-CODE
;S
```

SCREEN # 36

```
( ROMABLE Z-80 FORTH --- < > FILL )

CODE <          DE POP          HL POP              A, A OR
                HL, DE SBC      HL, # 1 LD          M, HPUSH JP
                HL DEC          HPUSH JP            END-CODE

CODE >          HL POP          DE POP              A, A OR
                HL, DE SBC      HL, # 1 LD          M, HPUSH JP
                HL DEC          HPUSH JP            END-CODE

CODE FILL       EXX             DE POP              BC POP
                HL POP          HERE LABEL FILL1
                A, B LD         A, C OR             Z, FILL2 JR
                (HL), E LD      HL INC              BC DEC
                FILL1 JP        HERE LABEL FILL2
                EXX             NEXT JP             END-CODE    ;S
```

SCREEN # 37

```
( ROMABLE Z-80 FORTH --- P@ P! )

CODE P@         EXX             BC POP              L, (C) IN
                H, # 0 LD       HL PUSH             EXX
                NEXT JP         END-CODE

CODE P!         EXX             BC POP              HL POP
                (C), L OUT      EXX                 NEXT JP
                END-CODE

;S
```

SCREEN # 38

```
( ROMABLE Z-80 FORTH --- S= )

CODE S=         EXX             BC POP              HL POP
                DE POP
                HERE LABEL STREQ1
                A, B LD         A, C OR             Z, STREQ2 JR
                A, (DE) LD      CPI                 NZ, STREQ3 JR
                DE INC          STREQ1 JP
                HERE LABEL STREQ2
                EXX             HL, # 1 LD          HPUSH JP
                HERE LABEL STREQ3
                EXX             HL, # 0 LD          HPUSH JP
;S
```

```
SCREEN # 39
( ROMABLE Z-80 FORTH --- ROT S->D MON )

CODE ROT         DE POP            HL POP            (SP), HL EX
                 DPUSH JP          END-CODE

CODE S->D        DE POP            HL, # 0 LD        A, D LD
                 A, # 080 AND      Z, STOD1 JP       HL DEC
                 HERE LABEL STOD1
                 DPUSH JP          END-CODE

CODE MON         0 JP END-CODE
;S
```

```
SCREEN # 40
( ROMABLE Z-80 FORTH --- CONSTANT USER : DOES> )

: CONSTANT     CREATE SMUDGE ,
               ;CODE DE INC   DE, HL EX   E, (HL) LD   HL INC
               D, (HL) LD   DE PUSH   NEXT JP   END-CODE
: USER         CONSTANT
               ;CODE   DE INC   DE, HL EX   E, (HL) LD   D, # 0 LD
               HL, UP LD   HL, DE ADD   HPUSH JP   END-CODE
: :            ?EXEC !CSP CURRENT @ CONTEXT ! CREATE [COMPILE] ]
               ;CODE   IY DEC   (IY), B LD   IY DEC   (IY), C LD
               DE INC   C, E LD   B, D LD   NEXT JP   END-CODE
: DOES>        R> LATEST PFA !   ;CODE   IY DEC   (IY), B LD
               IY DEC   (IY), C LD   DE INC   DE, HL EX
               C, (HL) LD   HL INC   B, (HL) LD   HL INC
               HPUSH JP   END-CODE
;S
```

```
SCREEN # 41
( ROMABLE Z-80 FORTH --- VARIABLE & VOCABULARY )

: VARIABLE                   CREATE SMUDGE HERE 2+ , , ;CODE
                             DE INC   DE, HL EX   E, (HL) LD   HL INC
                             D, (HL) LD   DE PUSH   NEXT JP   END-CODE

: VOCABULARY                 <BUILDS HERE 4 + ,
                             HERE VOC-LINK @ , VOC-LINK !
                             A081 , CURRENT @ CFA ,
                             DOES> @ 2+ CONTEXT ! ;

VOCABULARY FORTH IMMEDIATE
;S
```

```
SCREEN # 42
( ROMABLE Z-80 FORTH --- USER-DEFINITIONS )

06 USER S0       08 USER R0             0A USER TIB
0C USER WIDTH    0E USER WARNING        10 USER FENCE
12 USER DP       14 USER VOC-LINK       16 USER BLK
18 USER IN       1A USER OUT            1C USER SCR
20 USER CONTEXT  22 USER CURRENT
24 USER STATE    26 USER BASE           28 USER DPL
3A USER FLD      2C USER CSP            2E USER R#
30 USER HLD
3C USER 'EMIT



;S

SCREEN # 43
( ROMABLE Z-80 FORTH --- +ORIGIN CFA LATEST TRAVERSE PFA )
: +ORIGIN          ORIGIN + ;
: CFA              2 - ;
: LATEST           CURRENT @ @ ;
: TRAVERSE         SWAP BEGIN OVER + 07F OVER C@
                   < UNTIL SWAP DROP ;
: PFA              1 TRAVERSE 5 + ;
: (;CODE)          R> LATEST PFA CFA ! ;
: HERE             DP @ ;
: ALLOT            DP +! ;
: ,                HERE ! 2 ALLOT ;
: !CSP             SP@ CSP ! ;
: HOLD             -1 HLD +! HLD @ C! ;
: SMUDGE           LATEST 20 TOGGLE ;
;S

SCREEN # 44
( ROMABLE Z-80 FORTH --- ?COMP COMPILE LITERAL COUNT TYPE )
: ?COMP            STATE @ 0= 11 ?ERROR ;
: COMPILE          ?COMP R> DUP 2+ >R @ , ;
: LITERAL          STATE @ IF COMPILE LIT , ENDIF ; IMMEDIATE
: DLITERAL         STATE @ IF SWAP [COMPILE] LITERAL
                   [COMPILE] LITERAL ENDIF ; IMMEDIATE
: COUNT            DUP 1+ SWAP C@ ;
: -DUP             DUP IF DUP ENDIF ;
: TYPE             -DUP IF OVER + SWAP DO I C@ EMIT LOOP
                   ELSE DROP ENDIF ;
: (.")             R COUNT DUP 1+ R> + >R TYPE ;
: PAD              HERE 44 + ;
: #>               DROP DROP HLD @ PAD OVER - ;
: SIGN             ROT 0< IF 2D HOLD ENDIF ;
;S
```

```
SCREEN # 45
  ( ROMABLE Z-80 FORTH --- M/MOD # #S D+- DABS +- ABS M/ /MOD )
  : M/MOD                >R 0 R U/ R> SWAP >R U/ R> ;
  : #                    BASE @ M/MOD ROT 9 OVER < IF 7 + ENDIF
                         30 + HOLD ;
  : #S                   BEGIN # 2DUP OR 0= UNTIL ;
  : <#                   PAD HLD ! ;
  : D+-                  0< IF DMINUS ENDIF ;
  : DABS                 DUP D+- ;
  : +-                   0< IF MINUS ENDIF ;
  : ABS                  DUP +- ;
  : M/                   OVER >R >R DABS R ABS U/ R> R XOR +-
                         SWAP R> +- SWAP ;
  : /MOD                 >R S->D R> M/ ;
  : /                    /MOD SWAP DROP ;
  : MAX                  2DUP < IF SWAP ENDIF DROP ;
  ;S

SCREEN # 46
  ( ROMABLE Z-80 FORTH --- SPACES D.R D. .CPU M* * */MOD U. )
  : SPACE                BL EMIT ;
  : SPACES               0 MAX -DUP IF 0 DO SPACE LOOP ENDIF ;
  : D.R                  >R SWAP OVER DABS <# #S SIGN #> R>
                         OVER - SPACES TYPE ;
  : D.                   0 D.R SPACE ;
  : .CPU                 BASE @ 24 BASE ! 22 +ORIGIN 2@ D. BASE ! ;
  : .                    S->D D. ;
  : M*                   2DUP XOR >R ABS SWAP ABS U* R> D+- ;
  : *                    M* DROP ;
  : */MOD                >R M* R> M/ ;
  : -TRAILING            DUP 0 DO OVER OVER + 1 - C@ BL - IF LEAVE
                         ELSE 1 - ENDIF LOOP ;
  : U.                   0 D. ;
  ;S

SCREEN # 47
  ( ROMABLE Z-80 FORTH --- TERMINAL I/O )
  ( PORT ADDRESSES AND BIT MASKS ARE EQUATES IN SCREEN 9 )
  HEX
  : EMIT                 'EMIT @ EXECUTE ;
  : CR                   0D EMIT 0A EMIT ;
  : ?TERMINAL            A-STATUS-PORT P@ RDA AND
                         IF 1 ELSE 0 ENDIF ;
  : KEY                  BEGIN ?TERMINAL UNTIL A-DATA-PORT P@ 07F AND ;
  ;S
```

```
SCREEN # 48
  ( ROMABLE Z-80 FORTH --- MESSAGE (ABORT ERROR NUMBER ?EXEC )
  : MESSAGE           -DUP IF ."  MESSAGE # " . ENDIF ;
  : (ABORT)           ABORT ;
  : ERROR             WARNING @ 0< IF (ABORT) ENDIF HERE COUNT TYPE
                      ." ? " MESSAGE SP! BLK @ -DUP
                      IF IN @ SWAP ENDIF QUIT ;
  : ?ERROR            SWAP IF ERROR ELSE DROP ENDIF ;
  : (NUMBER)          BEGIN 1+ DUP >R C@ BASE @ DIGIT WHILE SWAP
                      BASE @ U* DROP ROT BASE @ U* D+ DPL @ 1+
                      IF 1 DPL +! ENDIF R> REPEAT R> ;
  : NUMBER            0 0 ROT DUP 1+ C@ 2D = DUP >R + -1 BEGIN DPL !
                      (NUMBER) DUP C@ BL -
                      WHILE DUP C@ 2E - 0 ?ERROR 0 REPEAT
                      DROP R> IF DMINUS ENDIF ;
  : ?EXEC             STATE @ 12 ?ERROR ;
  ;S

SCREEN # 49
  ( ROMABLE Z-80 FORTH ---  U< ?STACK BLANKS WORD -FIND NFA ETC.)
  : U<                2DUP XOR 0< IF DROP 0< 0= ELSE - 0< ENDIF ;
  : ?STACK            SP@ S0 @ SWAP U< 1 ?ERROR SP@ HERE
                      80 + U< 7 ?ERROR ;
  : BLANKS            BL FILL ;
  : WORD              TIB @ IN @ + SWAP
                      ENCLOSE HERE 22 BLANKS IN +! OVER - >R
                      R HERE C! + HERE 1+ R> CMOVE ;
  : -FIND             BL WORD HERE CONTEXT @ @ (FIND) DUP 0=
                      IF DROP HERE LATEST (FIND) ENDIF ;
  : NFA               5 - -1 TRAVERSE ;
  : LFA               4 - ;
  : ID.               PAD 20 5F FILL DUP PFA LFA OVER - PAD SWAP
                      CMOVE PAD COUNT 1F AND TYPE SPACE ;
  : HEX               10 BASE ! ;
  ;S

SCREEN # 50
  ( ROMABLE Z-80 FORTH --- EXPECT NULL MIN CREATE INTERPRET )
  : EXPECT OVER + OVER DO KEY DUP 0E +ORIGIN @ = IF DROP DUP I =
    DUP R> 2 - + >R IF BELL ELSE BSOUT EMIT BL EMIT BSOUT
    ENDIF ELSE DUP 0D = IF LEAVE DROP
    BL 0 ELSE DUP ENDIF R C! 0 R 1+ ! ENDIF EMIT LOOP DROP ;
  : X                 R> DROP ; IMMEDIATE IS-X
  : MIN               2DUP > IF SWAP ENDIF DROP ;
  : CREATE -FIND IF DROP NFA ID. 4 MESSAGE SPACE ENDIF HERE
    DUP C@ WIDTH @ MIN 1+ ALLOT DUP A0 TOGGLE HERE 1 - 80
    TOGGLE LATEST , CURRENT @ ! HERE 2+ , ;
  : INTERPRET BEGIN -FIND IF STATE @ < IF CFA , ELSE CFA EXECUTE
    ENDIF ?STACK ELSE HERE NUMBER DPL @ 1+ IF [COMPILE] DLITERAL
    ELSE DROP [COMPILE] LITERAL ENDIF ?STACK ENDIF AGAIN ;
    FF VARIABLE PUSH>  0 VARIABLE POPPER>
  : INITIALIZE-CBUFFER  FF PUSH> !    0 POPPER> ! ;
    ;S
```

SCREEN # 51

```
( ROMABLE Z-80 FORTH --- QUERY QUIT DEFINITIONS DECIMAL ETC. )
: QUERY                TIB @ 50 EXPECT 0 IN ! ;
: [                    0 STATE ! ; IMMEDIATE
: ]                    C0 STATE ! ; IMMEDIATE
: QUIT                 0 BLK ! [COMPILE] [ BEGIN CR RP! QUERY
                       INTERPRET STATE @ 0= IF CONSOLE ." OK" ENDIF
                       AGAIN ;
: DEFINITIONS          CONTEXT @ CURRENT ! ;
: DECIMAL              0A BASE ! ;
: <BUILDS              0 CONSTANT ;
: ABORT       SP! DECIMAL ?STACK INITIALIZE-UARTS CONSOLE CR
              .CPU ." FIG-FORTH [ LLNL VERSION ] " CR
              [COMPILE] FORTH DEFINITIONS HEX 48 P@ 80 AND 80 =
              IF INIT RUN THEN CONSOLE CR QUIT ;

  ;S
```

SCREEN # 52

```
( ROMABLE Z-80 FORTH --- ERASE ?PAIRS BACK BEGIN ENDIF ETC. )
( *** WARNING:  BACK AND ENDIF CHANGED FROM FIG-FORTH MODEL )
HEX
: ERASE                0 FILL ;
: ?PAIRS               - 13 ?ERROR ;
: BACK                 , ;
: BEGIN                ?COMP HERE 1 ; IMMEDIATE
: ENDIF                ?COMP 2 ?PAIRS HERE SWAP ! ; IMMEDIATE
: THEN                 [COMPILE] ENDIF ; IMMEDIATE
: DO                   COMPILE (DO) HERE 3 ; IMMEDIATE
: LOOP                 3 ?PAIRS COMPILE (LOOP) BACK ; IMMEDIATE
: COLD                 INIT-R0 RAM-START !
                       INIT-RAM DUP >R 4 + RAM-START 2+ R> @ 2 - CMOVE
                       12 +ORIGIN UP @ 6 + 10 CMOVE
;S                     0C +ORIGIN @ ' FORTH 2+ @ 2+ ! ABORT ;
```

SCREEN # 53

```
( ROMABLE Z-80 FORTH --- +LOOP UNTIL END AGAIN REPEAT IF ETC. )
: +LOOP                3 ?PAIRS COMPILE (+LOOP) BACK ; IMMEDIATE
: UNTIL                1 ?PAIRS COMPILE 0BRANCH BACK ; IMMEDIATE
: END                  [COMPILE] UNTIL ; IMMEDIATE
: AGAIN                1 ?PAIRS COMPILE BRANCH BACK ; IMMEDIATE
: REPEAT               >R >R [COMPILE] AGAIN R> R> 2 -
                       [COMPILE] ENDIF ; IMMEDIATE
: IF                   COMPILE 0BRANCH HERE 0 , 2 ; IMMEDIATE
: ELSE                 2 ?PAIRS COMPILE BRANCH HERE 0 , SWAP 2
                       [COMPILE] ENDIF 2 ; IMMEDIATE
: WHILE                [COMPILE] IF 2+ ; IMMEDIATE
: ?CSP                 SP@ CSP @ - 14 ?ERROR ;
: ;                    ?CSP COMPILE ;S SMUDGE [COMPILE] [ ; IMMEDIATE
;S
```

```
SCREEN # 54
( ROMABLE Z-80 FORTH --- .R HEX IMMEDIATE [COMPILE] ' ." WARM )
: .R                >R S->D R> D.R ;
: WARM              ABORT ;
: ."
                    22 STATE @ IF COMPILE (.") WORD HERE C@ 1+ ALLOT
                    ELSE WORD HERE COUNT TYPE ENDIF ; IMMEDIATE
: IMMEDIATE         LATEST 40 TOGGLE ;
: (                 29 WORD ; IMMEDIATE
: [COMPILE]         -FIND 0= 0 ?ERROR DROP CFA , ; IMMEDIATE
: '                 -FIND 0= 0 ?ERROR DROP
                    [COMPILE]   LITERAL ; IMMEDIATE

20 CONSTANT BL
40 CONSTANT C/L
: BINARY            2 BASE ! ;
  ;S

SCREEN # 55
( ROMABLE Z-80 FORTH --- MOD ? FORGET VLIST NOOP TASK )
: MOD               /MOD DROP ;
: C,                HERE C! 1 ALLOT ;
: ?                 @ . ;
: FORGET            CURRENT @ CONTEXT @ - 18 ?ERROR [COMPILE] ' DUP
                    FENCE @ < 15 ?ERROR DUP NFA DP !
                    LFA @ CURRENT @ ! ;
: VLIST             C/L OUT ! CONTEXT @ @ BEGIN
                    C/L OUT @ - OVER C@ 01F AND 4 + <
                    IF CR 0 OUT ! ENDIF
                    DUP ID. SPACE SPACE PFA LFA @ DUP 0=
                    ?TERMINAL OR UNTIL DROP ;
: NOOP              ;
: TASK              ; IS-FENCE
 0 VARIABLE IND      0 VARIABLE IND1
;S

SCREEN # 56















;S
```

```
SCREEN # 57
( I/O PRIMATIVES - PORT-EQUATES )
HEX
E0 EQU BAUD-RATE-PORT    E1 EQU B-DATA-PORT
E2 EQU B-STATUS-PORT     E2 EQU B-COMMAND-PORT

: INITIALIZE-UARTS
   36 BAUD-RATE-PORT P!
   4E A-COMMAND-PORT P!
  07 A-COMMAND-PORT P!
4E B-COMMAND-PORT P!
  07 B-COMMAND-PORT P! ;

40 EQU AD-MUX-REG      41 EQU AD-STAT-REG    48 EQU SYNC-BYTE
42 EQU AD-DATA-L       43 EQU AD-DATA-H
: INIT-AD 80 AD-MUX-REG P! 60 AD-STAT-REG P! ;
   ;S
```

```
SCREEN # 58
( I/O PRIMATIVES - CONSOLE, DISPLAY, SERVICE-ROUTINES )

: PRINT-SERV BEGIN B-STATUS-PORT P@ TBE AND UNTIL
  B-DATA-PORT P!  1 OUT +! ;
: DISPLAY-SERV BEGIN A-STATUS-PORT P@ 01 AND UNTIL
  A-DATA-PORT P!  1 OUT +! ;

   ' PRINT-SERV CFA CONSTANT PRINTER-SERVICE
   ' DISPLAY-SERV CFA CONSTANT DISPLAY-SERVICE

: CONSOLE   DISPLAY-SERVICE 'EMIT ! ;
: PRINT     PRINTER-SERVICE 'EMIT ! ;



   ;S
```

```
SCREEN # 59
( MEMORY DUMP )
( DISPLAY N MEMORY LOCATIONS IN HEX AND ASCII, STARTING )
( AT ADDR ROUNDED TO NEXT LOWER 16 BYTE BOUNDARY ) DECIMAL
: DUMP    ( ADDR N DUMP -> )
  BASE @ >R HEX CR CR 5 SPACES          ( SAVE CURRENT BASE )
  16 0 DO I 3 .R LOOP 2 SPACES          ( PRINT TITLES )
  16 0 DO I 0 <# # #> TYPE LOOP CR
  OVER + SWAP DUP 15 AND XOR DO         ( ROUND STARTING ADDRESS )
  CR I 0 4 D.R 1 SPACES                 ( PRINT ADDRESS )
  I 16 + I 2DUP
              DO I C@ SPACE 0 <# # # #> TYPE LOOP    ( HEX )
              2 SPACES
              DO I C@ DUP 32 < IF DROP 46 ENDIF      ( ASCII )
                     DUP 127 > IF DROP 46 ENDIF EMIT LOOP
  16 +LOOP CR R> BASE ! ;                   ( RESTORE BASE )
  HEX  ;S
```

```
SCREEN # 60
( INTERRUPT SERVICE -CIRCULAR BUFFER )    HEX
CODE INT-SERVICE-A
AF PUSH    BC PUSH    DE PUSH    HL PUSH
 A, PUSH> LD    A INC     PUSH> A LD
 E, A LD    D, # 40 LD    A, SYNC-BYTE IN   A, # 01 AND   B, A LD
 A, AD-DATA-L IN  A, # FC AND  A, B OR  (DE), A LD
 A, PUSH> LD    A INC     PUSH> A LD
 E, A LD    D, # 40 LD    A, AD-DATA-H IN (DE), A LD
A, PUSH> LD A, # 00FF AND  PUSH> A LD
HL POP    DE POP    BC POP    AF POP
EI RETI  END-CODE
HEX  C3 38 C!  ' INT-SERVICE-A 39 ! ( STUFF INTERRUPT JMP )

SCREEN # 61
( INTERRUPT SERVICE SUPPORT )
CODE ENABLE-INT  EI NEXT JP END-CODE
CODE INT-MODE-1  IM1 NEXT JP END-CODE
CODE +P>    A, PUSH> LD    A INC     PUSH> A LD   NEXT JP END-CODE
: SET-INT-AD  INT-MODE-1 ENABLE-INT  INIT-AD ;
CODE @PUSH>  HL, PUSH> LD  HL PUSH  NEXT JP END-CODE
   ;S

SCREEN # 62
( DIAGONISTIC A/D WORDS )
: MUX-REG     HEX 40 P@ ." MUX     REG " ;
: STAT-REG HEX 41 P@ ." STATUS REG " ;
: LOW-BYTE    HEX 42 P@ ." LOW    BYTE " ;
: HIGH-BYTE   HEX 43 P@ ." HIGH   BYTE " ;
: SPA   5 SPACES ;
: AK   PRINT ."       AK " CONSOLE ;
: AK1   4 48 P! DL1 AK ." AK SENT " 8 48 P! DL2 ;
: AD-OFF   0 41 P! ;
   ;S
```

SCREEN # 63

```
( VARIABLE  AD WORDS   )
0 VARIABLE REF1 2 ALLOT-RAM 0 VARIABLE REF2 2 ALLOT-RAM
0 VARIABLE SIG  2 ALLOT-RAM 0 VARIABLE H2O  2 ALLOT-RAM
0 VARIABLE DARK1     2 ALLOT-RAM 0 VARIABLE DARK2     2 ALLOT-RAM
0 VARIABLE DARK3     2 ALLOT-RAM 0 VARIABLE DARK4     2 ALLOT-RAM
0 VARIABLE CH1       2 ALLOT-RAM 0 VARIABLE CH2       2 ALLOT-RAM
0 VARIABLE CH3       2 ALLOT-RAM 0 VARIABLE CH4       2 ALLOT-RAM
0 VARIABLE CH5       2 ALLOT-RAM 0 VARIABLE CH6       2 ALLOT-RAM
0 VARIABLE CH7       2 ALLOT-RAM 0 VARIABLE PF        1 ALLOT-RAM
0 VARIABLE V1        1 ALLOT-RAM 0 VARIABLE NUMB      1 ALLOT-RAM
0 VARIABLE PF1       1 ALLOT-RAM
;S
```

SCREEN # 64

```
( CIRCULAR BUFFER WORDS   )       HEX
: DATA-RDY
     PUSH> @ POPPER> @ - DUP
     0< IF 100 + ENDIF
     80 > IF 1 ELSE 0 ENDIF ;
;S
```

SCREEN # 65

```
( CIRCULAR BUFFER MANAGEMENT )
      ;S
```

SCREEN # 66

```
( CONTROL WORDS )
: ICP    POPPER> @ 2 + 00FF AND POPPER> ! ;
: SYNCH   HEX BEGIN 48 P@ 1 AND UNTIL 00FF PUSH> ! ;  ( BUF SYNC )
: PT1     CR ." SYNC RESTORED " CR ;
: RSYNC HEX POPPER> @ 4000 + C@ 1 AND 0= IF SYNCH    THEN ;
: SCALE   HEX  DUP DUP 3FF2 > IF 3FF2 - 1 - ELSE 2004 >
   IF DROP 0 ELSE 11 + THEN THEN ;
: BCH   E2 P@ 02 AND ;  ( INPUT BUFFER FLAG)
: GCH   E1 P@ ;         ( GET CHR IN INPUT  BUFFER)
: OFF   02 48 P! 0 PF  ! ." HCL UNIT OFF " CR  ;
: DL1 800 0 DO LOOP ;
: DL2  80 0 DO LOOP ;
: OPEN   HEX 10 48 P!  ." HOOD OPEN " CR ;
: CLOSE HEX 20 48 P!  ." HOOD CLOSED " CR ;
;S
```

SCREEN # 67

```
( CONTROL WORDS )
: CRF   46 = IF AK1 OFF THEN ;          ( CHECK CHR F )
: CRP   50 = IF AK1 OPEN THEN ;         ( CHECK CHR P )
: CRC   43 = IF AK1 CLOSE THEN ;        ( CHECK CHR C )
: CRT   54 = IF AK1 QUIT THEN ; ( CHECK CHR T AND QUIT )
: DLL   FF 0 DO FFF 0 DO LOOP LOOP ; ( LONG DELAY LOOP )
: TXON   4 48 P! DL1 ." TX IS ON " CR  ; ( TX-MITTER ON  )
: TXOFF   8 48 P! DL2 ." TX IS OFF" CR ;  ( TURN OFF TRANS )
: NXTCHR 200 0 DO BCH IF GCH V1 C! LEAVE THEN LOOP ;
: CONT   V1 C@ DUP CRN DUP CRF DUP CRP DUP CRC CRT ;
: M1   BEGIN BCH UNTIL GCH 4F = IF NXTCHR CONT THEN PF @ ;
: RDATA   BEGIN M1 UNTIL DROP ;
: RD2   5000 0 DO BCH IF GCH 4F = IF NXTCHR CONT THEN THEN
   LOOP ;
: PFINV  PF @ 0 = IF 1 PF1 ! ELSE 0 PF1 ! THEN ;
;S
```

SCREEN # 68

```
( DIAGNOSTIC WORDS )
: DMP  HEX 4000 100 DUMP ;
: LINE ." 10000 20000 30000 40000 50000 60000 70000 80000 " ;
: ADPT1  PRINT ACHR LINE BCHR CONSOLE ;
: DELAY  0 DO 4000 0 DO LOOP LOOP ;
: DL3  4000 0 DO LOOP ;
: START1 0 DO  ADPT1 8 DELAY LOOP ;



: SP10 9 0 DO 20 EMIT LOOP ;
: CHR@ 40 EMIT 40 EMIT ;
: CHR* 0A EMIT 0D EMIT 2A EMIT 2A EMIT ;
: NMB  NUMB @ DUP 8 > IF DROP 0 DUP NUMB ! ELSE 1 + DUP
  NUMB ! THEN DECIMAL . SPACE HEX ;
;S
```

```
SCREEN # 69
( DATA PROCESSING WORDS )
: CONV  HEX POPPER> @ 4000 + DUP C@ 4 / SWAP 1 + C@ 40 * +
  SCALE ;
: D-ZERO 0 0 REF1 2! 0 0 REF2 2! 0 0 SIG 2! 0 0 H20 2!
  0 0 DARK1 2! 0 0 DARK2 2! 0 0 DARK3 2! 0 0 DARK4 2! ;
: ZP  0 POPPER> ! D-ZERO ;
: AREF1    CONV  0 REF1 2@ D+ REF1 2! ;
: AREF2    CONV  0 REF2 2@ D+ REF2 2! ;
: AH20     CONV  0 H20  2@ D+ H20  2! ;
: ASIG     CONV  0 SIG  2@ D+ SIG  2! ;
: ADARK1   CONV  0 DARK1    2@ D+ DARK1    2! ;
: ADARK2   CONV  0 DARK2    2@ D+ DARK2    2! ;
: ADARK3   CONV  0 DARK3    2@ D+ DARK3    2! ;
: ADARK4   CONV  0 DARK4    2@ D+ DARK4    2! ;
: ADATA    IND @ 0 DO AREF1 ICP ADARK1 ICP AREF2 ICP ADARK2 ICP
  ASIG ICP ADARK3 ICP AH20 ICP ADARK4 ICP LOOP ;    ;S

SCREEN # 70
( DATA PROCESSING WORDS  )
: DIV  2@ IND @ M/ SWAP DROP 0 ;
: INIT ZP 8 IND ! SET-INT-AD SYNCH ;
: DREF1    REF1 DIV REF1 2! ;
: DREF2    REF2 DIV REF2 2! ;
: DSIG     SIG  DIV SIG  2! ;
: DH20     H20  DIV H20  2! ;
: DDARK1   DARK1    DIV DARK1    2! ;
: DDARK2   DARK2    DIV DARK2    2! ;
: DDARK3   DARK3    DIV DARK3    2! ;
: DDARK4   DARK4    DIV DARK4    2! ;
: DDATA    DREF1 DREF2 DSIG DH20 DDARK1
      DDARK2 DDARK3 DDARK4 ;
: ON 01 48 P! 1 PF ! INIT ." HCL UNIT ON " CR ;
: CRN  4E = IF AK1 ON THEN ;   ( CHECK FOR CHR N )
;S

SCREEN # 71
( DATA PROCESSING WORDS )
: BCHR 43 EMIT   ;
: ACHR 42 EMIT ;
: PT  HEX 2@ DECIMAL 5 D.R 1 SPACE DROP HEX ;
: HANDAR CHR* NMB REF1 PT DARK1 PT REF2 PT DARK2 PT
      SIG PT DARK3 PT H20 PT DARK4 PT CHR@ SP10 ;
: DATP  ADATA DDATA PRINT HANDAR CONSOLE D-ZERO ;
: START   BEGIN DATA-RDY UNTIL DATP RSYNC  ;
: RLOP  BEGIN TXON START TXOFF RD2 PFINV PF1 @ UNTIL DROP ;
: RUN  OFF BEGIN TXOFF RDATA DLL RLOP AGAIN ;
: RUN1 OFF BEGIN TXOFF RDATA RLOP AGAIN ;
: START2 0 DO START LOOP ;
    ;S
```

Z-80 FORTH

LABORATORY MICROSYSTEMS

```
SCREEN # 72
( DATA PROCESSING WORDS )
FINIS
    ;S
```

```
SCREEN # 73
```

APPENDIX C

CENTRAL DATA ACQUISITION STATION SOFTWARE

The software that is used to control the acquisition of data from the sensor at the CDAS was written using the ASYST scientific programming package. ASYST is actually a modified FORTH compiler/interpreter that has many useful scientific programming words incorporated within it. The CDAS control software was written and tested within ASYST, and then compiled to produce a separate executable image that can be run without the need to interact with the general ASYST program. It is, however, necessary to use the ASYST "fingerprint" disk (a copy-protection feature) to enter the CDAS program. This disk is supplied with the sensor. In the event of damage to this disk, it is necessary to contact the ASYST manufacturer for a replacement copy. The ASYST manuals are included with the sensor, to aid in modifying the program for future improvements to the sensor system.

The compiled version of the ASYST program is called "SENSOR.COM" and is installed on the hard disk in the CDAS personal computer (the uncompiled source code is "SENSOR.I"). The program runs from a single screen display, which is illustrated in Figure C.1. The screen contains a list of function key commands, a graphics display area (called VUPORT in ASYST), a sensor status display area (SENSON) (indicating whether the sensor is on or off), a hood status display area (HOOD) (indicating whether the hood is opened or closed), a data display area (DATAS) (showing calculated data such as transmittances or HCl concentration, depending upon the command being executed), and two raw data display areas - one being a line that shows single-shot data (EVERY) and the other showing a running average of ten of these points (AVERAGE). In each of these lines, the first four numbers are the data values for each of the four channels (varying between about 1 and 7000 counts). The backgrounds have already been subtracted from each of these values. The remaining three numbers are the ratios of channels 1, 2, and 4 to channel 3

A brief summary of the function-key commands is listed below. More specific operating instructions for the program are provided in Section V (Sensor operation).

- Sensor on - Turns the sensor on. Displays "Sensor on" in SENSON window.

- Sensor off - Turns the sensor off. Displays "Sensor off" in SENSON window.

- Hood open - Opens the White cell hood (not presently installed). Displays "Hood open" in HOOD window.

- Hood close - Closes the hood. Displays "Hood closed" in HOOD window.

- Lab calibrate - This is a data collection command that can be used in the lab to calibrate the sensor with the PGSG and the MNHG When it is executed, it prompts the user for scaling factors and then proceeds to collect and display transmittance data for channels 1,2, and 4 in the VUPORT. Data are displayed in EVERY and AVERAGE windows. Calculated transmittances are shown in the DATAS window and updated each time new data are received.

- Field calibrate - This is a data collection command that is used to calibrate the sensor in the field using the quartz calibration cells and the field portable humidity chamber. It can also be used for routine displaying of data at any time. When executed, the computer collects a user-supplied number of sets of data points from the sensor and then numerically displays the average value of these readings from channel 1 and 2. The only screen display during the execution of this command is in the EVERY and AVERAGE windows.

• HCl collect - This is a data collection mode that is used to collect HCl concentration data in real time. Raw data are shown in the EVERY and AVERAGE windows. The computer uses these values and calibration coefficients that must be input into the sensor, to calculate the HCl concentration. Concentration readings are displayed numerically in the DATAS window, and graphically in the VUPORT.

• Save data - This command saves five arrays of data into both an ASYST format file and an ASCII format file. The arrays saved are the four channel readings accumulated during a run, and the array of HCl concentrations corresponding to these readings.

• Retrieve data - This command reads the saved data from a specified ASYST file and plots it on the screen. It can only be used with files collected using the "HCl collect" command.

When commands are transmitted to the sensor, the CDAS waits for an acknowledgment string to be transmitted back, indicating that the command has been executed. If this is not received, a transmission failure message will be displayed in either the SENSON or HOOD windows.

A general flowchart for the operation of the CDAS software is given in Figure C.2. The source code for the "SENSOR.I" program follows.

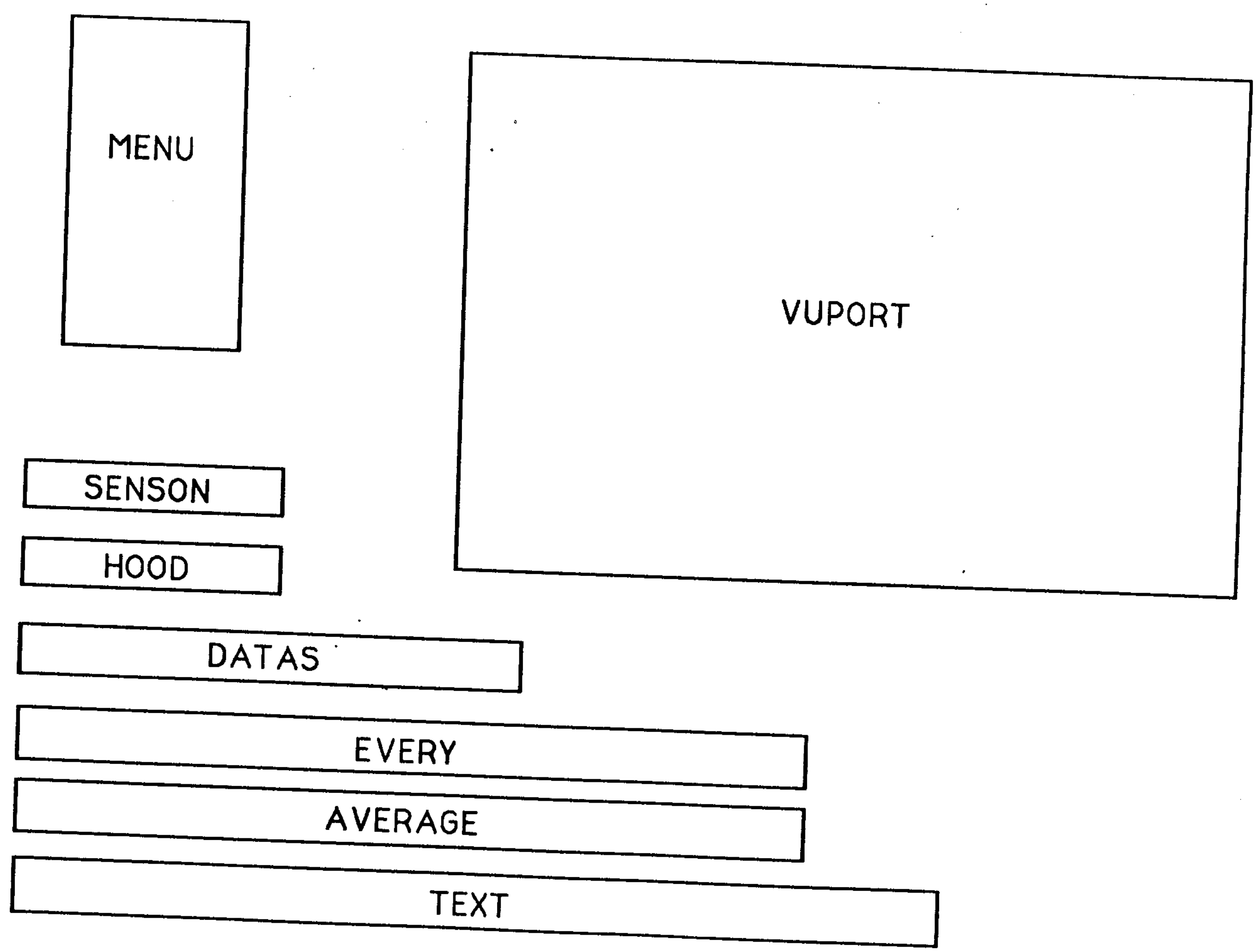


Figure C.1 Schematic of the screen display areas for the CDAS operating system software.

RUN

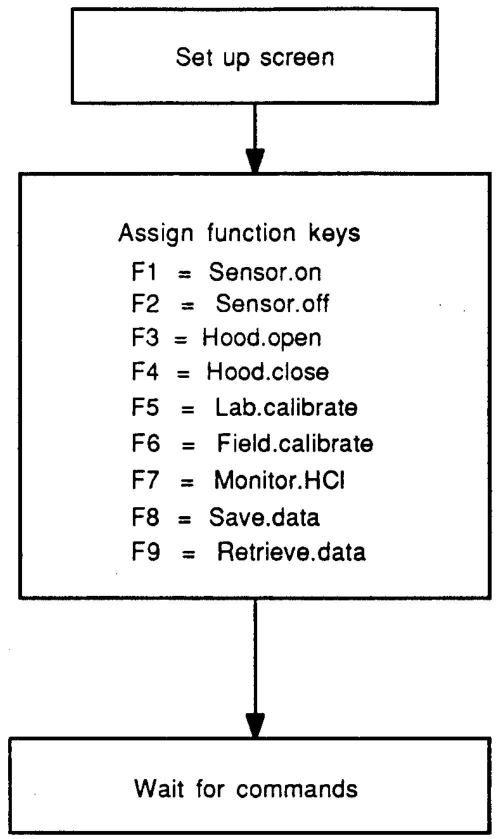


Figure C.2 - CDAS Software Flowchart - Flowchart for RUN word. See following pages for more flowchart information.

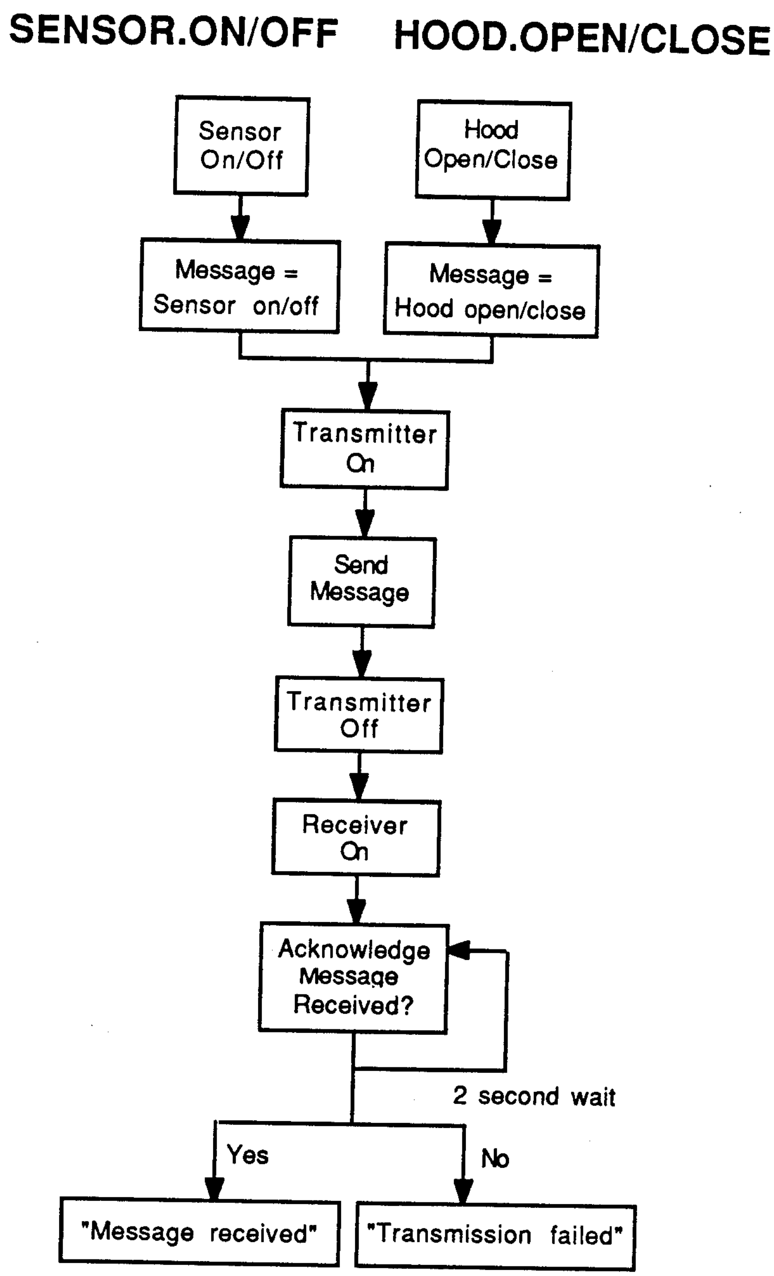


Figure C.2 (cont'd) - CDAS Software Flowchart - flowchart for sensor.on,off and hood.open,close.

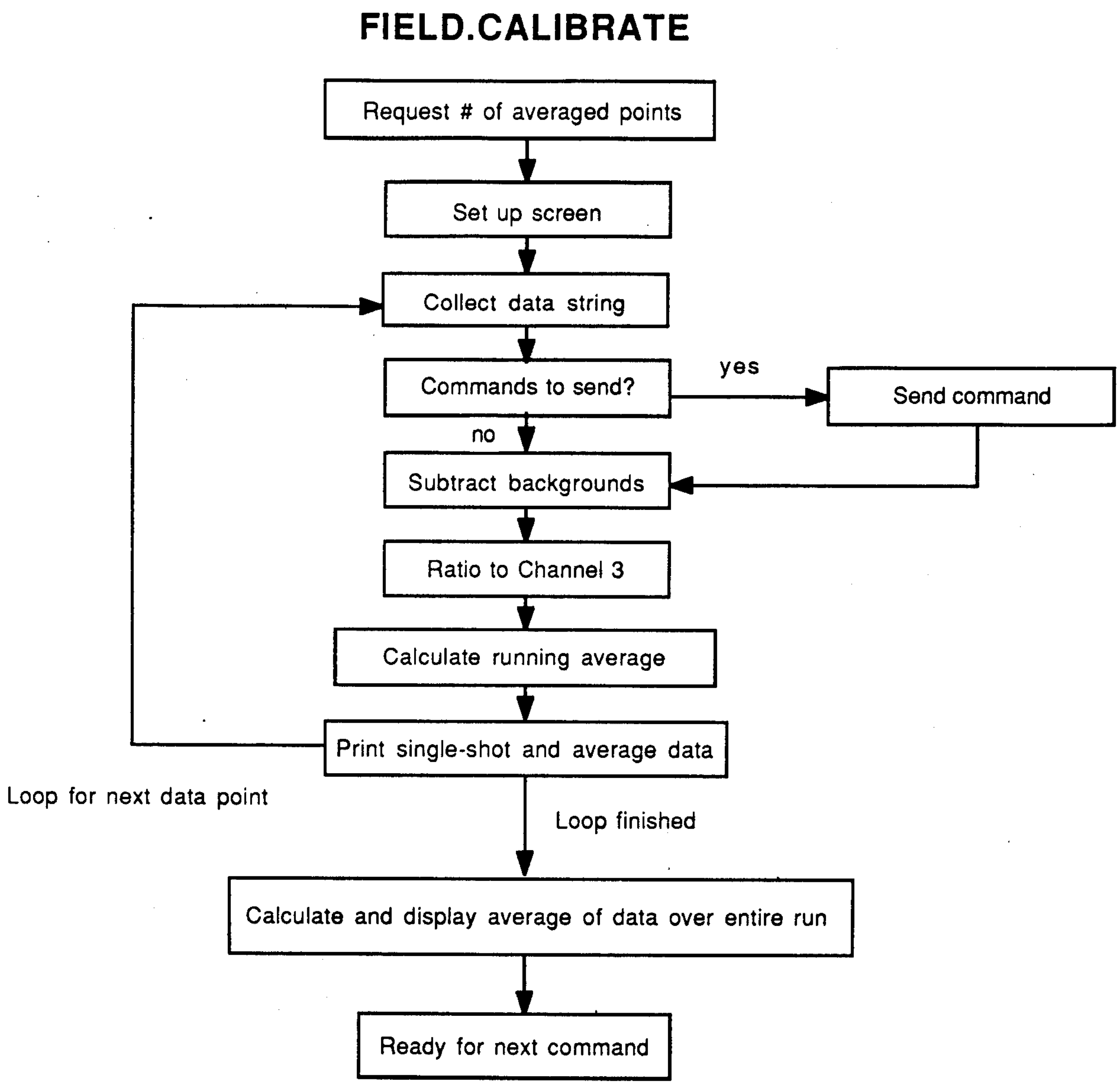


Figure C.2 (cont'd) - CDAS Software Flowchart - flowchart for FIELD.CALIBRATE word.

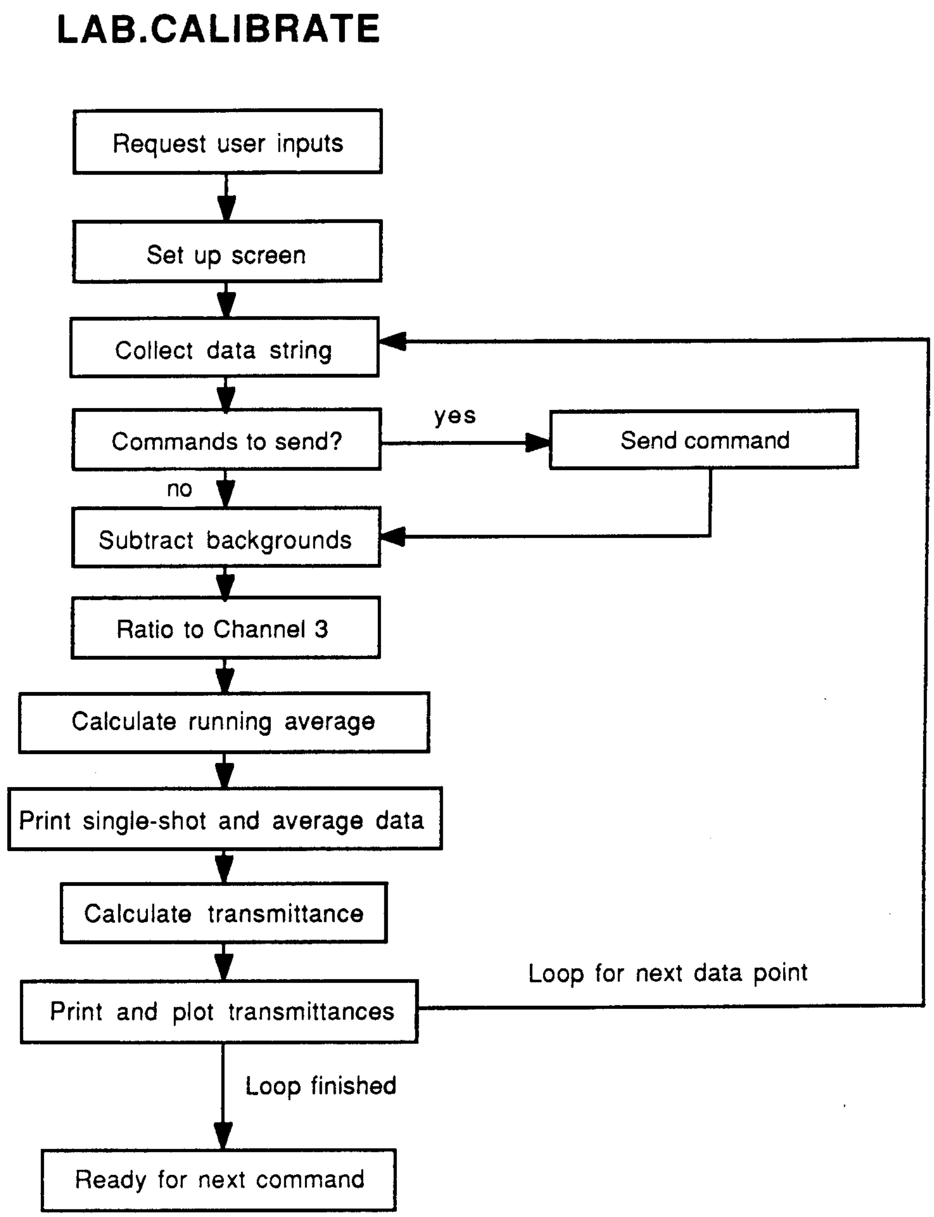


Figure C.2 (cont'd) - CDAS Software Flowchart - flowchart for LAB.CALIBRATE word.

```
\ Variable definitions

25 STRING YLABEL

REAL DIM[ 2 ] ARRAY MX&MN
REAL DIM[ 2 ] ARRAY FX&IX
REAL DIM[ 2 ] ARRAY SP&EP
REAL DIM[ 100 ] ARRAY VALUES

DP.REAL DIM[ 1000 ] ARRAY HCLCONC

REAL SCALAR LABPOS

DP.REAL SCALAR SLPW1
DP.REAL SCALAR SLPW2
DP.REAL SCALAR SLPH1
DP.REAL SCALAR SLPH2
DP.REAL SCALAR OFST
DP.REAL SCALAR WATERCON
DP.REAL SCALAR FSUM
DP.REAL SCALAR RATIO1
DP.REAL SCALAR RATIO2
DP.REAL SCALAR RATIO4
DP.REAL SCALAR IRAT1
DP.REAL SCALAR IRAT2
DP.REAL SCALAR IRAT4
DP.REAL SCALAR SLOPE
DP.REAL SCALAR FULRAT
DP.REAL SCALAR OLDVAL
DP.REAL SCALAR OLDVL1
DP.REAL SCALAR OLDVL2
DP.REAL SCALAR OLDVL4
DP.REAL SCALAR TAU1
DP.REAL SCALAR TAU2
DP.REAL SCALAR TAU4
DP.REAL SCALAR TIMER
DP.REAL SCALAR SUM1
DP.REAL SCALAR SUM2
DP.REAL SCALAR SUM3
DP.REAL SCALAR SUM4

15 0 15 22 WINDOW SENSON
16 0 16 22 WINDOW HOOD
19 0 19 79 WINDOW DATAS
21 0 21 79 WINDOW EVERY
22 0 22 79 WINDOW AVERAGE
23 0 24 79 WINDOW TEXTS

0 0 12 22 WINDOW FUNCTIONS

2 STRING TEST
2 STRING VALUE
14 STRING FILENAME
40 STRING IN.MESSAGE
```

```
INTEGER SCALAR NPTS
INTEGER SCALAR KK
INTEGER SCALAR JJ
INTEGER SCALAR SENDVAR
INTEGER SCALAR HOODVAR
INTEGER SCALAR SENSVAR
INTEGER SCALAR INDEX
INTEGER SCALAR ACCUM

INTEGER DIM[ 4 ] ARRAY YVALS
INTEGER DIM[ 4 ] ARRAY BASVALS
INTEGER DIM[ 1000 ] ARRAY XVALS
INTEGER DIM[ 500 ] ARRAY ACK
INTEGER DIM[ 1000 ] ARRAY CHAN1
INTEGER DIM[ 1000 ] ARRAY CHAN2
INTEGER DIM[ 1000 ] ARRAY CHAN3
INTEGER DIM[ 1000 ] ARRAY CHAN4
INTEGER DIM[ 60 ] ARRAY VALUES

\ Set up RS232 interface

COM1
8 SET.DATA.BITS
4800 SET.BAUD
0 SET.PARITY
1 SET.STOP.BITS
RS232.INT.MODE

\ This word is used to input data from the screen. It recognizes invalid
\ (i.e. non-numerical) inputs, and produces an error message.


: GET.VALID.#
  BEGIN
    #INPUT NOT
  WHILE
    CR ." INVALID NUMBER. REENTER " BELL BELL
  REPEAT
;

\ The following series of words are used for transmission of commands to
\ the radios and to the sensor. The radio base-station is interfaced through
\ the RS-232 serial port.

\ This word turns the radio transmitter on.

 : TX.ON
   3 1020 PORT.OUT
  200 MSEC.DELAY
 ;

\ This word turns the radio transmitter off.

: TX.OFF
  0 1020 PORT.OUT
  50 MSEC.DELAY
;
```

```

\ This word test to see if data has arrived at the serial port.

: DATA.IN?
  1021 PORT.IN #>MASK
  1, AND
;

\ This word tests the array ACK to see if it contains the string "AK"
\ which is sent by the sensor to acknowledge the receipt of a command.
\ The ACK array is read in by the next word.

: AK.IN?
  500 1 DO
   ACK [ I ] 65 =
    IF
      ACK [ I 1 + ] 75 =
      IF
        CR IN.MESSAGE "TYPE
        LEAVE
      THEN
    THEN
    I 499 =
    IF
      CR ." TRANSMISSION FAILED "
    THEN
  LOOP
;

\ This word repeatedly (500 times) reads the contents of port 1016 into the
\ array ACK after ASCII character 32 has been received. It also contains a
timer
\ to time-out of the wait state if that character has not been received. The
\ array should contain within it the "AK" signal from the sensor. The word
\ "AK.IN?" then looks through the array to see if that message has arrived.

: ACKNOWLEDGE
  REL.TIME TIMER :=
  0 ACK :=
  BEGIN
    DATA.IN?
    1016 PORT.IN 32 = AND
    REL.TIME TIMER - 2000. > OR
  UNTIL
  500 1 DO
    1016 PORT.IN ACK [ I ] :=
  LOOP
  AK.IN?
;

\ This word sends the commands to the sensor. The two character ASCII codes
\ that the sensor expects for the various commands are as follows:
\           Sensor on          ON
\           Sensor off         OF
\           Hood open          OP
\           Hood close         OC
\ Because they all have the character "O" in common, the radio always
```

```
transmits
 \ that character (ASCII 79). The second character is determined by the word
 \ that calls SENDER.

 : SENDER
    TX.ON
    140 MSEC.DELAY
    79 1016 PORT.OUT
    1 MSEC.DELAY
    SENDVAR 1016 PORT.OUT
    10 MSEC.DELAY
    TX.OFF
    ACKNOWLEDGE
 ;

 \ This word turns the sensor on.

 : SENSOR.ON
   " SENSOR TURNED ON " IN.MESSAGE ":=
   1 SENSVAR :=
   78 SENDVAR :=
   SENSON
   SENDER
   TEXTS
 ;

 \ This word turns the sensor off.

 : SENSOR.OFF
   " SENSOR TURNED OFF " IN.MESSAGE ":=
   0 SENSVAR :=
   70 SENDVAR :=
   SENSON
   SENDER
   TEXTS
 ;

 \ This word opens the hood (hood is presently not installed on sensor,
 \ but the control circuits for it are installed).

 : HOOD.OPEN
   " HOOD OPENED " IN.MESSAGE ":=
   1 HOODVAR :=
   80 SENDVAR :=
   HOOD
   SENDER
   TEXTS
 ;

 \ This word closes the hood.

 : HOOD.CLOSE
   " HOOD CLOSED " IN.MESSAGE ":=
   0 HOODVAR :=
   67 SENDVAR :=
   HOOD
   SENDER
```

```
  TEXTS
;

\ This word produces labels for the function key operations on the screen in
\ window "FUNCTIONS".

: LABEL.KEYS
  FUNCTIONS
  SCREEN.CLEAR
  CR
  ." F1 = SENSOR ON " CR
  ." F2 = SENSOR OFF " CR
  ." F3 = HOOD OPEN " CR
  ." F4 = HOOD CLOSE " CR
  ." F5 = LAB CALIBRATE " CR
  ." F6 = FIELD CALIBRATE " CR
  ." F7 = HCL COLLECT " CR
  ." F8 = SAVE DATA " CR
  ." F9 = RETREIVE DATA " CR
  ." CNTRL-BK = STOP " CR
  TEXTS
;


\ This word labels the axes of the graph. They are labeled with the
\ time interval on the x-axis and the label "YLABEL" on the y-axis.

: LABEL.AXES
  CURSOR.OFF
  NORMAL.COORDS
  .3 .05 POSITION
  " TIME INTERVAL (8 SEC EACH) " LABEL
  .025 LABPOS POSITION
  270 LABEL.DIR
  YLABEL LABEL
  WORLD.COORDS
;

\ This word generates the axes of the plot. They are scaled according to
\ the arrays MX&MN and FX&IX.

: MAKE.AXES
  CURSOR.OFF
  0 FX&IX [ 1 ] :=
  0 SP&EP [ 1 ] :=
  CR ." NUMBER OF POINTS TO COLLECT? " GET.VALID.# FX&IX [ 2 ] :=
  FX&IX MX&MN XY.DATA.FIT
  XY.AXIS.PLOT
  LABEL.AXES
;

\ This word is used to extract the data from the array "VALUES". That array
\ contains the data string sent by the sensor for a given 8 second interval.
\ The data is then converted from ASCII to integer.

: READER
  INDEX :=
```

```
  0 ACCUM :=
  5 1 DO
    VALUES [ INDEX ] 48 -
    DUP 0 >=
    DUP 9 <= AND
    IF
      1000 10 I 1 - ** / *
      ACCUM + ACCUM :=
    ELSE
      DROP
    THEN
    INDEX 1 + INDEX :=
  LOOP
;

\ This word collects a string of data from the RS-232 interface.
\ The structure of the ASCII string that is sent by the sensor is
\ as follows:
\
\    _**_11111_B1111_22222_B2222_33333_B3333_44444_B4444_@@
\
\ where 11111 are the 5 ASCII characters corresponding to the Channel 1
\ data, B1111 are the characters corresponding to the Channel 1 background,
\ 22222 are the Channel 2 data characters, etc. To confirm that the data
\ in the buffer are actually data from the sensor, the program looks for the
\ start character, *. If found, the code then parses out the signal and
\ background values and places them in the arrays called YVALS and BASVALS.
\ Finally, the background readings are subtracted from the signal readings
\ and the result is placed into the YVALS array.

: COLLECT
  0 YVALS :=
  BEGIN
    DATA.IN?
    IF
      1016 PORT.IN
        42 = IF
          60 1 DO
            BEGIN
              DATA.IN?
            UNTIL
            1016 PORT.IN VALUES [ I ] :=
          LOOP

\ Parse out data and background values

           6 READER ACCUM YVALS [ 1 ] :=
          12 READER ACCUM BASVALS [ 1 ] :=
          18 READER ACCUM YVALS [ 2 ] :=
          24 READER ACCUM BASVALS [ 2 ] :=
          30 READER ACCUM YVALS [ 3 ] :=
          36 READER ACCUM BASVALS [ 3 ] :=
          42 READER ACCUM YVALS [ 4 ] :=
          48 READER ACCUM BASVALS [ 4 ] :=

\ Subtract backgrounds from data.
```

```
            YVALS [ 1 ] BASVALS [ 1 ] - YVALS [ 1 ] :=
            YVALS [ 2 ] BASVALS [ 2 ] - YVALS [ 2 ] :=
            YVALS [ 3 ] BASVALS [ 3 ] - YVALS [ 3 ] :=
            YVALS [ 4 ] BASVALS [ 4 ] - YVALS [ 4 ] :=
        THEN
      THEN
     YVALS [ 1 ] 0 <= NOT
     YVALS [ 2 ] 0 <= NOT AND
     YVALS [ 3 ] 0 <= NOT AND
     YVALS [ 4 ] 0 <= NOT AND
     UNTIL
   ;


   \ This word is used to draw a line between points on the data plot.

   : DRAW.LINE
     SCREEN.CLEAR ." COLLECTING DATA "
     CURSOR.OFF
     1 KK =
     IF
       POSITION
     ELSE
       DUP
       MX&MN [ 1 ] <
       IF
         DROP
         MX&MN [ 1 ]
         SCREEN.CLEAR ." DATA OUT OF BOUNDS "
       THEN
       DUP
       MX&MN [ 2 ] >
       IF
         DROP
         MX&MN [ 2 ]
         SCREEN.CLEAR ." DATA OUT OF BOUNDS "
       THEN
         KK 1 -
         OLDVAL
         POSITION
         DRAW.TO
     THEN
   ;

   \ This word is responsible for sending commands to the sensor during
   \ data collection.

   : COMMAND
     500 MSEC.DELAY
     ?KEY
     IF
       KEY 0 =
       IF
         KEY
          CASE
            61 OF HOOD HOOD.OPEN TEXTS ENDOF
            62 OF HOOD HOOD.CLOSE TEXTS ENDOF
```

```
          64 OF CR ." COLLECTION TERMINATED " EXIT ENDOF
        ENDCASE
     THEN
  THEN
;

\ This word produces 10-point running averages of the signals for each
\ filter channel.

: AVERAGER
  0 SUM1 :=
  0 SUM2 :=
  0 SUM3 :=
  0 SUM4 :=
  1 JJ :=
  BEGIN
    JJ 11 <
    WHILE
      CHAN1 [ I JJ - ] SUM1 + SUM1 :=
      CHAN2 [ I JJ - ] SUM2 + SUM2 :=
      CHAN3 [ I JJ - ] SUM3 + SUM3 :=
      CHAN4 [ I JJ - ] SUM4 + SUM4 :=
      JJ 1 + JJ :=
  REPEAT
  SUM1 10. / SUM1 :=
  SUM2 10. / SUM2 :=
  SUM3 10. / SUM3 :=
  SUM4 10. / SUM4 :=
;

\ This word zeroes all necessary variables.

: ZERO
  0 RATIO1 :=
  0 RATIO2 :=
  0 RATIO4 :=
  0 CHAN1 :=
  0 CHAN2 :=
  0 CHAN3 :=
  0 CHAN4 :=
  0 KK :=
  0 SUM1 :=
  0 SUM2 :=
  0 SUM3 :=
  0 SUM4 :=
;

\ This word calculates the ratios of the data channels, and displays
\ the raw data and the ratios on the screen in the raw data display
\ windows. The window called "EVERY" displays every data set received.
\ The window called "AVERAGE" shows the 10 point running averages.

: PROCESS.DATA

\ Read the data from the "YVALS" array to the arrays CHAN1 through CHAN4

  YVALS [ 1 ] CHAN1 [ I ] :=
```

```
    YVALS [ 2 ] CHAN2 [ I ] :=
    YVALS [ 3 ] CHAN3 [ I ] :=
    YVALS [ 4 ] CHAN4 [ I ] :=
    I 10 >
    IF
      AVERAGER
    THEN
    CHAN1 [ I ] FLOAT
    CHAN3 [ I ]
    / RATIO1 :=
    CHAN2 [ I ] FLOAT
    CHAN3 [ I ]
    / RATIO2 :=
    CHAN4 [ I ] FLOAT
    CHAN3 [ I ]
    / RATIO4 :=
    EVERY
    CR YVALS . 5 SPACES RATIO1 . RATIO2 . RATIO4 .
    I 10 > IF
      AVERAGE
      CR SUM1 FIX . SUM2 FIX 1 SPACES .
      SUM3 FIX 1 SPACES . SUM4 FIX 1 SPACES .
      5 SPACES SUM1 SUM3 / . SUM2 SUM3 / . SUM4 SUM3 / .
    THEN
    TEXTS
  ;

  \ This word is used to collect the data and plot the HCl concentration
  \ in real-time on the computer screen. It displays the raw data in the
  \ EVERY and AVERAGE windows, and also numerically displays the single point
  \ HCl concentration in the window DATAS.

  : MONITOR.HCL
    VUPORT.CLEAR

  \ Request user supplied inputs and produce axis of graph

    CR ." ENTER FULL TRANSMISSION RATIO (CH 1) " GET.VALID.# IRAT1 :=
    CR ." ENTER FULL TRANSMISSION RATIO (CH 2) " GET.VALID.# IRAT2 :=
    CR ." ENTER H20 SLOPE (CH 1) " GET.VALID.# SLPW1 :=
    CR ." ENTER H20 SLOPE (CH 2) " GET.VALID.# SLPW2 :=
    CR ." ENTER HCL WEAK-LINE SLOPE " GET.VALID.# SLPH1 :=
    CR ." ENTER HCL STRONG-LINE SLOPE " GET.VALID.# SLPH2 :=
    CR ." ENTER HCL STRONG-LINE OFFSET " GET.VALID.# OFST :=
    CR ." INPUT MINIMUM CONCENTRATION " GET.VALID.# MX&MN [ 1 ] :=
    CR ." INPUT MAXIMUM CONCENTRATION " GET.VALID.# MX&MN [ 2 ] :=

  \ Set up screen

    DATAS
    SCREEN.CLEAR
    AVERAGE
    SCREEN.CLEAR
    TEXTS
    " HCL  PPM " YLABEL ":=
    .8 LABPOS :=
    MAKE.AXES
```

```

\ Begin data collection

  CR ." COLLECTING DATA "
  ZERO
  FX&IX [ 2 ] 1 DO
    KK 1 + KK :=
    KK XVALS [ I ] :=
      COLLECT
      COMMAND
      PROCESS.DATA

\ This section of code calculates the HCl concentration. First, it
determines
\ the transmissions of channels 1 and 2. It then calculates the water
\ concentration from the channel 1 data and uses it to subtract out the
water
\ contribution to the channel 2 data. With the corrected transmittance, the
\ HCl concentration is determined. If the value of the term -10000*lnT/L is
\ less than 25, the weak-line calibration is used. If it is greater, the
\ strong-line relation is used.

      RATIO1 IRAT1 / TAU1 :=
      RATIO2 IRAT2 / TAU2 :=
      TAU1 LN -4 / 100 * SLPW1 /
      WATERCON :=
      TAU2 LN -4 /
      WATERCON SLPW2 * 100 / -
      10000 *
      DUP
      25 <
      IF
        SLPH1 /
        HCLCONC [ I ] :=
      ELSE
        OFST -
        SLPH2 /
        **
        HCLCONC [ I ] :=
      THEN
      XVALS [ I ]
      HCLCONC [ I ]
 DRAW.LINE
 HCLCONC [ I ] OLDVAL :=
 DATAS SCREEN.CLEAR ." HCL CONCENTRATION = " HCLCONC [ I ] .
 ." PPM "
 TEXTS
 LOOP
;

\ This word prints only the values of the filter channels and their
\ respective ratios in the EVERY and AVERAGE windows. It requests a
\ number of points to be collected and, at the end of the collection,
\ prints the averages of the three ratios over this total number of
\ data readings. It is to be used in the field calibration process,
\ or whenever it is necessary to continuously display the channel signals.
\ (such as during alignment or while waiting for sensor warmup).
```

```
: FIELD.CALIBRATE

\ Begin data collection

  VUPORT.CLEAR
  DATAS
  SCREEN.CLEAR
  AVERAGE
  SCREEN.CLEAR
  TEXTS
  SCREEN.CLEAR
  ." NUMBER OF POINTS TO COLLECT? "
  GET.VALID.# NPTS :=
  SCREEN.CLEAR
  CR ." COLLECTING DATA "
  ZERO
  0 FSUM :=
  NPTS 1 DO
    KK 1 + KK :=
    KK XVALS [ I ] :=
      COLLECT
      COMMAND
      PROCESS.DATA
      FSUM CHAN2 [ I ] + FSUM :=
  LOOP
  FSUM 20 / CR ." AVERAGE COUNTS = " .
;

\ This word is used in the laboratory calibration process. It displays a
plot
\ of the transmittance of channels 1, 2, and 4. It also displays raw data in
\ the EVERY and AVERAGE windows, and the single-point transmission values
\ in the DATAS window.

: LAB.CALIBRATE
  VUPORT.CLEAR
\ Request user supplied inputs and produce axis of graph

  CR ." ENTER FULL TRANSMISSION RATIO (CH1) " GET.VALID.# IRAT1 :=
  CR ." ENTER FULL TRANSMISSION RATIO (CH2) " GET.VALID.# IRAT2 :=
  CR ." ENTER FULL TRANSMISSION RATIO (CH4) " GET.VALID.# IRAT4 :=
  CR ." INPUT Y MINIMUM " GET.VALID.# MX&MN [ 1 ] :=
  CR ." INPUT Y MAXIMUM " GET.VALID.# MX&MN [ 2 ] :=

  DATAS
  SCREEN.CLEAR
  AVERAGE
  SCREEN.CLEAR
  TEXTS
  " TRANS " YLABEL ":=
  .7 LABPOS :=
  MAKE.AXES

\ Begin data collection

  CR ." COLLECTING DATA "
```

```
  ZERO
  FX&IX [ 2 ] 1 DO
    KK 1 + KK :=
    KK XVALS [ I ] :=
      COLLECT
      COMMAND
      PROCESS.DATA
      RATIO1 IRAT1 / TAU1 :=
      RATIO2 IRAT2 / TAU2 :=
      RATIO4 IRAT4 / TAU4 :=
      OLDVL1 OLDVAL :=
      XVALS [ I ]
      TAU1
      DRAW.LINE
      OLDVL2 OLDVAL :=
      XVALS [ I ]
      TAU2
      DRAW.LINE
      OLDVL4 OLDVAL :=
      XVALS [ I ]
      TAU4
      DRAW.LINE
      TAU1 OLDVL1 :=
      TAU2 OLDVL2 :=
      TAU4 OLDVL4 :=
      DATAS SCREEN.CLEAR ." TRANSMITTANCES ARE: "
      TAU1 . TAU2 . TAU4 . TEXTS
 LOOP
;

\ This word saves data in two files: and ASYST formatted file that can only
\ be opened by ASYST, and an ASCII file that can be read with an ordinary
\ text editor. Specifically, the data that is saved is the 4 raw data arrays
\ (CHAN1-4), the HCl data array (HCLCONC), and the array of corresponding
\ data point numbers (XVALS).

: SAVE.DATA
  KK FX&IX [ 2 ] :=
  FILE.TEMPLATE
    HCLCONC []FORM.SUBFILE
    XVALS []FORM.SUBFILE
    CHAN1 []FORM.SUBFILE
    CHAN2 []FORM.SUBFILE
    CHAN3 []FORM.SUBFILE
    CHAN4 []FORM.SUBFILE
    FX&IX []FORM.SUBFILE
  END
  CR ." NAME OF ASYST DATAFILE? "
  "INPUT FILENAME ":=
  FILENAME DEFER> FILE.CREATE
  FILENAME DEFER> FILE.OPEN
    1 SUBFILE HCLCONC ARRAY>FILE
    2 SUBFILE XVALS ARRAY>FILE
    3 SUBFILE CHAN1 ARRAY>FILE
    4 SUBFILE CHAN2 ARRAY>FILE
    5 SUBFILE CHAN3 ARRAY>FILE
    6 SUBFILE CHAN4 ARRAY>FILE
```

```
      7 SUBFILE FX&IX ARRAY>FILE
   FILE.CLOSE

   CR ." NAME OF ASCII DATAFILE? "
   "INPUT DEFER> OUT>FILE
   KK 1 + 1 DO
   CR HCLCONC [ I ] . XVALS [ I ] .
      CHAN1 [ I ] . CHAN2 [ I ] . CHAN3 [ I ] . CHAN4 [ I ] .
   LOOP
   OUT>FILE.CLOSE
;

\ This word is used to input and plot HCl data from a saved ASYST file.
\ Only HCl concentration data can be plotted, so it can only be used
\ with files created by the MONITOR.HCl word (function key F7).

: VIEW.DATA
  CR ." NAME OF DATAFILE? "
  "INPUT FILENAME ":=
  FILENAME DEFER> FILE.OPEN
  0 HCLCONC :=
  0 XVALS :=
  0 CHAN1 :=
  0 CHAN2 :=
  0 CHAN3 :=
  0 CHAN4 :=
  1 SUBFILE HCLCONC FILE>ARRAY
  2 SUBFILE XVALS FILE>ARRAY
  3 SUBFILE CHAN1 FILE>ARRAY
  4 SUBFILE CHAN2 FILE>ARRAY
  5 SUBFILE CHAN3 FILE>ARRAY
  6 SUBFILE CHAN4 FILE>ARRAY
  7 SUBFILE FX&IX FILE>ARRAY
  VUPORT.CLEAR
  XVALS SUB[ 1 , FX&IX [ 2 ] ]
  HCLCONC SUB[ 1 , FX&IX [ 2 ] ]
  XY.AUTO.PLOT
  " HCL - PPM " YLABEL ":=
  LABEL.AXES
  FILE.CLOSE
;

\ This word runs the program. It assigns the various words to their
\ corresponding function keys and sets up the screen. Further program
\ control is then accomplished by hitting the function keys.

: RUN

\ Set up graphics display

  6 GRAPHICS.DISPLAY.MODE
  GRAPHICS.DISPLAY
  .3 .3 VUPORT.ORIG
  .7 .7 VUPORT.SIZE
  VUPORT.CLEAR
  LABEL.KEYS
```

```
    F1 FUNCTION.KEY.DOES SENSOR.ON
    F2 FUNCTION.KEY.DOES SENSOR.OFF
    F3 FUNCTION.KEY.DOES HOOD.OPEN
    F4 FUNCTION.KEY.DOES HOOD.CLOSE
    F5 FUNCTION.KEY.DOES LAB.CALIBRATE
    F6 FUNCTION.KEY.DOES FIELD.CALIBRATE
    F7 FUNCTION.KEY.DOES MONITOR.HCL
    F8 FUNCTION.KEY.DOES SAVE.DATA
    F9 FUNCTION.KEY.DOES VIEW.DATA
    CR ." IS HOOD OPEN? (1=YES, 0=NO) "
    GET.VALID.# DUP HOODVAR :=
    HOOD
    SCREEN.CLEAR
    1 = IF
    ." HOOD OPENED "
    ELSE
    ." HOOD CLOSED "
    THEN
    TEXTS
    CR ." IS SENSOR ON? (1=YES, 0=NO) "
    GET.VALID.# DUP SENSVAR :=
    SENSON
    SCREEN.CLEAR
    1 = IF
    ." SENSOR ON "
    ELSE
    ." SENSOR OFF "
    THEN
    TEXTS
;
```

APPENDIX D

MECHANICAL DRAWINGS

The system mechanical drawings that accompany the Sensor System Design Manual are listed in Table D.1.

TABLE D.1. LIST OF SYSTEM MECHANICAL DRAWINGS

Item	Drawing #
Border drawing	HCL-1
Fixed mirror mount	HCL-2
Adjustable mirror mount	" "
Adjustable mirror mount plate #1	HCL-3
Adjustable mirror mount plate #2	" "
Mirror hold-down devices	" "
Mirror mounting rods	HCL-4
Calibration cell holder	" "
Lens mounting plate	HCL-5
Lens mounting ring	HCL-6
Lens retaining ring, washer	" "
Back case mounting plate	HCL-7
Instrument cover	HCL-8
Filter wheel	HCL-9
Timing light mount	HCL-10
IR source form	" "
IR source insulation	" "
IR source insulation case	" "
IR source case	HCL-11
IR source rear retaining ring	" "
IR source front aperture and heat sink	"...."