TECHNICAL REPORT LWL-CR-03-P-68B

AIRBORNE VAPOR SURVEILLANCE SYSTEM

by

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Final Report
Contract No. DAAD05-70-C-0197

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U. S. ARMY LAND WARFARE LABORATORY
Aberdeen Proving Ground, Maryland 21005

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Atmospheric Monitoring	Personnel Detection	

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Contract number DAAD05-70-C-0197 was undertaken with the objective to construct and test two transportable vapor detection systems suitable for mounting on a variety of platforms, including rotary and fixed-wing aircraft and land vehicles. The equipment was designed to be fully computer controlled with on-line data processing and digitally controlled displays. Two different computers were used, and each is compatible with the system by way of an adapter/digital interface unit. Prior to completion of construction, the systems were diverted

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from their multipurpose role to a specific application of national interest at the time. Extensive operational tests were conducted with each unit. The first was installed in a van and the second in a fixed-wing aircraft. Both performed satisfactorily against the target materials and such difficulties as occurred were to a large extent resultant from the intense pace of the program and lack of experience with the equipment. From the test data in this program it can properly be inferred that the equipment should perform well for targets of Army interest such as explosive reclamation facilities and contraband. Although little testing has been carried out with these targets, the demonstrated sensitivity in the part per billion range for trace vapors should allow satisfactory detections.

FOREWORD

This contract is a continuation of work started under contract No. DAAD05-68-C-0335. Under this contract a feasibility breadboard mass spectrometer detection system was developed and field tested. The purpose of this contract was to develop an improved system with an on-line computer to operate the system and process the data. This system was to be suitable for installation in a helicopter or ground vehicle and was to have a real-time read-out of target detections. The system was designed to be used for plume intercept detection of effluents generated or given off by the target. The original targets envisioned to be of interest to the Army included concealed personnel, explosive reclamation facilities, and caches of explosives. During the course of the contract other targets such as caches of narcotics and atmospheric pollutants became of interest and were also considered.

This effort was sponsored by the US Army Land Warfare Laboratory (USALWL), Applied Physics Branch, under the technical supervision of H. Clay McDowell. This project was designated 03-P-68, Vapor Surveillance.

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I. INTRODUCTION

The feasibility of a transportable membrane separator-mass spectrometer system for the detection of trace vapors in the ambient atmosphere was demonstrated under Contract No. DAADO5-68-C-0335. In this contract, sponsored by the US Army Land Warfare Laboratory (LWL), Varian Associates developed a system which permitted detection of organic materials in the atmosphere at levels as low as one part per billion. Measurements with the system could be made with either analog or digital control and output formats. Digitally-recorded data could be processed off line with laboratory computer equipments.

The demonstration of the forerunning equipment and its use in a series of field tests led to a decision by the Army to develop an instrument more specifically designed for vehicular and airborne installation, with provision for on-line data processing and display to exploit further the capability of trace vapor detection and analysis against a variety of targets. Accordingly, a program to develop and test such equipment was entered into under Contract No. DAADO5-70-C-0197.

As the equipment was being developed, in addition to earlier applications contemplated, the capability of the equipment to detect a specific class of chemicals became of great interest and dominated much of the program during the remainder of the contract. Several government agencies engaged in a fruitful collaboration to explore the feasibility of the instrumental approach and to test the equipment developed under DAADO5-70-C-0197 in several realistic simulations. Many of the actual tests were conducted under separate contracts, including DAADO5-70-C-0109 and DAADO5-72-C-0091, and are separately reported. This report will be principally concerned with the development and engineering of the two systems, and with the first use of full on-line computer control and data processing incorporated.

II. VAPOR DETECTION SYSTEM DESCRIPTION AND CONSTRUCTION

Earlier work showed the utility of the Llewellyn membrane separator for direct air sampling of trace vapor samples. The principal benefit of this device lies in the enrichment of the sample relative to the total load of air gases presented to the (high vacuum) analyzer used. Without the separator, a mass spectrometer applied to part-per-billion detection would be faced with a hopeless problem of dynamic range requirement, as well as one of total sample limitation due to constraints of its high-vacuum pumping needs. The use of the membrane separator, which allows sample enrichment by factors as great as 10^5, brings both the dynamic range requirement for the mass spectrometer and the vacuum pumping needs with adequate sample transmission into manageable proportions.

The predecessor system also demonstrated the suitability of the quadrupole mass spectrometer to the requirements of a vapor detection system which was digitally controlled and adapted to rapid scanning of ion peaks in a spectrum. The quadrupole is stable and may be swept rapidly and repeatably by a linear command signal. Its source sensitivity for ion masses at least up to M/e = 200 is quite good, and its construction can be relatively small and light weight.

For data processing and analysis of spectrometer response to specified target materials, the small and relatively inexpensive "mini computers" offer more than adequate performance and internal memory. The equipment furnished used two different mini computers, one a standard Varian model 620 i, and the other a Rolm Nova militarized computer system. While the militarized version has some remarkable environmental specifications and has the advantage for size, weight and power consumption, the less-expensive standard computer proved to be quite adequate in terms of reliability in the service demands made of it. Software was developed in a format which was easily translated into the language of either computer, with algorithms designed to increase the perception of detection events.

The overall system is built up of a number of functional components as shown in the block diagram (see Figure 1). The principal components of this system are described in the sections below.

A. INLET AND SEPARATOR

Sample air is drawn into the separator via an inlet tube at flow rates of 1 to a few milliliters per second. A variety of inlet tubes has been used. The principal requirements of the inlet tube are:

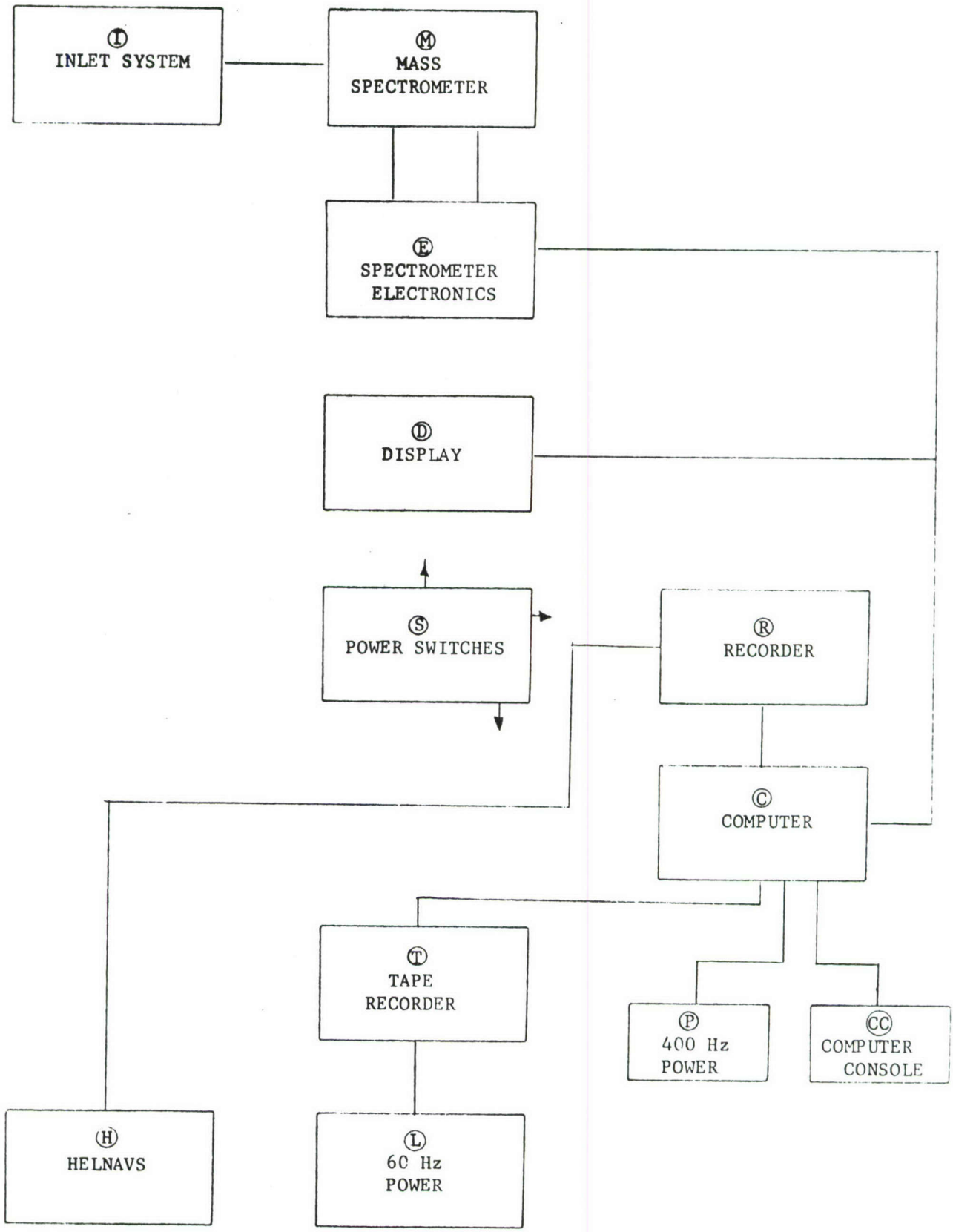


Figure 1. Block Diagram of Vapor Detection System (Configuration for U-10 Installation)

(1) That it be noncontaminating and leak free;

(2) That it have a minimum effect of partition or trapping of the trace sample materials (this requirement has usually been accommodated by use of stainless steel tubing heated to 100 - 150°C);

(3) That the transmission time from the entry to the separator be short. For long inlets, large-bore tubing with fast air flow serves to bring the ambient sample quickly to a short section of smaller bore, where flow rates of 1 mℓ per second can be used.

The separator itself is a three-stage device patterned after the separator used previously. It is pictured schematically in Figure 2 along with analogous electrical diagrams showing the conductance of both air gases and sample vapors to the various ports. In the figure, the membranes M_1, M_2, M_3 are mounted on stainless steel discs, as shown, captured in gold wire sealing rings to form the sealed chambers S_1, S_2, S_3. The conductance properties of the membrane in the 2 cm size used are such as to transmit the air gases with a conductance $G^{(A)} \cong 10^{-6}$ liter per second, and to transmit the sample with conductance $G^{(S)} \cong 10^{-3}$ liter per second. These conductances are called out respectively in the diagrams B and C of Figure 2.

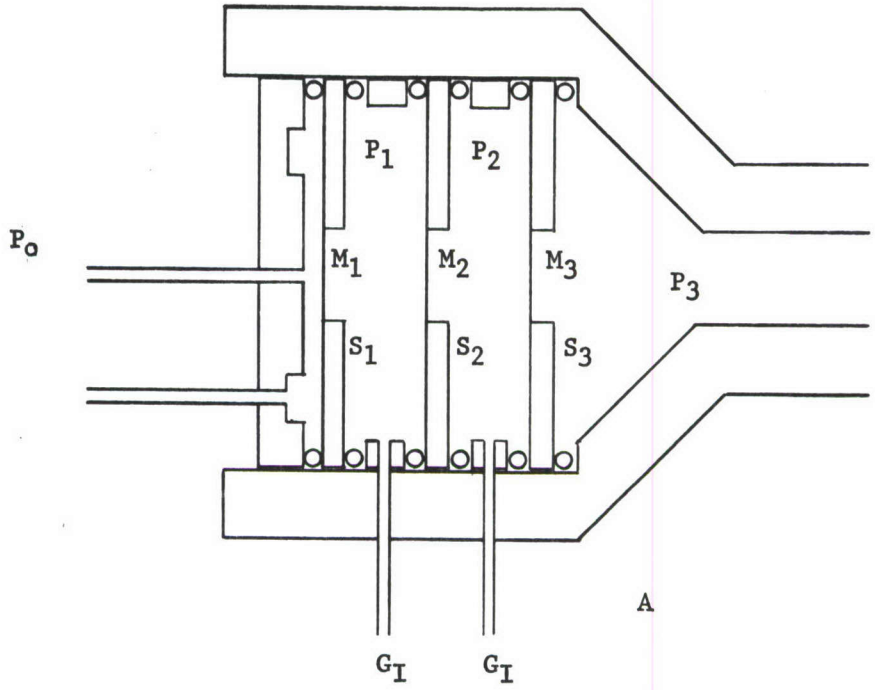
Enrichment of the sample will occur if $G^{(I)}$ of the interstage pumping port is much larger than $G^{(A)}$. It may be taken to be comparable to $G^{(S)}$. In this case, approximate values may be found for the pressures of air and sample in the high vacuum chamber S_3, given $G^{(V)}$, the conductance of the high vacuum pump equal to approximately 1 liter per second. Pressures are stated in atmospheres:

$$P_o^{(A)} = 1$$

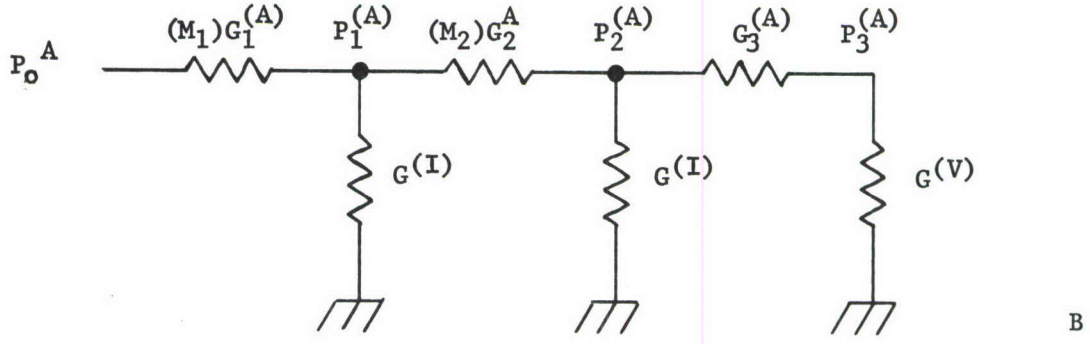
$$P_1^{(A)} \cong \frac{G_1^{(A)}}{G_1^{(I)}} P_o = 10^{-3} \text{ A}$$

$$P_2^{(A)} \cong \frac{G_2^{(A)}}{G_2^{(I)}} P_1 = 10^{-6} \text{ A}$$

$$P_3^{(A)} \cong \frac{G_3^{(A)}}{G^{(V)}} P_2 = 10^{-12} \text{ A} \cong 10^{-9} \text{ Torr}$$



For N_2, O_2, A, He, H_2O, etc



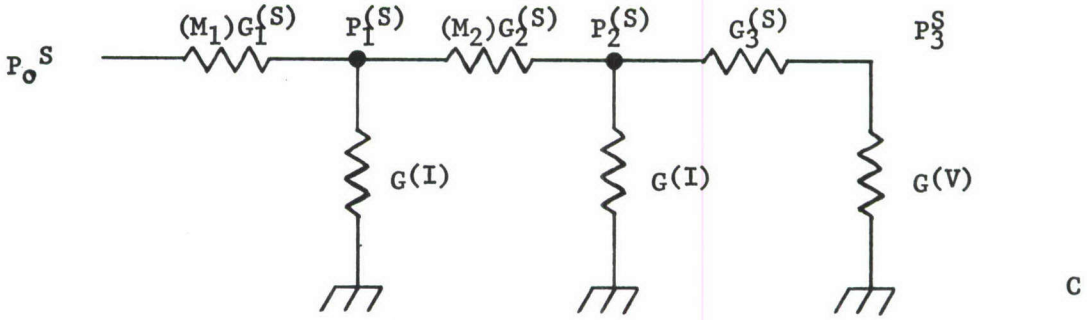


Figure 2. Detail of Membrane Separator

$$P_o^{(S)} = 10^{-9}$$

$$P_1^{(S)} \cong \frac{G_1^{(S)}}{G_1^{(S)} + G^{(I)}} = 5 \times 10^{-10} \text{ A}$$

$$P_2^{(S)} \cong \frac{G_2^{(S)}}{G_2^{(S)} + G_2^{(I)}} = 2.5 \times 10^{-10} \text{ A}$$

$$P_3^{(S)} \cong \frac{G_3^{(S)}}{G^V} = 2.5 \times 10^{-13} \text{ A} \cong 2.5 \times 10^{-10} \text{ Torr}$$

From these approximate expressions, what was to begin with an air-to-sample partial pressure ratio of 10^9 has become a ratio of 4. (In fact, transmissions are somewhat different from the values shown, and in practical cases with interstage pumping adjusted for optimum transmission and time constants, sample enrichment is more nearly in the range of 10^6 giving an air-to-sample ratio of 10^3.)

B. IONIZER

Molecules of air and sample passing the separator are ionized by electron impact. The ionizer used is based on the inverted diode patterned after the Alpert high-vacuum gauge tube. This particular ionizer was fabricated by Uthe Technology, Inc., and is the standard ionizer used in the UTI Model 100 B quadrupole mass spectrometer. It was adapted and mounted to the Varian MAT quadrupoles used in the systems. This ionizer represents a substantial improvement over the original one supplied with the MAT quadrupoles in the specification of source sensitivity, operating life time, and reliability. Figure 3 shows the construction of the ionizer. Electrons furnished by the heated filament, C, are accelerated to an energy of about 70 volts by the field between the anode A and the shield S. Most of the electrons pass through the open structure of the anode into the ionizing region, I, where they may collide with a molecule to give an ion. Electrons which do not collide on the first pass will traverse the structure and be reflected by the shield to return to the ionizing region several times before being captured by the anode. They will always be at the same energy within the anode structure. Positive ions (+), formed in the ionizing region, will be attracted to the focus electrode F, which is at a negative potential, and will be drawn out to the quadrupole structure through its aperture. This ionizer has proven to be very reliable and satisfactory in its performance.

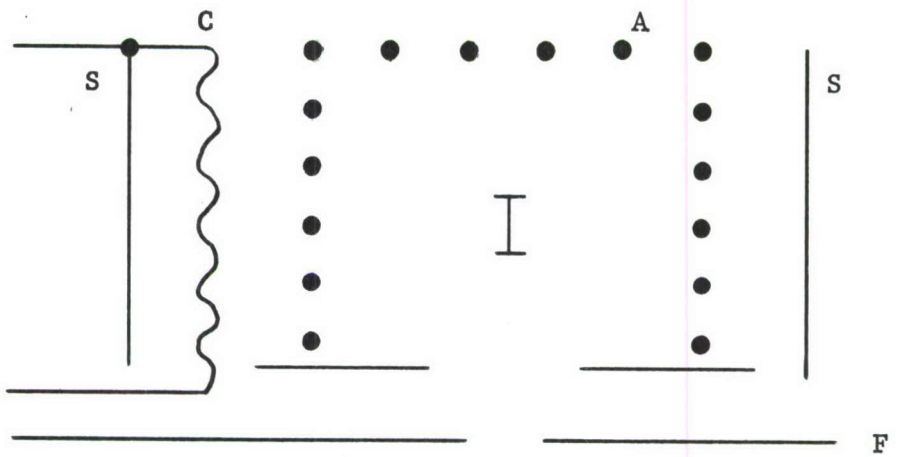


Figure 3. Ionizer Structure

C. QUADRUPOLE MASS FILTER

The quadrupole mass filter is a structure of four conducting rods which extend longitudinally along the path of ions formed in the ionizer. The rods are excited with dc and rf potentials whose fields in the ion path, as determined by the details of the rod shapes, allow the transmission of ions of selected mass-to-charge ratio. The performance of the quadrupole mass filter is critically dependent on the precision of its geometry and on the stability of the rf and dc potentials applied. Figure 4 is a schematic representation of the quadrupole structure. Ideally, the inward-facing surfaces of the rods should have contours of equilateral hyperbolae. With proper spacing, the cylindrical rods approximate these contours satisfactorily for the resolution required. In the transverse plane of the structure, electric potentials in the central region can be described by the expression:

$$V(x,y) = (y^2 - x^2)(A + B\cos\omega t) \tag{1}$$

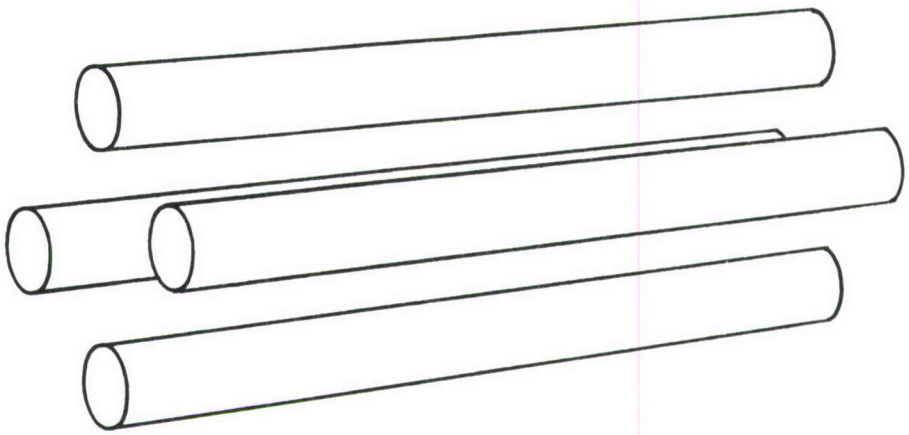
and the accelerations of a particle of charge e and mass M are given by

$$\frac{d^2x}{dt^2} = \frac{2e}{M}(A + B\cos\omega t)\,x \tag{2}$$

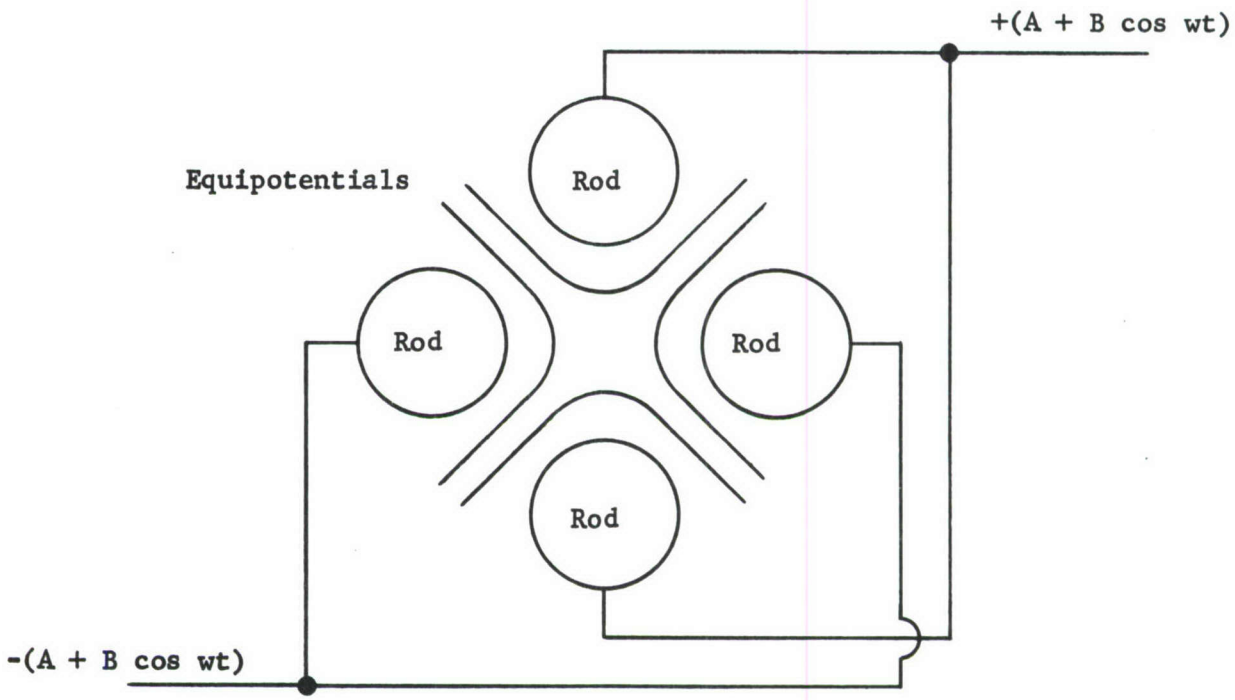
$$\frac{d^2y}{dt^2} = -\frac{2e}{M}(A + B\cos\omega t)\,y \tag{3}$$

where A and B are the amplitudes of the dc and rf potentials and ω is the circular frequency of the rf.

The equations of motion for the ions have the general form of the Mathieu equation. For a given value of the mass-to-charge ratio M/e, there is a range of values of A, B, and ω for which solutions of both (2) and (3) are stable. These solutions describe the motion of a particle which will be passed longitudinally through the mass filter. Other solutions for the same A, B, and ω but different M/e can be unstable in x or y or both, and the motions of such particles will be divergent in the transverse direction. These particles will not be passed through the mass filter. By proper adjustment of A, B, and ω, the mass filter can be used to transmit very narrow bands of M/e (and hence M). For this condition, the ratio of A to B is constant and approximately equal to 1/6, while the values of A and B are directly proportional to M/e with constant ω.



A. Quadrupole rods



B. Transverse Section

Figure 4. Quadrupole Mass Filter

The geometrical precision of the structure used in the quadrupole must be very carefully preserved to retain high transmission for a very narrow range of masses, (1 AMU resolution). The characteristic radius in the MAT quadrupole is about 4 millimeters, and precision to one part in 1000 or 0.004 mm is required of the entire structure. The quadrupole rods are assembled in quasi-kinematic supports to achieve and retain the precision, and the materials of construction are chosen having thermal expansion coefficients such that changes in temperature will not destroy the geometrical relationships.

The mass filter, along with the ionizer and the electron multiplier (see below), are housed in a stainless steel high-vacuum enclosure which is pumped by a VacIon® pump to operating pressure in the 10^{-6} Torr range.

D. ELECTRON MULTIPLIER

In order to increase the speed and sensitivity of detection, the mass spectrometer is furnished with a 16-stage electron multiplier. This commonly-used element is distinguished by a special geometry applied to the structure to reduce the otherwise troublesome photo-electric background levels found in conventional multiplier installations.

As mentioned above, ions in the mass filter which are not transmitted will be unstable laterally and will eventually collide with the rod structure with energy equal to the maximum rf plus dc potentials. Such collisions have a probability of dislodging secondary electrons which themselves can further strike the rods and generate photons. These photons are sufficiently energetic to give rise to photo electrons in the electron multiplier which can contribute a substantial background current. The confirmed level of this background current is found to be directly proportional to the intensity of screened-out ions, and is approximately proportional to the square of the rf-dc voltage levels.

In addition to the photo electrons generated by the two-step process described above, photo electrons resulting from direct exposure of the multiplier to illumination by the ionizer filament can also occur. Both of these sources are almost completely eliminated in the mounting arrangement by the simple expedient of removing the multiplier from the optical path to the sources. The input to the multiplier is operated at negative voltages of as much as -3 kV. This creates electric fields which draw most of the ions energing from the mass filter into a curved path for detection with the multiplier.

E. MASS SPECTROMETER AND VACUUM SYSTEM ASSEMBLY

The mass spectrometer with its membrane separator is mounted together with the vacuum system in an enclosed frame dimensioned to fit in a standard relay rack. Electrical connections are made via connectors on the rear. The entire assembly occupies 5-1/4 inches of vertical rack space. Placement of the parts is shown schematically in Figure 5. The high-vacuum analyzer housing is attached with a bellows coupler directly to the 15 ℓ/s VacIon pump which maintains vacuum, ideally at pressure in the 10^{-6} Torr range. A manually-closed valve, V_1, interconnects the high-vacuum section with the second interstage canister and canister replenishment facility to provide for initial pumpdown.

Two zeolite canisters are provided to furnish the interstage pumping needs. These canisters provide sufficient pumping reserve for a day's operation before requiring replenishment. The system is provided with valves and quick-disconnect fittings to facilitate the daily replenishment service. In addition, special fittings are attached to the interstage pumping lines for the connection of one-shot storable pumped canisters which can be applied on the front panel in emergency. These fittings are provided with vacuum seals to isolate the emergency canisters from atmospheric pressure with a very small captured volume, transfer valves to shift the interstage lines to the emergency canisters, and cutters to breach their seals. (Although the application of emergency canisters has been satisfactorily tested, they have never been required in actual service.)

Details of the vacuum valving system not apparent in Figure 5 are shown in Figure 6. It should be noted that proper sequencing of valves is mandatory in order not to apply back pressure to the separator membranes. Failure to observe the proper sequence may rupture the membranes.

One additional element is housed with the spectrometer and vacuum system; namely, the oscillator, modulator and final amplifier for the rf source. This element is best located near the spectrometer to avoid the impedance problems and microphonics of long cables.

F. MASS SPECTROMETER ANALOG ELECTRONICS

The electronics required to furnish all the analog services, including individual power supplies, is housed in a chassis which is dimensioned to fit into a standard relay rack with a rack height of 5-1/4 inches. Manual controls as required are placed on the front of this chassis, and interconnect cable connectors are placed at the back. The location of the various elements of this system are shown in plan form in Figure 7. The functions of the principal elements are described in the sections following.

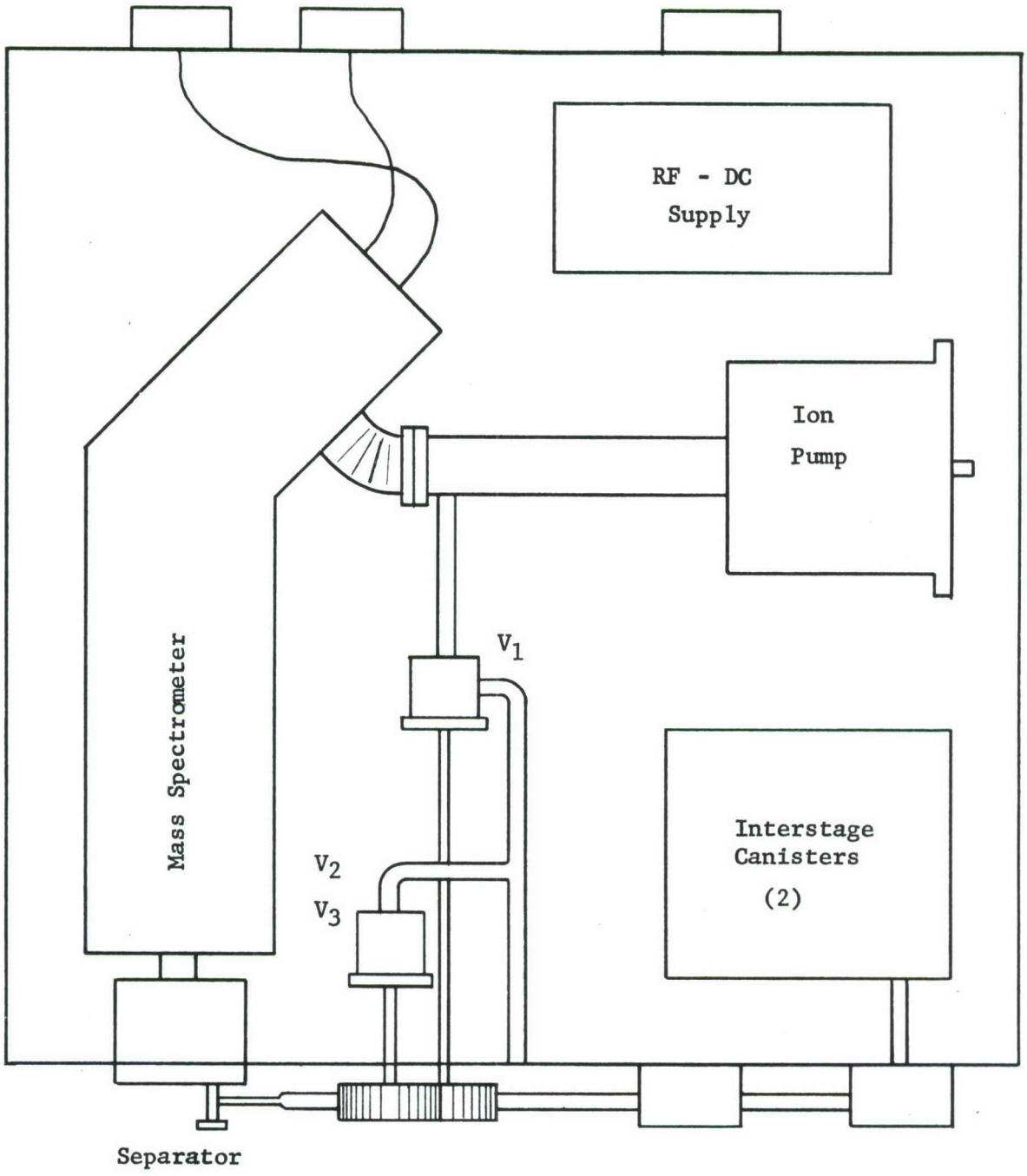


Figure 5. Mass Spectrometer and Vacuum System

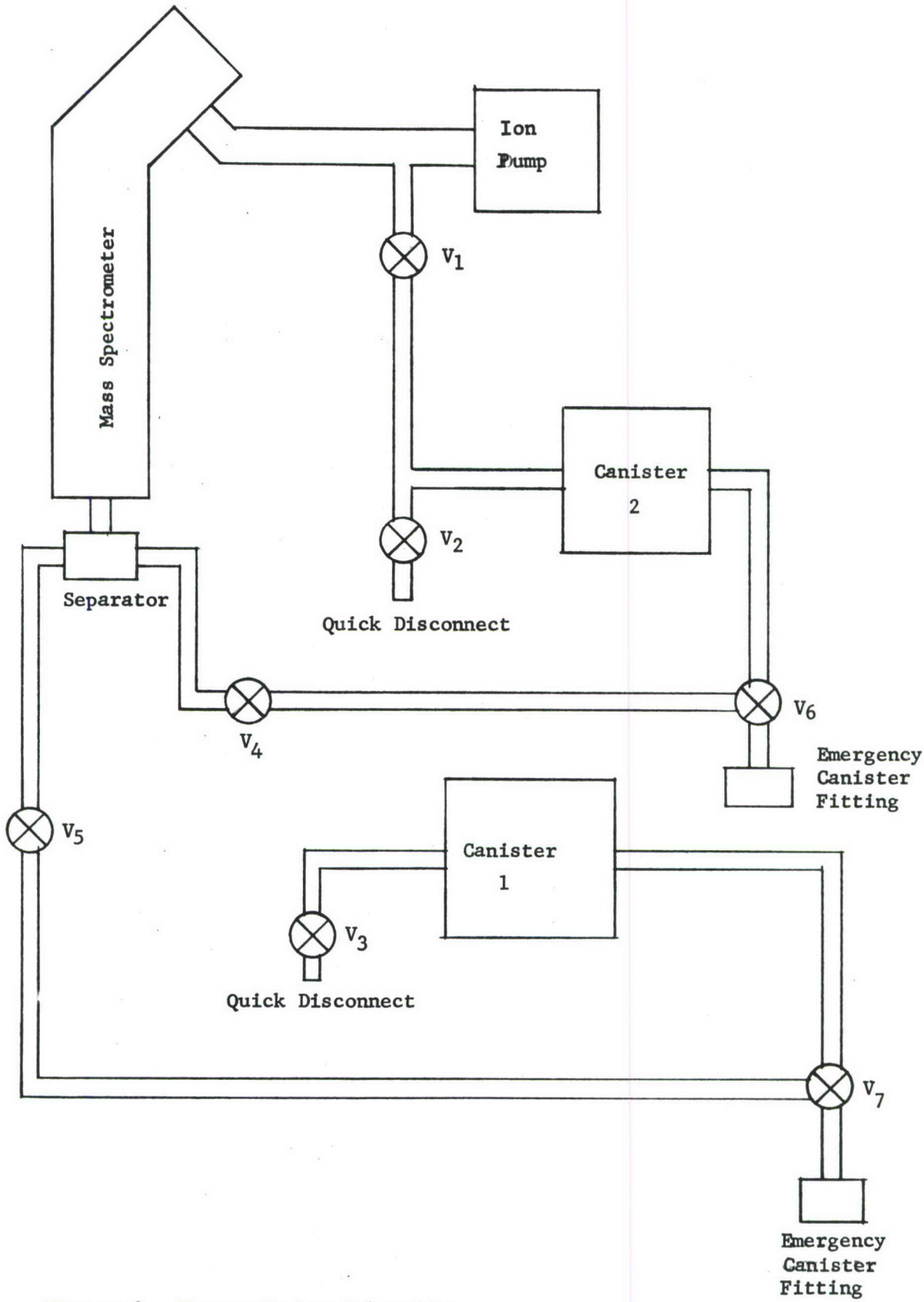


Figure 6. Vacuum System Schematic

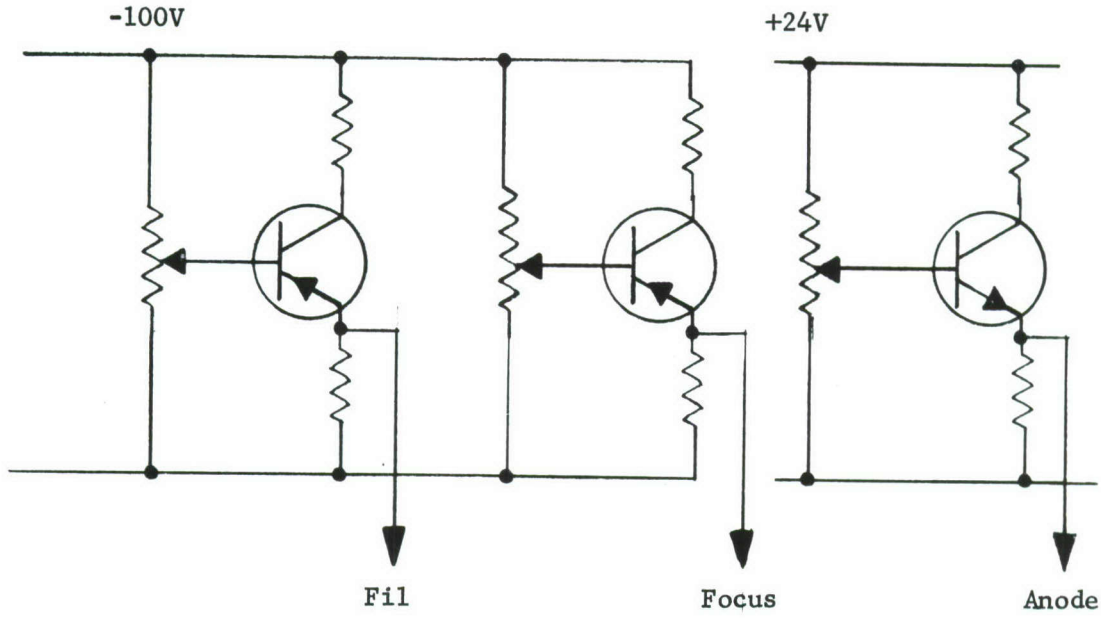


Figure 7. Ionizer Electrode Supplies

1. Ionizer and Filament Supply

The ionizer is provided with three adjustable power supplies to furnish the necessary bias to its elements. These supplies are maintained from simple emitter-follower drivers with Zener diode stabilization and potentiometer adjustment provided on the source board. Filament bias is normally set at -55 volts. The anode supply is set at approximately +15 volts, which also provides the ion energy setting. The focus electrode is set for best transmission and line shape, usually at about -30 volts.

The filament itself is driven by a commercial low-voltage power supply which has been modified to be programmable by an external control current. Filament temperature governs the electron emission, and is set by a servo which maintains a constant electron emission in accordance with the setting of a manual control switch. A schematic diagram of this servo is shown in Figure 8. The emission current is measured by the resistance, R_1, which terminates at +15 volts. When a current of 1 milliampere flows in the selected resistance of 15 kΩ, input to the servo amplifier, A, is at the neutral point and the filament power supply control current from the collector of Q_1 is stabilized. Any deviation from the nominal emission current generates the appropriate correction of the control current furnished by Q_1, thereby correcting the emission current to the nominal 1 milliampere.

2. Analog Sweep Generator

A conventional integrating ramp generator is provided to supply an analog sweep for operation of the spectrometer. Sweep rate, sweep width and sweep starting mass may be controlled from front panel settings. When computer sweep control is used, the manual sweep generator is switched off. The operation of this sweep generator is shown schematically in Figure 9. The ramp generator, A1, provides a ramp which rises to a fixed amplitude which is sensed by the reset sensor, A2. When the reference level is reached, A2 resets the ramp generator by means of the reset relay. Ramp slope which governs sweep time is controlled by switch Sw 1. The ramp signal is fed to the sweep summing amplifier, A3, via switched resistors which, by selection, determine the total sweep width. Into the same summing junction, the starting mass control current is added, and the output of A3 provides the desired sweep signal to the spectrometer control line. Control on this line is at about 100 AMU per volt.

3. Rf-Dc Drivers

The sweep control voltage coming from either the analog sweep generator or the computer is led first to a precision unity gain inverter. This circuit provides the control for the quadrupole-rod dc driver amplifiers which operate with precisely fixed gain. The outputs of these driver amplifiers are applied directly to the return lines of the final rf output transformers, thereby supplying the dc voltage required by the quadrupole rods.

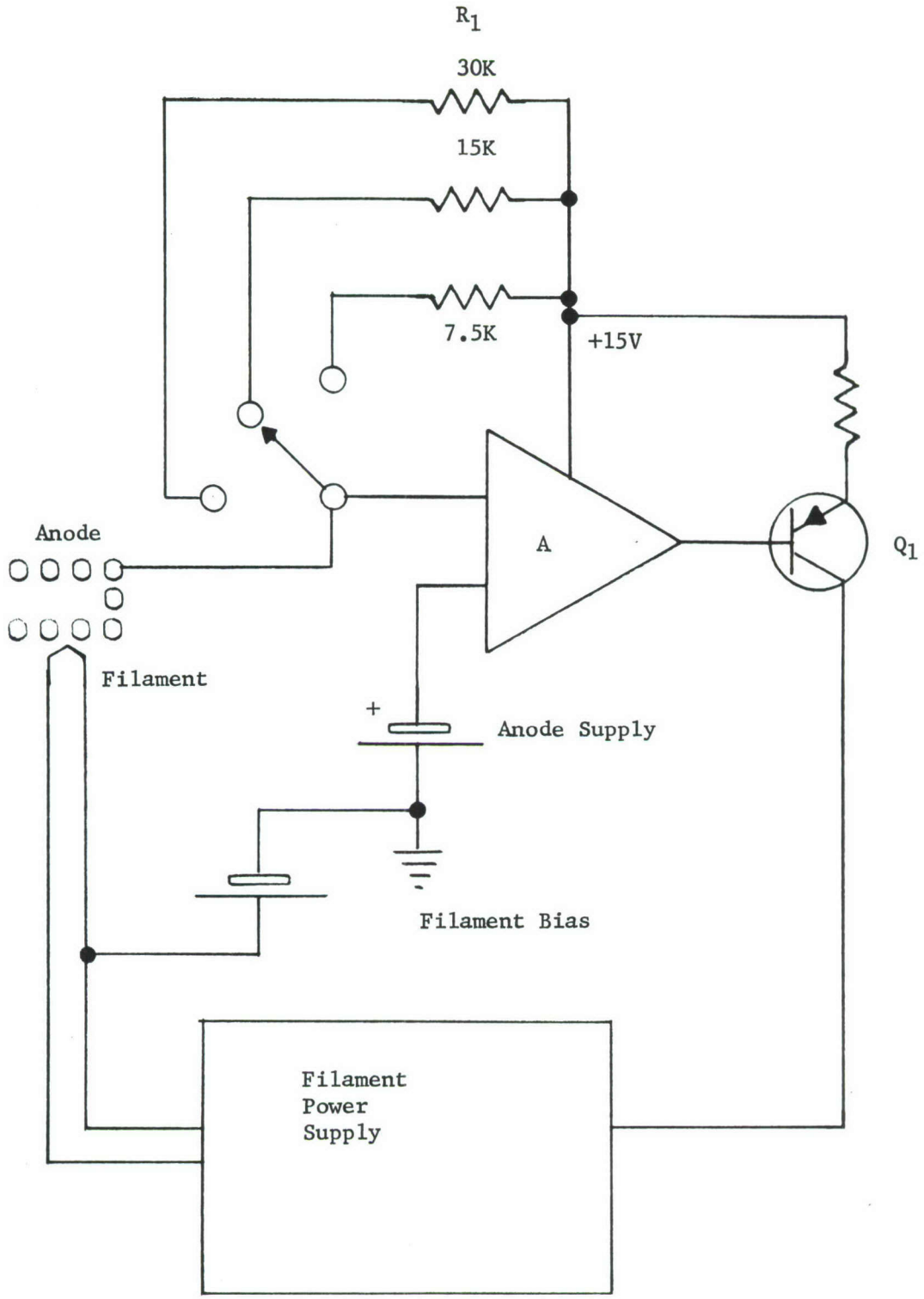


Figure 8. Filament Power Supply Regulator

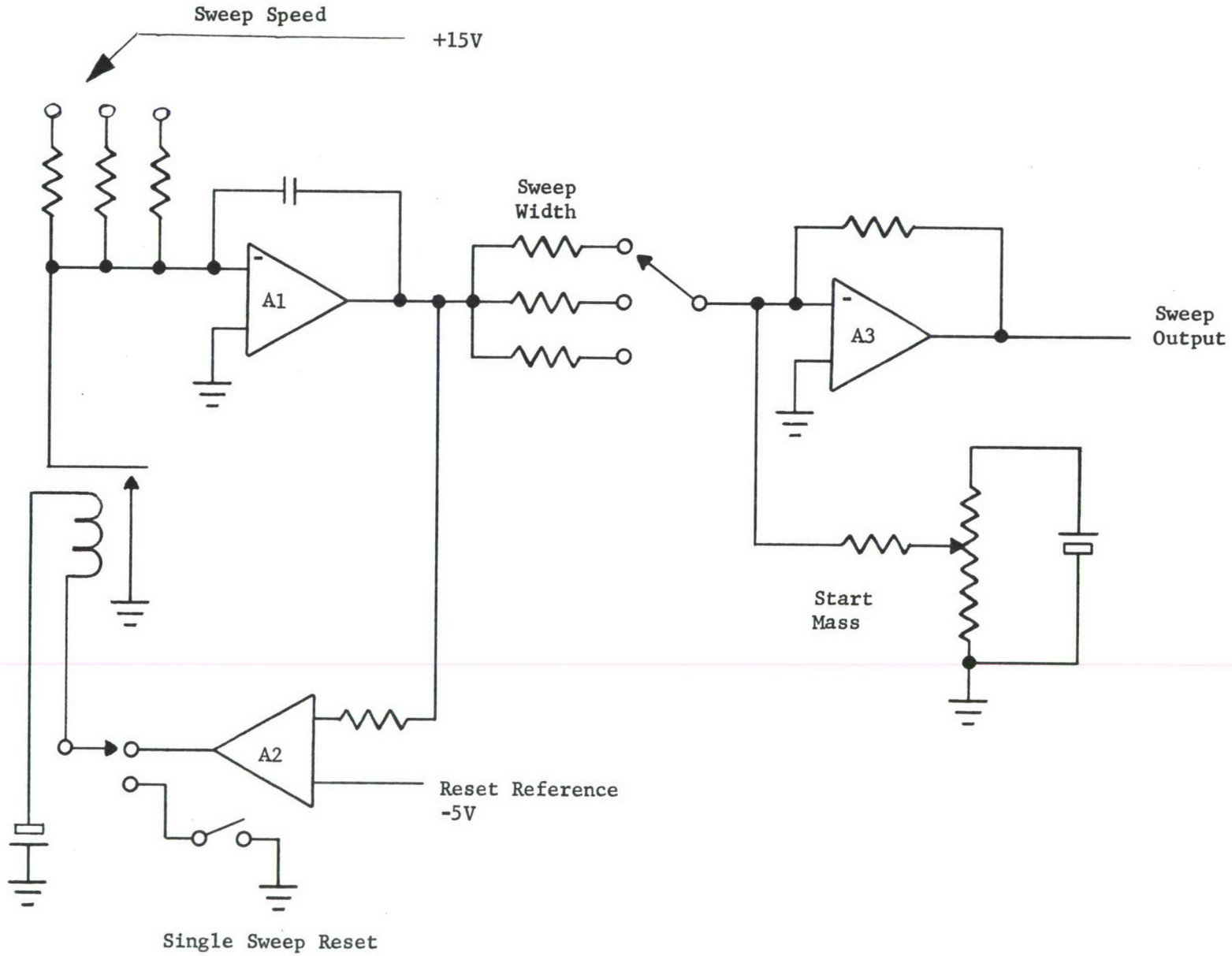


Figure 9. Sweep Generator

The sweep control voltage is also applied to the rf servo control, where it is compared with the output of the rf voltage sensor to generate a suitable modulator signal.

The rf-dc system is diagramed schematically in Figure 10. In this figure, the sweep control signal is applied at S. The unity gain inverter A1 provides the mirror signal $\overline{S}$. These two signals are first amplified by A2 and A3 to furnish driving signals for the high voltage amplifiers Q2, Q1 and Q3, Q4. The outputs of these amplifiers are fed back to the inputs of A2 and A3 to provide precise gain from S and $\overline{S}$. The outputs also connect to the rf ground ends of the two coils on the rf output transformer as shown.

The inverted sweep control $\overline{S}$ is also directed to the rf servo amplifier A4 via an adjustable resistor which determines the rf-dc ratio. The output of this amplifier, determined by the comparison of the voltage from $\overline{S}$ to the voltage from the rf detector, drives the modulator in the rf chain. This modulator corrects the output of the rf power amplifier, Q5, to apply the proper rf voltages to the rods via the rf output transformer.

4. Autoranging Electrometer

One of the major problems in examining an unknown and uncontrolled mixture of samples lies in the dynamic range of detection required. This problem for the case of the mass spectrometer is compounded by the fact that in a normal background situation, not to mention the presence of samples, peak intensities may vary by a factor of 100 or more between masses 40 and 140. A single electrometer range setting will not accommodate measurement of the smallest peaks without, at the same time, giving saturation at the larger peaks. To accommodate this problem, an autoranging integrating electrometer was devised. The scheme of this electometer is shown in Figure 11. Amplifier A1 has a high gain and an input impedance of $10^{12}\ \Omega$. Due to the feedback arrangement, a current supplied at the input deposits its charge on one or more of the capacitors whenever X4 is open. If X1, X2, X3 are open, the charge builds up on C, leading to an output voltage

$$V = \int_0^T \frac{i}{c}\, dt \quad .$$

When the current is small, the value of V during the computer-controlled integrating time, T, does not rise above the reference level, V_R, applied to the sense amplifier A2 and X1, X2, X3 stay open. If the current is sufficiently high, the voltage, V, will reach the value of V_R before the end of time T. At this point the switch X1 will be closed by the action of A2 and the logic. When the switch is closed, the total

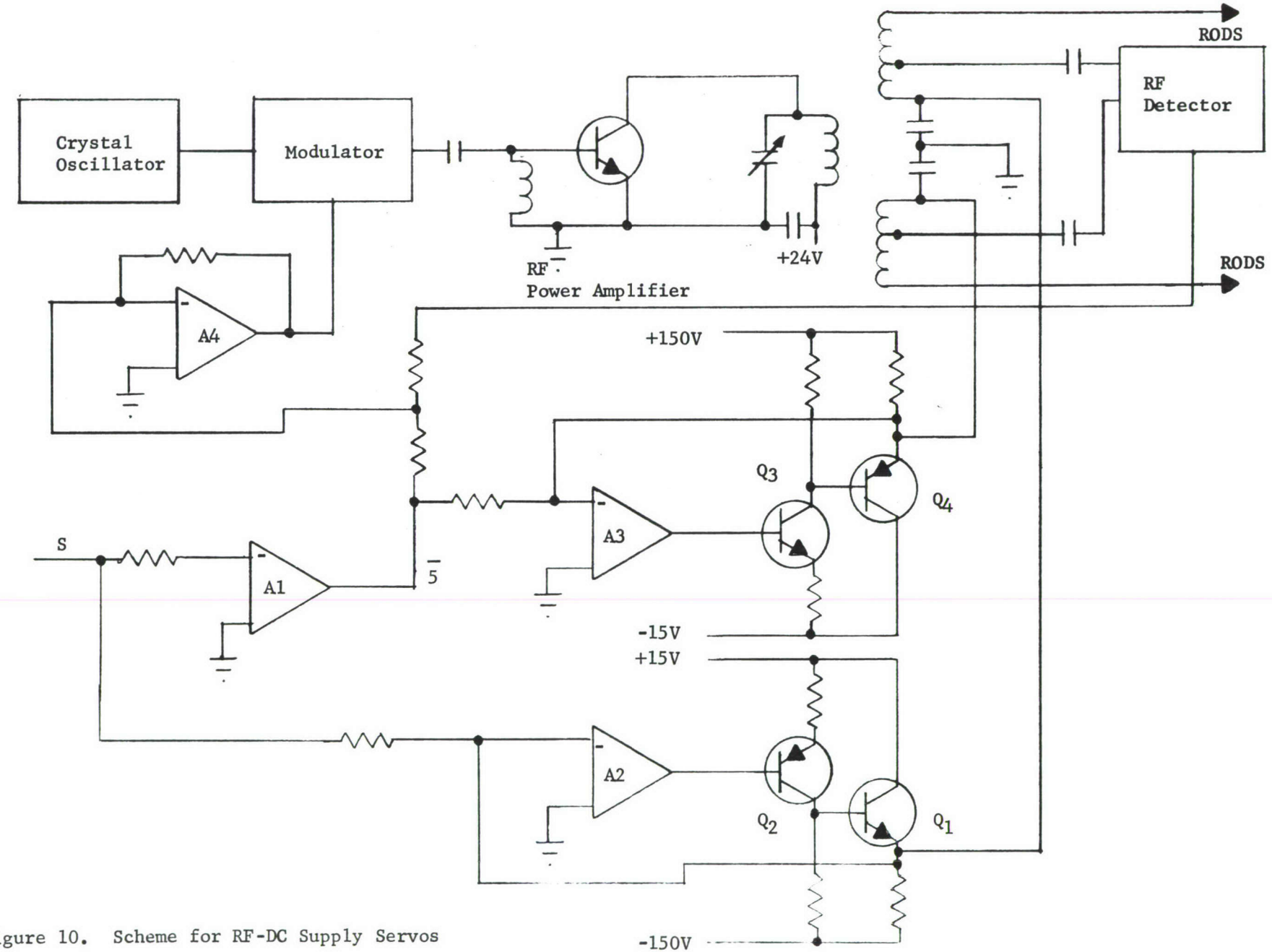


Figure 10. Scheme for RF-DC Supply Servos

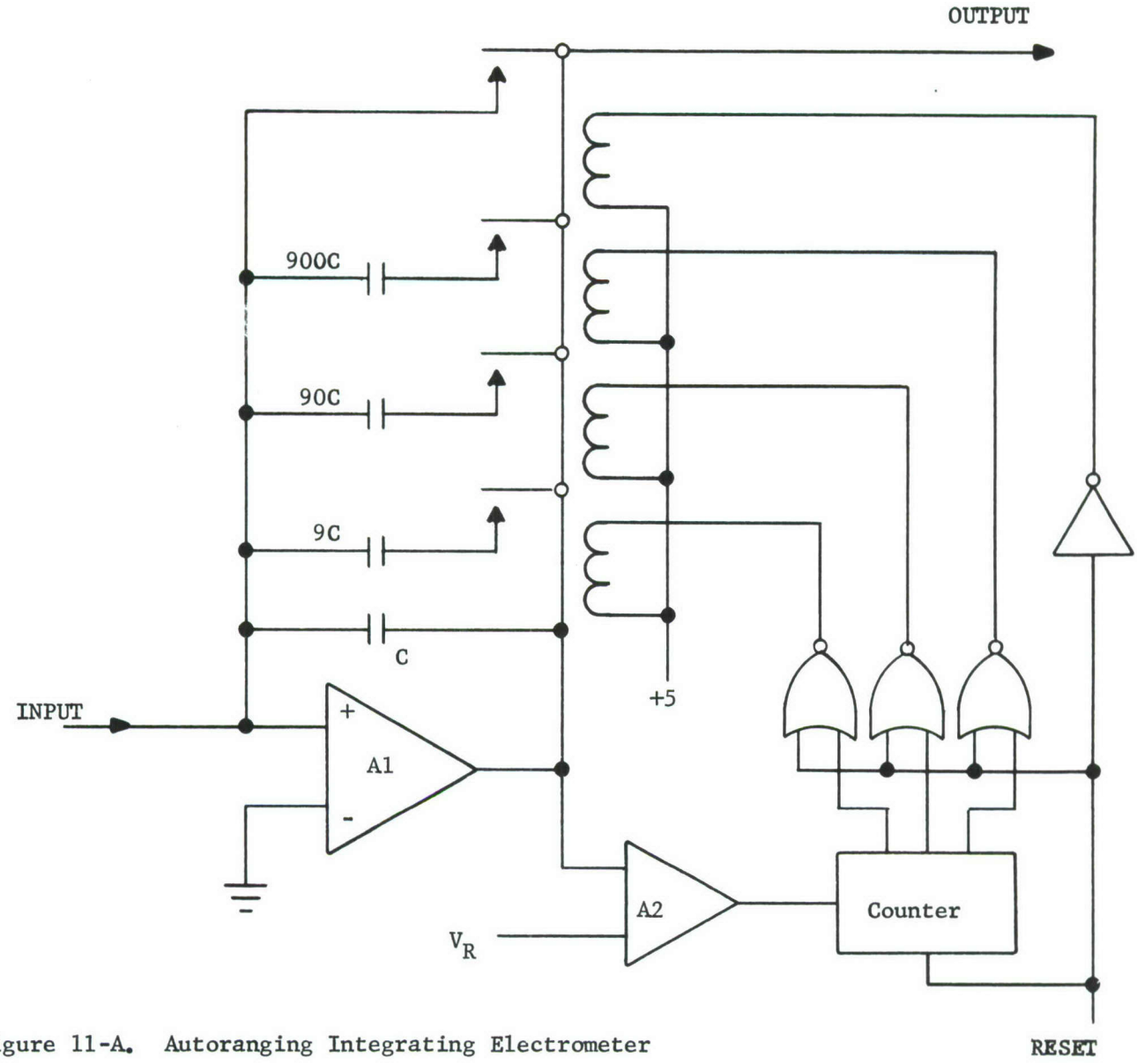


Figure 11-A. Autoranging Integrating Electrometer

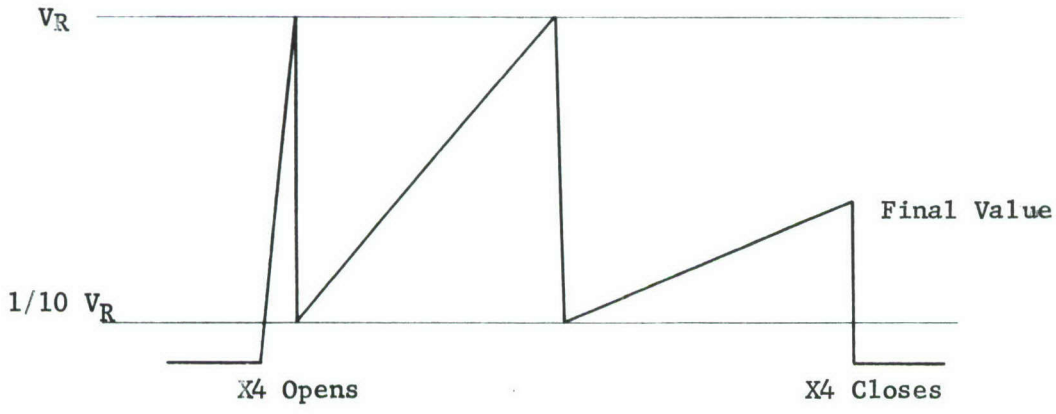


Figure 11-B. Waveform for Moderate Current

capacitance in the circuit is increased by a factor of 10, the charge originally lodged on c is now distributed to c and 9c, and the voltage V drops to 1/10 V_R. This process can be repeated through X2 and X3 for large currents, leading to an improvement in dynamic range by a factor of 1000.

Upon completion of the integrating cycle, the computer can read the final value of the output voltage and the switch positions to acquire a reading of the integrated input current. When this value is registered, the computer can issue a signal to reset, and all of the capacitors are discharged by X4.

In addition to circuits performing the functions described above, the analog electronics section houses the various power supplies required for these functions and, in addition, high voltage power supplies for the ion pump and the electron multiplier. Other requirements of the system are served by temperature-control circuits for heating the mass spectrometer and separator and an interlock system which disconnects the ionizer, the rf-dc circuits, and the electron multiplier when a vacuum overpressure is sensed.

G. COMPUTER AND DIGITAL ELECTRONIC SYSTEM

The mass spectrometer system is basically an analog device. It is capable of generating spectroscopic data at a rate far in excess of an operator's capacity to interpret. Moreover, in a detection scenario, the memory span of an operator is not sufficient to keep track of the continuously moving situation. Finally, the detection of trace levels of target materials in the presence of a large coherent and changing background situation is difficult even for a practiced operator. These difficulties can be substantially ameliorated by the use of a digital computer, both to control the spectrometer and to store and process the data generated.

The ability of the computer to aid in data interpretation was demonstrated with off-line processing in an earlier project under Contract No. DAAD05-68-C-0335. In the present systems, computers are used on line to control and to process data. The standard digital minicomputer has adequate computational capacity to perform the functions required using a memory of 4096 words. Since the format of the computer is digital, a digital-to-analog interface is required. This function is provided in a very standard and conventional way.

The contract required that two different computer systems; namely the Varian 620 and the militarized ROLM-NOVA be fitted interchangeably to the mass spectrometer systems. Interfacing requires, in addition to the digital-to-analog and analog-to-digital conversions, a series of control and sense lines for status monitoring and system control. For simplicity of operation, a cycling stored program in the computer is required, and this software must be adapted to the needs of the specific vapor detection operations undertaken.

The basic computer installation is shown in block form in Figure 12. The two computers differ in that the ROLM-NOVA had DAC and ADC functions internal to itself whereas for the 620 these components are external. The adapter unit is required specifically for just one of the two display units furnished. Only one adapter unit was furnished. It performs the function of a digital interface with facility to address eight separate registers of 16 bits and to read eight separate 16 bit input busses. These functions were used in conjunction with the display and control unit having digital entry and display capability. The adapter connects directly to the data buss of either computer and performs the input and output data routing required. Its organization scheme is shown in Figure 13. The ROLM-NOVA computer is furnished with an internally decoded device selector buss, while the 620 requires external decoding. The busses are connected to the selected input switches or output latches based on the select lines called by the program codes in the computer. Data are shunted via the data busses under computer control.

In operation, outputs 2 - 7 were used to drive the display panel light emitting diodes; output 1 was used for an event counter; and output 8 was left unused. Inputs 2 - 7 were used for the digi-switches; input 1 was used to read the program and mode selector switches; and input 8 was not used.

Although the system is complex, it is straightforward in concept and it functioned well. Both computers could be accessed from computer control panel switches and via teletype control. The ROLM NOVA computer was also provided with a Sykes Compucorder which allowed rapid computer loading and continuous data recording for later off-line analysis. The 620 could be loaded only from the teletype via paper tape or from its control panel switches.

H. POWER SYSTEMS

The vapor detection systems were initially designed to be operated primarily from a nominal 28 Vdc source. Exigencies of rapid deployment into unanticipated applications led to some departures from the purity of this purpose. While both complete systems have been operated from 28 Vdc primary sources, some of the elements which could not be modified in the time scale required were operated by either rotary or solid state sources of 115 V alternating current. Except for a modest weight penalty, the rotary source is very satisfactory, having reasonable stability of frequency and regulation and very good surge capacity.

In the first installation made in a Volkswagen Microbus two rotary sources each of 750 volt-ampere capacity were used. These units supplied the primary power for the 620 computer system which was served by the factory engineered 115 V, 60 Hz power system incorporated. They also served the primary power needs of the display oscilloscope and certain internal power supplies which were incorporated into the mass spectrometer analog electronics. The results were sufficiently successful that

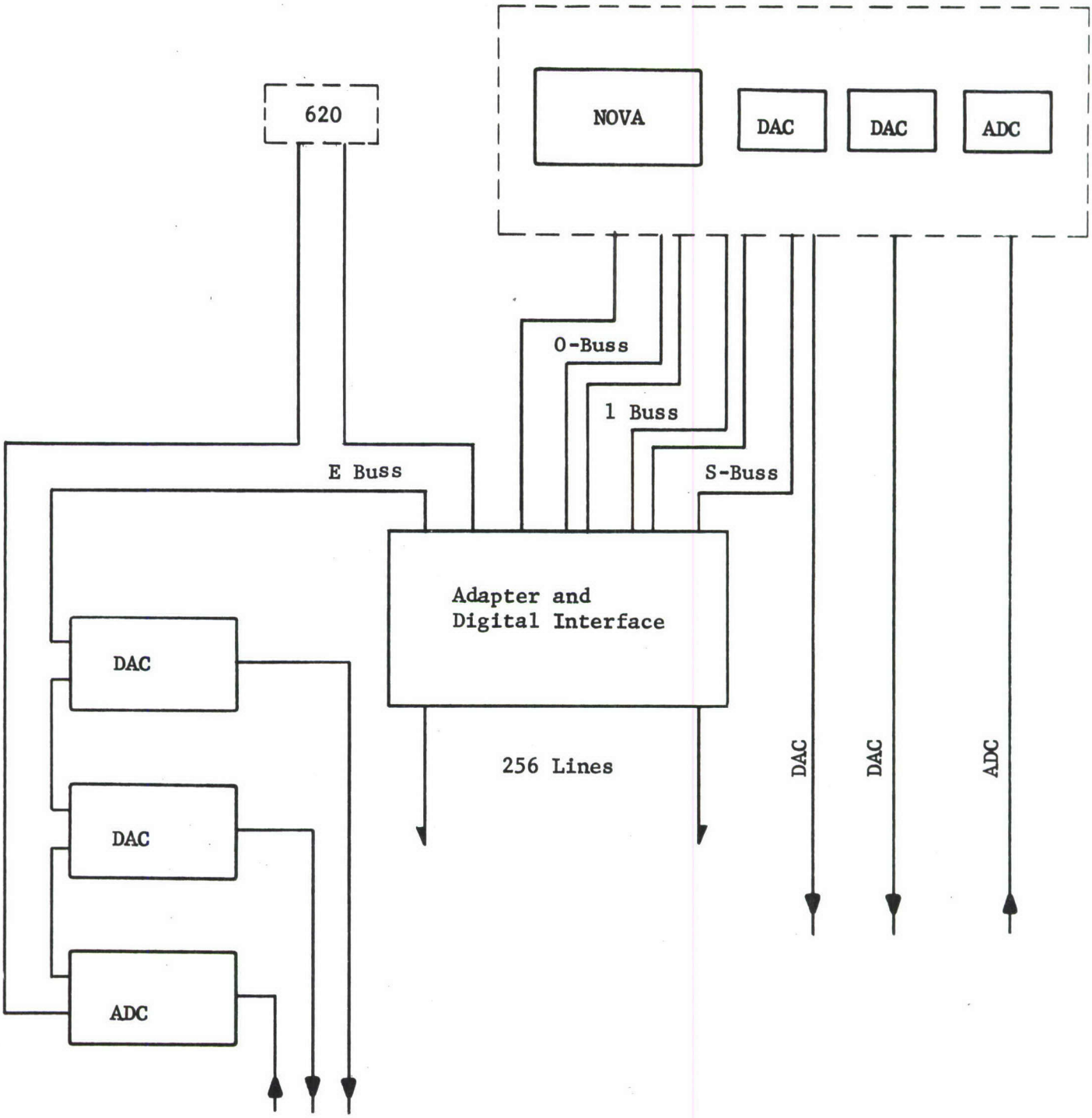


Figure 12. Computer Installation

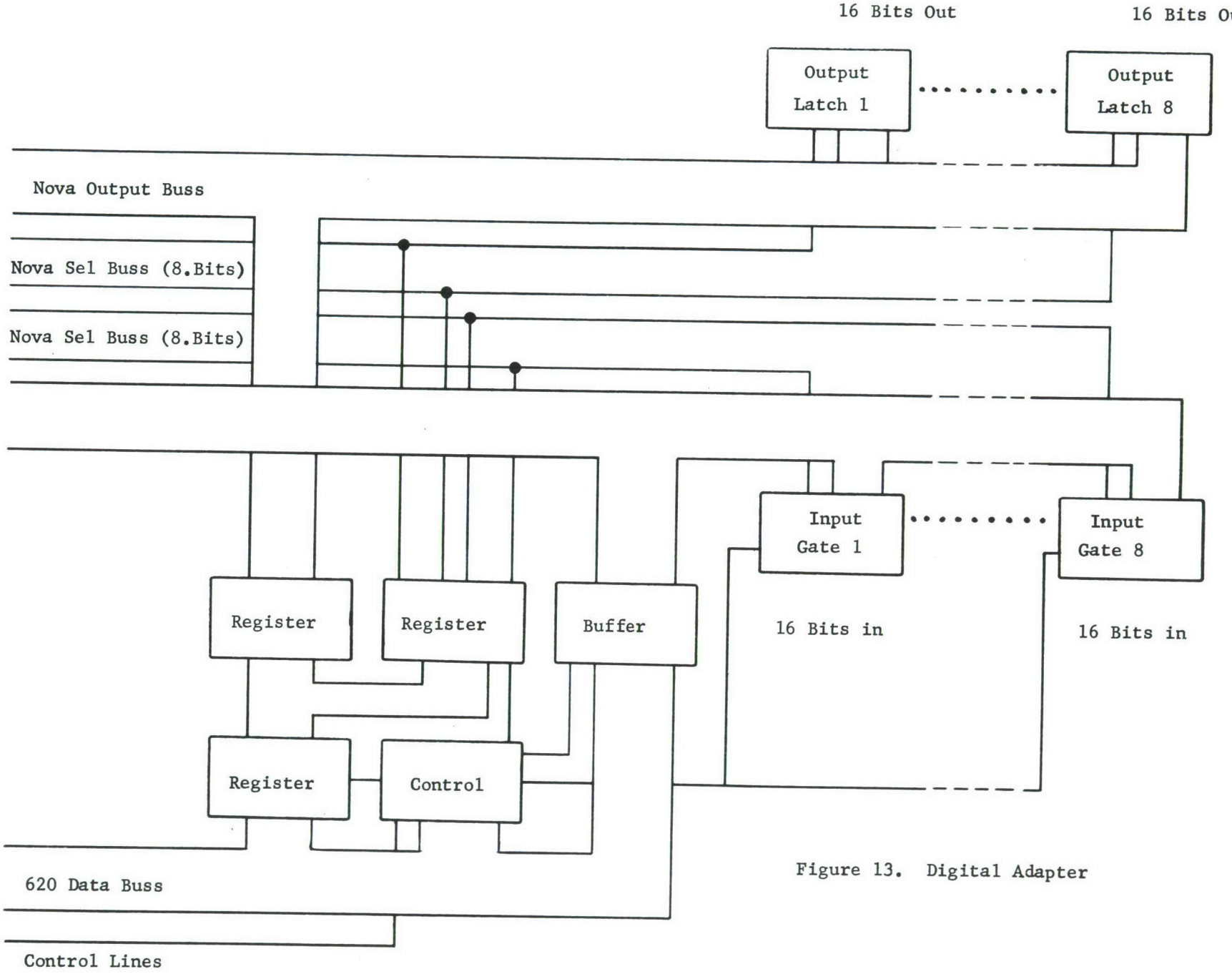


Figure 13. Digital Adapter

rotary converters were introduced into the power design of a series of four vehicle-mounted units being prosecuted under Contract No. DAAD05-73-C-0091. The Microbus application carried an on-line teletypewriter which has more stringent frequency requirements than other equipment served. Power for this unit was furnished from a high grade solid state converter rated at 500 volt-amperes with specified frequency stability of 0.1%. This unit was subject to frequent failures to satisfy the starting demand of the teletypewriter.

The Microbus engine supplied primary power to the system with an engine-driven generator of 28 Vdc at 70 A. This generator was buffered by a 24 V battery made up of two 12-V heavy duty lead-acid automotive batteries. This system presented a noticeable but not excessive load to the Volkswagen engine. It was completely satisfactory for continuous operation after early problems of belt slipping had been solved. (The engine also carried the load of an air conditioning system.) Overload protection for this system was provided by high grade fuses. One fuse failure occurred in service as a result of the continuous load rather than a fault.

In the second system installed in a fixed wing aircraft, it was possible to omit the need for large amounts of 110 V 60 Hz power. This system was fitted with the ROLM-NOVA computer which is powered by a 110 V 400 Hz solid state source furnished by ROLM and modified to operate from 28 Vdc primary power. The spectrometer system itself was for the most part operated from 28 V primary power. The Sykes compucorder, requiring 115 V 60 Hz power, was operated from a small 250 volt-ampere solid state converter. All of the equipment was attached via circuit breakers to the aircraft 28 V battery buss, and the engine driven generator had ample reserve current to supply the system.

Each of the systems, of course, required continuous power at 28 Vdc to drive the ion pump power supply. Since this supply placed a demand of less than 1 A, battery reserve was quite adequate to maintain the pump supply with generator power off in both installations.

III. INSTALLATIONS AND UTILIZATIONS

During the course of equipment development under Contract No. DAAD05-70-C-0197, a series of tests were conducted to test the feasibility of the vapor detection method for detection of chemical effluents of interest to the Dept of Justice. The early success of these tests persuaded the Land Warfare Laboratory to place equipment being developed under Contract No. DAAD05-70-C-0197 on loan for tests and operational evaluation. These tests and operations are reported elsewhere; however it is appropriate to mention briefly the installations and utilizations herewith.

A. FIRST INSTALLATION, VOLKSWAGEN MICROBUS

The first installation was hastily performed under contracts numbered DAAD05-72-C-0091 and DAAD05-72-C-0109 in a Volkswagen Microbus. (Mention has already been made of the power system used.) When the requirement was placed, a Microbus was procured and outfitting commenced immediately. The windowless rear compartment was curtained off from the drivers compartment, and fitted for the needs of the vapor detection system and reasonable comfort of the operators. A two section L-shaped table was installed for working space and to mount the equipment. The equipment table which was approximately four square feet in size, was shock mounted to reduce vibration on the equipment. Chairs were installed for the operators. The entire compartment was insulated and carpeted to reduce noise and to promote operator comfort. An air conditioner was installed and lighting and radio communications equipment were furnished. The essential elements of the installation, exclusive of the primary power source weighed approximately 250 pounds and required about 1200 watts of power. Photographs of the Microbus installation appear as Figure 14 and 15.

The mass spectrometer system and its required support equipment were mounted on the tables and floor of the compartment. Main power and power controls were installed; the entire system was self-contained in the vehicle. An inlet system was added by way of a port through the roof of the vehicle. This inlet, patterned after earlier designs, was made up of two heated sections, one to bring sample air rapidly to the vicinity of the inlet, and a second to intercept a central portion of this air and deliver it to the separator inlet port, see Figure 16. Short and long inlet stacks were furnished. No attempt was made at this stage to disguise them.

When the system was installed it was tested briefly on a local basis. The installation represented the first assembly of a fully computer controlled system. The software had only recently been written, and although it was debugged it was not yet completely familiar. Operation of the computer at this stage had to be accomplished through front panel controls and the teletypewriter installed. In spite of this early stage of development, it was possible to demonstrate in a qualitative fashion the performance of the equipment. Sensitivity was comparable to previous installations, and with some minor faults discovered and corrected, the entire system functioned satisfactorily.

Figure 14. Exterior of Microbus Installation

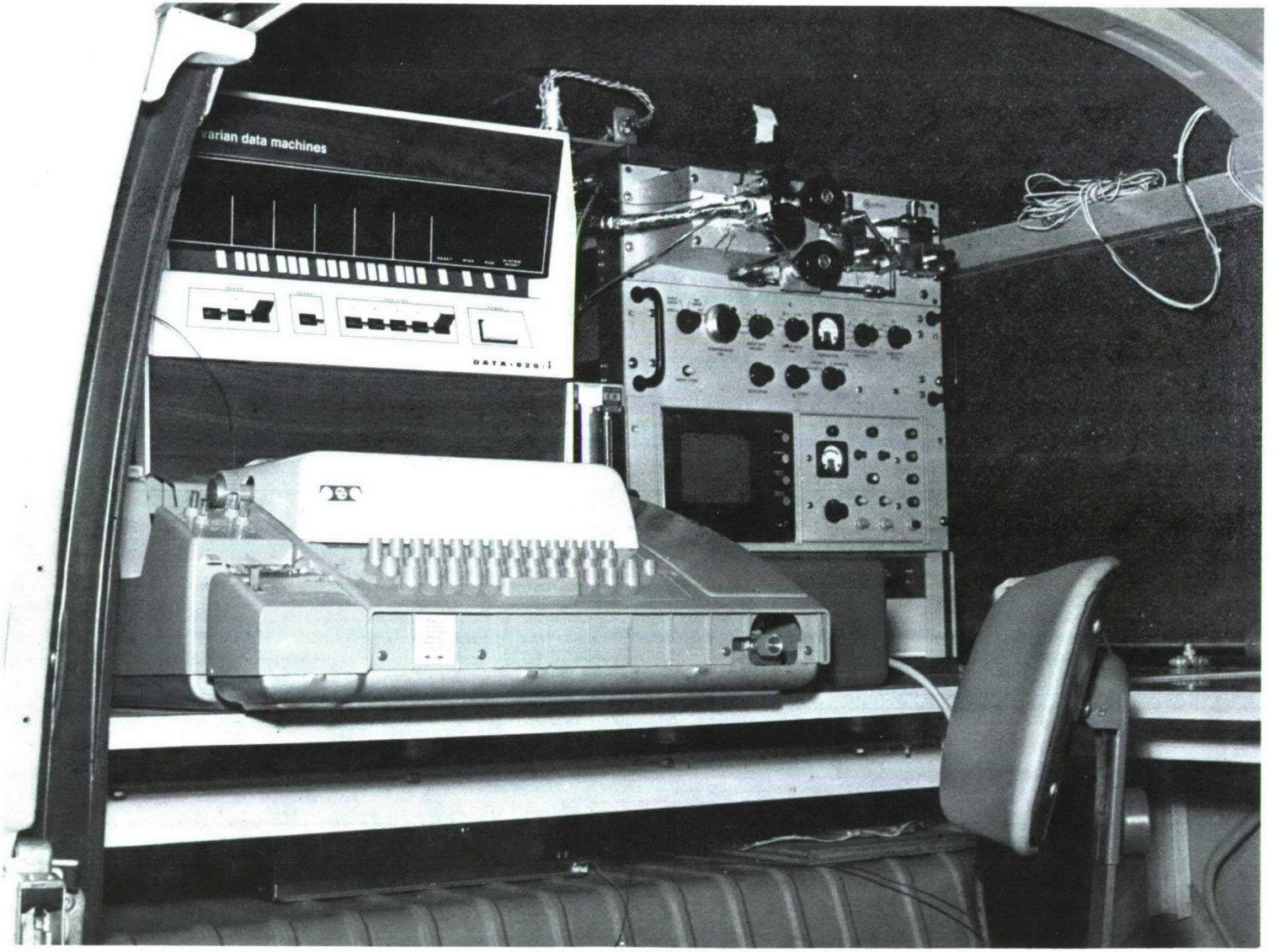
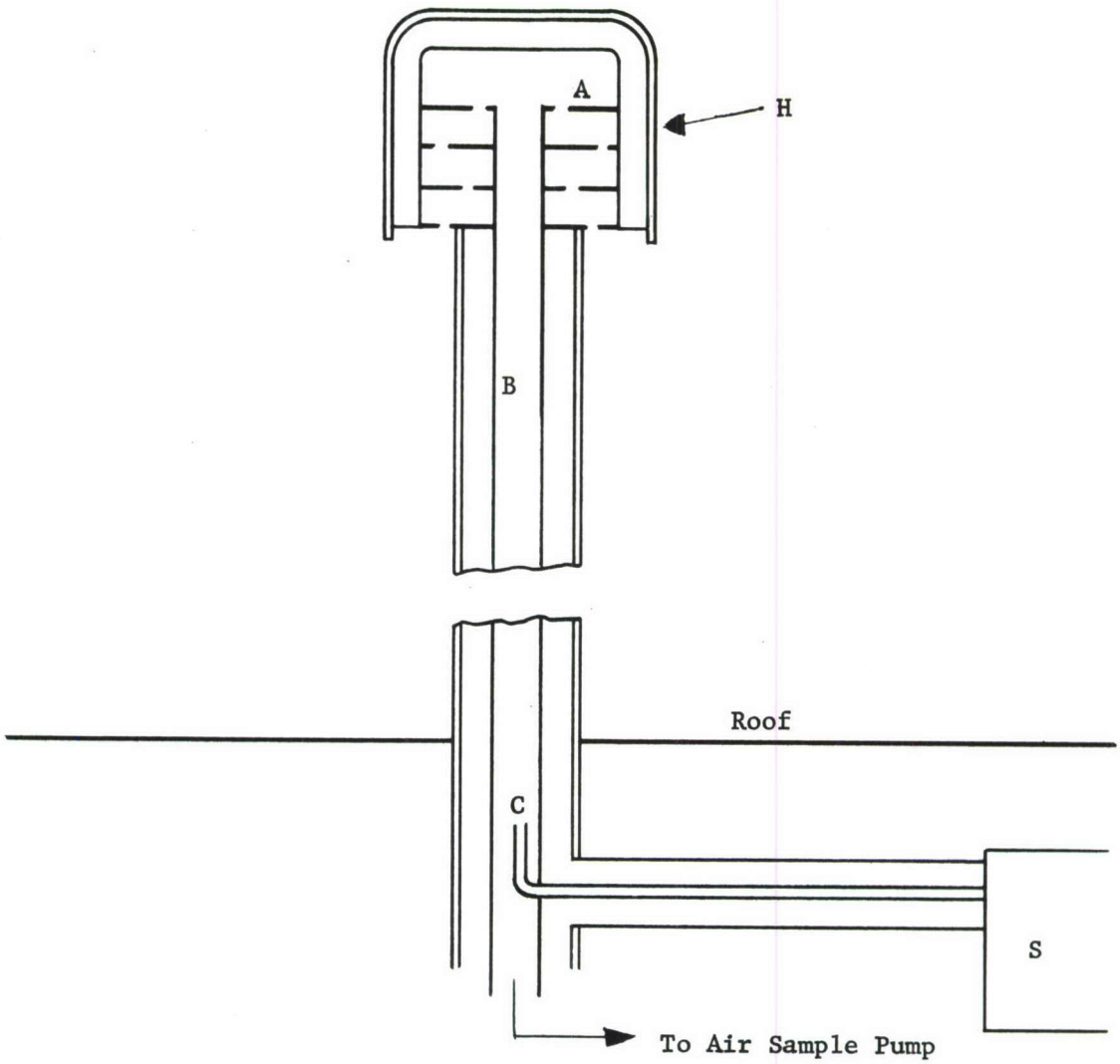


Figure 15. Interior of Microbus Showing Installation of Vapor Detection Equipment



A. Heated gold plated copper inlet baffle

B. Heated primary sample tube

C. Heated separator inlet tube

H. Weather shield

S. Separator

Figure 16. Microbus Sample Inlet

In August of 1971 a three-week series of tests in an operational environment was begun. During this exercise, the spectrometer system functioned consistently well. Considerable difficulty was encountered with the continued operation of the digital system. The most vulnerable element proved to be the teletypewriter. Minor modifications were made in the stored program to improve the presentation of processed data and reduce the vulnerability to teletypewriter faults.

Detections were made of effluents from controlled targets and targets of opportunity. Results of the tests showed that a great deal of importance must be given to local micrometeorology at the target sites in planning operations and strategy.

At the conclusion of the three week's exercise, system performance had become rather less reliable due primarily to deterioration of the teletypewriter, and the equipment was demounted from the vehicle and returned for renovation.

B. SECOND INSTALLATION, FIXED WING U-10 HELIOCOURIER

The second installation was made in the cabin of a United States Air Force Model U-10 Heliocourier fixed-wing aircraft. This installation, like that in the Volkswagen Microbus, was also constrained by a very short schedule of installation time. Specific installation details were in large part dictated by the necessary use of components which were immediately available. Limitations of size, weight and power indicated the use of the digital system based on the ROLM-NOVA computer rather than the Varian 620 system used in the Microbus. There was no room to include the teletypewriter for the in-flight operation. The only operator access to the stored program in flight was via the detachable ROLM-NOVA computer control console. This constraint was not serious with the entire system operating correctly. Improvements in software reduced the requirement for on-line access to the stored program, and a Sykes Compucorder was furnished to load program tapes and to record detection data.

The cabin installation is shown in Figure 17. The operator's seat faces the rear of the cabin. Principal components of the spectrometer system are supported in the rack which is about 24 inches high and mounted securely to the floor and chained to cabin structural members. Other elements of the system were mounted around the operator's seat and were within easy reach in flight. The power requirement was less than 1000 watts which was readily supplied ty the 28-volt DC generator main line of the aircraft.

Two features of the installation are worthy of special note; namely, the sample inlet tube and the installation of the HELNAVS navigation computer and coordinate printer.

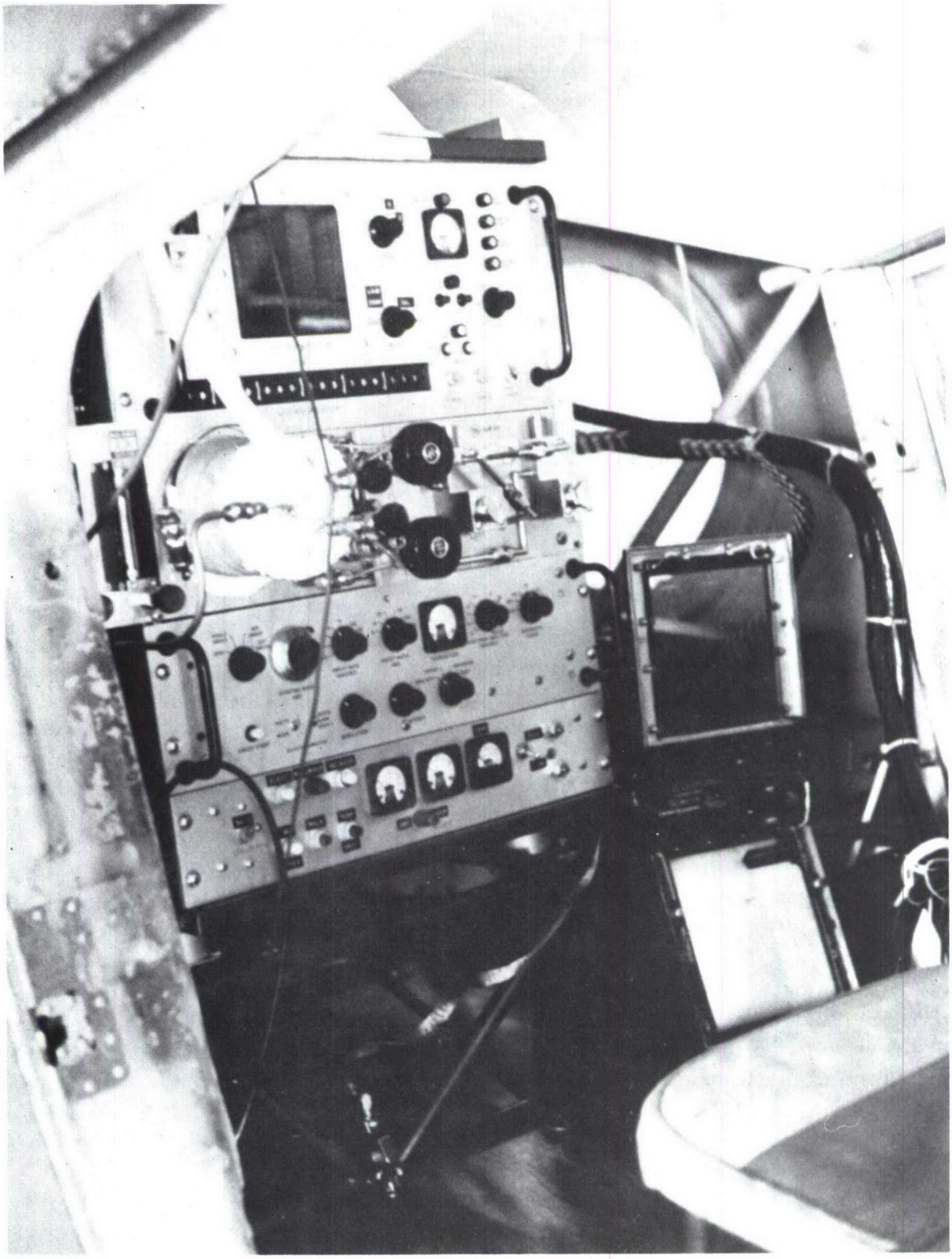


Figure 17. Operator's Station in U-10 Aircraft

The inlet tube is required to transport sample air containing traces of target vapors from the ambient air to the separator inlet of the mass spectrometer. This transmission must be rapid and sample losses due to condensation or partition on inner walls of the inlet tube must be avoided. In the U-10 installation, the sample probe was mounted under the wing of the aircraft at a point outside the projected propeller disc. This location required the inlet tube to be approximately 8 feet long. Previous experience has shown that to avoid condensation and partition of sample on the inner walls of an inlet tube, all surfaces in contact with the incoming air must be heated. Favorable surfaces are stainless steel and gold. To maintain surface temperature the inlet probe was fitted with a heavy gold-plated copper section which could be kept heated even in the airstream encountered in flight. Air flow in this section was turbulent, thereby ensuring the heating of the air entering the longer section of the inlet tube.

The long run of tubing from the gold-plated copper probe section to the interior of the aircraft was made of stainless steel. Tubing bore was approximately 0.330 inch, and flow rates were adjusted to give a transit time of less than three seconds. A small sample was extracted from this large flow at a point close to the inlet/separator section of the mass spectrometer. The entire arrangement permitted rapid transport of sample air to the spectrometer without loss of target materials by condensation or partition.

The second notable installation feature, (during the second deployment of the U-10 aircraft), was the HELNAVS navigation system. This unit was installed by LWL personnel. It is a sophisticated system operating with Loran signals which are computer processed to give navigational coordinates. These coordinates are displayed on the pilot's panel and, in addition, are printed in real time on the chart recorder which also writes a hard copy detection signal. By means of this record, in post-flight analysis, a true geographical plot of detections can be made to outline plume areas.

The U-10 aircraft installation was deployed for two separate field test cycles. Results of the flights are reported elsewhere.[2] The operation of the mass spectrometer was successful in detecting plumes. A principal conclusion of these operations was that the detections depend critically on the local micrometeorology. In addition, particularly during the second deployment, false alarms from other sources than the target were noted indicating a possible need for more refined data processing in the utilization of mass spectrometer vapor detection.

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The operation of the equipment in the U-10 installation was not without some difficulties. These were for the most part related to the operation of the digital equipment and were traceable in part to lack of sufficient experience in the operation

of the equipment and the software. Although the Sykes Compucorder could, in principle, load the stored program to the computer, the loading program itself was occasionally lost, and, on several occasions, the entire program had to be loaded tediously by hand using the externally attached teletypewriter. (Later use of the Sykes Compucorder was made much easier by the incorporation in the software of a very simple bootstrap loader which requires manual loading of only 16 instructions.)

IV. SOFTWARE

The software concept used for the equipment was based on an off-line computer reduction of field data gathered in the test of experimental vapor detection equipment built under Contract No. DAAD05-68-C-0335. In the systems, the computers perform three major tasks; namely, the control of the mass spectrometer, the processing of the data gathered, and the operation of the display systems.

The detection event is the recognition of the fact that selected peaks of the mass spectrum increase over their background values when target sample materials are presented to the mass spectrometer. This change occurs in a time period which is short when compared with the rate at which the background levels of these peaks vary. The structure of the program is designed to direct the spectrometer to scan selected peaks, to accumulate data over a period of time, and, after computation to present the short term variations of the peak values in a manner which can be interpreted by an operator.

Spectrometer control algorithms were assembled originally in an 8192 word program with an elaborate teletypewriter interactive routine for laboratory exploration of this function. Several valuable routines were refined from this program; notably the selection of a mass peak, its sweeping, and the accumulation of left and right half-peak intensity data. In addition, the program was provided with a routine for generating the proper sweep digital-to-analog, (DAC), values for peaks called. This was accomplished by use of a linear interpolation between stored key DAC numbers, thereby obviating the need to store DAC conversions for the entire span of the spectrum.

Out of this program, the following simplified sequence was developed for data acquisition:

1. Get tabular peak mass number
2. Get starting DAC value for spectrometer sweep
   a. Locate linear interpolation key DAC values
   b. Perform linear interpolation
3. Sweep the spectrometer, one-half peak or full peak as required
4. Get peak value from electrometer
5. Put value in temporary storage.

This sequence involves the use of several general and special purpose subroutines. These are incorporated in the final program to operate the spectrometer and the electrometer in a completely satisfactory way.

The next step in the structuring of the software was the generation of an executive routine to organize the utilization of the spectrometer routine above and to distribute raw data to the first column of a data matrix. This executive routine was a loop structure outlined in the following steps:

1. Begin idle loop
2. Test operator switch selection; if no switches are set, loop idle.
3. Set operation pointers in spectrometer sweep routine.
4. Call the sweep routine to acquire data from six selected peaks and one reference peak. Pointers indicate a mass table and direct data to Column 1 in the data matrix.
5. Return to idle loop.

When this sequence was operating satisfactorily, a data reduction routine was written. This routine generated three sets of moving average values for the primary data and distributed these values to second, third, and fourth columns of the data matrix. The algorithm for this computation is the following:

$$C_k^{(0)} = \left[A_k \; C_k^{(1)}\right] + (1 - A_k) \, C_{k-1}^{(0)}$$

Where C_k is the columnar value for the k^{th} column and the superscript (0) indicates the current value, while the superscript (1) implies the next previous value. "A_k" is a number less than unity which defines the filtering time for the data in column k. The computation in this data reduction step utilizes several subroutines incorporated in the final software, and the resulting data matrix after a complete cycle contains current values of the three moving averages computed without explicitly storing data from a large number of previous cycles. The use of this compact form of data accumulation does allow the necessary "long memory" for the interpretation required to recognize a detection event.

The final step performed by the computer is the generation of display elements from the processed data. The operator is presented with six pairs of visual information elements, each pair associated with one of six selected peaks. This information is represented by the height of bars or dots in the visual display, members of each pair being designated by B_M and D_M. These are scaled heights of departure of shorter term data from longer term average values for each mass M:

$$B_M = \frac{C_3 - C_4}{C_4} \qquad \text{(background changes)}$$

$$D_M = \frac{C_2 - C_3}{C_4} \qquad \text{(detection events)}$$

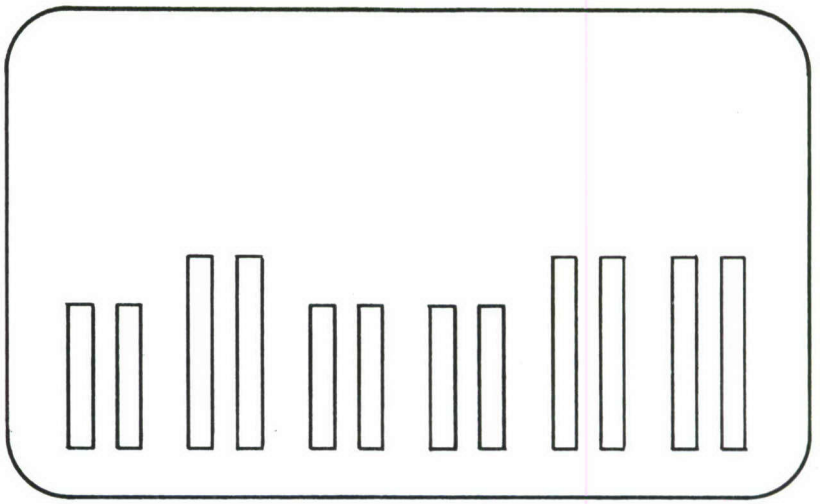
The selection of the columns of processed data used for generating B_M and D_M could, of course be varied as could the A_k. The selection of columns and averaging times best suited to a detection situation was chosen empirically to give the greatest detection contrast.

The final program was modified to incorporate scale factors for B_M and D_M such that

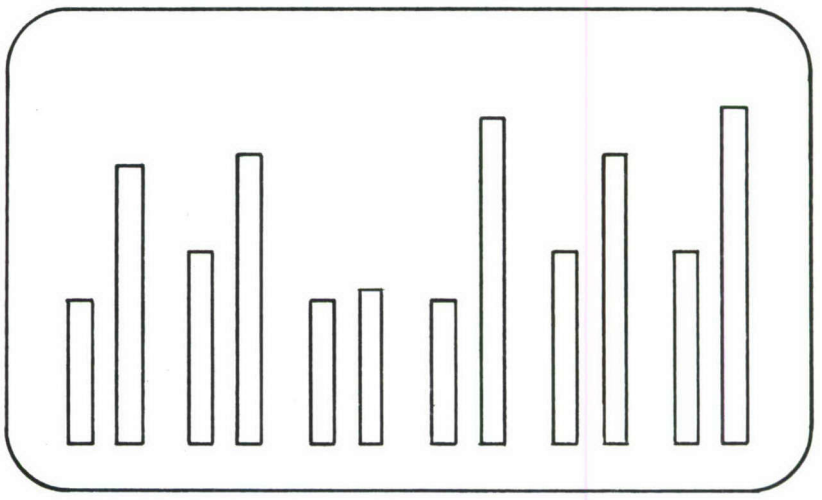
$$B_M \rightarrow F_M \frac{C_3 - C_4}{C_4}$$

$$D_M \rightarrow F_M \frac{C_2 - C_3}{C_4}$$

A diagram showing the appearance of a bar pattern display is shown in Figure 18 for both background and detection situations. The display of B_M and D_M was provided with scale compression to maintain a sensitive indication of small changes, while giving sufficient dynamic range to display large events. The display format was very effective in communicating to the operator the detection significance to be inferred from the very large number of data elements produced continuously by the mass spectrometer.



A: Background Indication



B: Detection on Five of the Six Peaks Selected

Figure 18. Operator's Display

V. CONCLUSIONS

The two vapor detection systems developed under this task successfully demonstrated the feasibility of producing, mounting and using portable mass spectrometer systems in an operational environment.

The evaluation, although concentrated on a specific class of chemicals, showed that targets of military interest could be detected by sampling distinctive effluents emanating from the targets. The detection of part-per-billion level trace vapors permits detection at operationally useful ranges under most weather conditions.

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